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Perspective

Utilizing multi-objective decision support tools for protected area selection

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https://doi.org/10.1016/j.oneear.2023.08.009

SUMMARY

Establishing and maintaining protected areas (PAs) is a key action in delivering post-2020 biodiversity targets. PAs often need to meet multiple objectives, ranging from biodiversity protection to ecosystem service provision and climate change mitigation, but available land and conservation funding is limited. Therefore, optimizing resources by selecting the most beneficial PAs is vital. Here, we advocate for a flexible and transparent approach to selecting PAs based on multiple objectives, and illustrate this with a decision support tool on a global scale. The tool allows weighting and prioritization of different conservation objectives according to user-specified preferences as well as real-time comparison of the outcome. Applying the tool across 1,346 terrestrial PAs, we demonstrate that decision makers frequently face trade-offs among conflicting objectives, e.g., between species protection and ecosystem integrity. Nevertheless, we show that transparent decision support tools can reveal synergies and trade-offs associated with PA selection, thereby helping to illuminate and resolve land-use conflicts embedded in divergent societal and political demands and values.

INTRODUCTION

Halting biodiversity loss is one of the major global challenges faced by humanity in the 21st century.[1,2] Human wellbeing, livelihoods, and economies all rely on biodiversity, and collaborative international efforts are needed to conserve it.[1,3] Protected areas (PAs) are a cornerstone of biodiversity conservation. Aichi Target 11 of the Convention on Biological Diversity called for an increase in PA coverage to 17% by 2020 for the terrestrial realm, with a focus on PAs that are of particular importance for biodiversity and ecosystem services, ecologically representative, and well connected[4]; this goal has only partly been reached.[5] Further, Aichi target 11 is increasingly seen as inadequate to safeguard biodiversity.[6–8] The Kunming-Montreal Global Biodiversity Framework (GBF), which builds on the Aichi targets, has set out 23 action-oriented global targets in line with an ambitious plan to implement broad action that should transform our societies' relationship with biodiversity by 2030.[9] Action Target 3 of the GBF calls for at least 30% of the terrestrial area to be effectively conserved by PAs or "other effective area based conservation measures."[9] This implies not only the transformation of large land areas into new PAs over the next decade but also stresses an urgent need for careful allocation of the long-term conservation funding necessary to effectively protect biological resources: PAs must be both sustainably funded and effectively managed, yet only about 20% of all PAs are considered to meet these criteria.[10] Meanwhile, many PAs have experienced PA downgrading, downsizing, or

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Table 1. Comparison of strengths and weaknesses of the approach advocated and implemented in this study vs. already existing approaches

Approach	Methods (tools)	Strengths and weaknesses	Example studies	Objectives considered in the example studies
Single objective	mapping	+ prioritization map based on one conservation objective − solution for one objective	Di Marco et al.,[35] Riggio et al.[36]	ecosystem integrity
Multiple objectives	mapping, stacked layers	+ combined prioritization map across multiple objectives − static solution, all objectives equally important	Jung et al.,[37] Dinerstein et al.[8]	biodiversity, ecosystem services, climate protection
Multiple objectives + fixed weights	mapping, stacked layers, consensus score	+ combined prioritization map across multiple objectives + objectives (or variables within objectives) can be weighted individually − static solution	Freudenberger et al.,[38] Girardello et al.[39]	biodiversity, ecosystem services, ecosystem integrity
Multiple objectives + flexible weights	mapping, stacked layers, weighted consensus score, individual ranking of sites	+ combined prioritization map across multiple objectives + comparison of trade-offs on the fly + flexible solution	this study	biodiversity, ecosystem integrity, climate protection, climatic stability, land-use stability, size

The table summarizes a literature review and gives a few selected examples. The review focused on studies that published global prioritization maps based on one or multiple conservation objectives and which identified individual sites of conservation importance rather than designed an optimized network of sites (see supplemental information and Table S1 for details and the considered studies).

degazettement (PADDD)[11] or are threatened by PADDD in the future.[11,12]

Both the allocation of sparse conservation funding for the strengthening of current PAs and the identification of additional sites to expand PA networks frequently require the application of prioritization approaches. A wealth of methods have been developed to inform conservation efforts, which vary widely in complexity. Some approaches evaluate individual sites based on their importance for the global persistence of biodiversity, e.g., the key biodiversity area approach, applying different threshold-based criteria including the proportion of threatened or geographically restricted species covered.[13] In contrast, others rely on complex algorithms to optimize conservation networks toward specific conservation goals, e.g., by considering complementarity, connectivity, or cost efficiency.[14–16]

Priority areas for biodiversity conservation can be defined based on one or more individual conservation objectives to identify areas of high conservation value under each or all given objectives. Initial approaches to identify such areas sought hotspots of various aspects of biodiversity such as species richness or endemism.[17–20] Other approaches highlight the protection of areas that will limit further impacts of global change on biodiversity, for example by identifying remaining ecologically intact ecosystems[21] or sites of high irrecoverable carbon storage.[22,23] Prioritization approaches that focus on more than one objective often combine different conservation goals such as protecting biodiversity and maintaining ecosystem services.

Here, we focus on those prioritization approaches that allow identification of individual sites of conservation importance rather than an optimized network of sites. We apply a transparent site-selection approach that allows users to prioritize sites based on various self-specified conservation objectives. The developed approach allows for an initial screening of potential priority sites for conservation. Trade-offs between different conservation objectives are identified and can be acknowledged explicitly and quantitatively.

THE CHALLENGE: ALIGNING CONSERVATION PRIORITIES

Aligning different conservation objectives has become increasingly important. For instance, conservation strategies that address both ongoing climate warming and biodiversity loss are urgently needed.[8,24] Nevertheless, setting priorities based on multiple goals is not always straightforward. If there are trade-offs among conservation objectives, a very different set of sites might be optimal under each objective, and a simple compromise among these might not select the best set for the group of objectives as a whole. Relying on approaches tailored toward a single conservation objective or the identification of one key element of the GBF targets may lead to the omission of other critical elements of the GBF vision.[25]

To date, a vast amount of literature on setting global priorities for conservation is available (see Table S1 for an overview relevant to this study). The different approaches vary in the number of objectives that are considered, ranging from one to multiple,

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and in the way the included variables are weighted, i.e., not at all or with equal or uneven weights (Table 1). One of the earliest efforts to highlight global areas of importance for biodiversity protection concerns the global biodiversity hotspots.[26] These were derived on the basis of the number of endemic species and habitat loss in the area. With the growing volume and availability of biodiversity data, more approaches to identify areas that are important for biodiversity protection have been introduced. Examples for individual or combined aspects of biodiversity that have been utilized for conservation priority maps are the global species richness patterns for terrestrial vertebrates or vascular plants as well as for various other taxonomic groups, but biodiversity metrics such as species endemism, phylogenetic and functional diversity, or threat status have also been used.[27–31] Similarly, increasing data availability and spatial resolution of those data has profited approaches that focus on prioritizing conservation sites based on the intactness of habitats and biomes or ecoregions.[32] Generally, priority maps for biodiversity protection can be derived on the basis of a single metric for biodiversity or be based on several combined metrics, for example by combining the biodiversity value of an area with the level of threat through human impacts such as habitat degradation within the area[33,34] (see Note S1 and Table S1 for more examples).

Several efforts have also been made to align multiple conservation objectives, such as the protection of biodiversity, the preservation of ecosystem services, and the preservation of areas important for climate mitigation. An example (Table 1) is the comparison of the spatial alignment of terrestrial biodiversity, carbon storage, and water quality regulation, and the identification of areas with the highest synergies among these objectives.[37,40,41] However, there is also evidence for trade-offs among conservation objectives; for example, biodiversity hotspots do not always overlap with different ecosystem services.[42] In summary, a wealth of spatial prioritization maps for conservation efforts has been produced by all these different approaches, either to combine different biodiversity metrics or to align different conservation objectives. In fact, Cimatti et al.[43] subsequently combined 63 different global prioritization maps to derive one spatial prioritization map and identify scientific consensus regions among the different approaches. Nevertheless, all of these selection approaches have one aspect in common: they result in a unique solution for one or a few specific and aligned objectives that select a static geographic set of priorities (Table 1). Here, we advocate a more flexible approach that can handle multiple and conflicting objectives.

The weaker the alignment is among different conservation objectives, the greater is the influence of priority setting (i.e., favoring specific conservation objectives) on the outcome of site-selection approaches. If trade-offs are prevalent, explicit values-based decision making is necessary. The relative priority of different conservation objectives varies among different societal groups, which differ in their demands and values.[44] Also, key local, national, and international actors—governments, corporations, non-governmental organizations (NGOs), scientists, and funders or sponsors—are likely to differ in their priorities.[45] Therefore, decisions as to which areas should be prioritized are often strongly values based, with the values underlying final compromises rarely being made entirely explicit and transparent. Societal and political values are also likely to change over time, since the purpose of conservation itself has been transient over time, with priorities changing to some degree from one generation to the next.[46] All of this substantiates the need for a flexible but transparent approach to priority setting, where different conservation objectives can be explicitly considered and weighed against each other, to facilitate deliberative societal and political decision making.

TOWARD A SOLUTION: FLEXIBLE AND TRANSPARENT SITE SELECTION

The allocation of conservation funding is one example whereby the use of a flexible and transparent prioritization approach can be advantageous, since the decision process is likely to involve multiple stakeholders, each of whom may have multiple objectives. Use of a decision support tool can support the identification of conservation synergies and trade-offs, facilitate deliberation and dialog among stakeholders, and enable evidence-informed, values-based collaborative decision making. Here, we illustrate these ideas using a site-selection tool that we developed for this task. We apply a transparent site-selection approach that allows users to identify investment priorities among existing PAs based on various self-specified conservation objectives. In contrast to other approaches, conservation objectives in our approach are explicitly weighted by the users and the results can be immediately assessed, aiding discussions during a transparent values-based decision-making process. We implemented the approach for the terrestrial realm, exclusively using biogeographic information that is publicly available at a global scale. We aimed to identify areas with the highest potential for a range of biodiversity and climate protection goals, but excluded any information on political and economic dimensions from the site-selection algorithm; although these considerations are crucial for conservation and should be evaluated equally transparently, we believe that they should be evaluated separately from biogeographic information as an additional step in the decision-making process.

We defined six different conservation objectives (Figure 1), which represent a broad agreement on priorities for safeguarding biodiversity, climate protection (in the sense of mitigating ongoing climate change), and the present and projected future status of individual sites (identified in an initial stakeholder dialog; see also case study details below). These objectives were: (1) high current biodiversity, focusing on high biodiversity values; (2) high current ecosystem integrity, which focuses on areas that have experienced relatively few anthropogenic impacts; (3) high climate protection, which selects for sites that have large, irrecoverable carbon stocks; (4) large size, which prioritizes larger sites; (5) high land-use stability, which focuses on the future likelihood of land-use change in the immediate surroundings of sites; and (6) high climatic stability, which highlights sites in which climate change is projected to have low impacts on current biodiversity.

We collated a broad set of conservation indicators that reflect these six conservation objectives (Figure 1). The biodiversity objective considered as indicators the total terrestrial species richness of four vertebrate taxa (birds, mammals, amphibians, and reptiles), as well as species endemism and evolutionary diversity[47] for each taxon, to capture the amount of biodiversity as

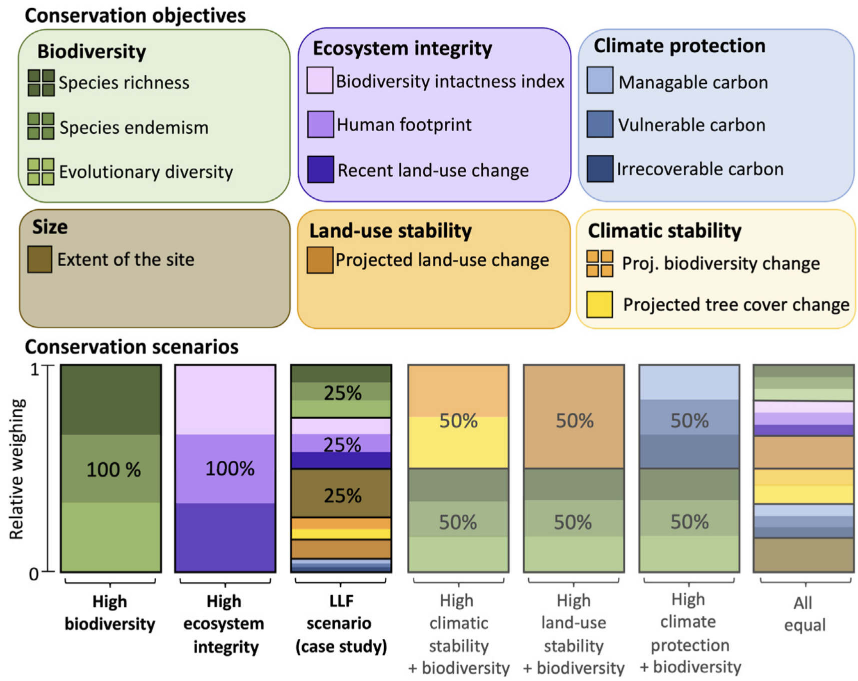

Figure 1. The included conservation objectives

The six conservation objectives defined to set priorities for the site selection, the indicators considered for each objective (note that biodiversity and climatic stability [of biodiversity] include indicators for four different vertebrate taxa), and examples for conservation scenarios based on these objectives. By applying a weighting approach, user-specified objectives can be combined into different conservation scenarios, which are therefore customized for specific conservation goals. The high biodiversity, high ecosystem integrity, and Legacy Landscapes Fund (LLF) scenarios are used in the case study.

well as its irreplaceability. The ecosystem integrity objective considered biodiversity intactness, recent land-use change, and the human footprint within the site. The climate protection objective considered the average amount of carbon per hectare that is stored in the vegetation and soil (up to 1 m below ground) of the site and its vulnerability to typical land conversion. The size objective covers the extent of the site in square kilometers. The land-use stability objective considered the projected change in land use in a buffer zone around the site. The climatic stability objective considered the biodiversity change based on the projected future compositional change (turnover)[48] of the four vertebrate taxa and the projected change in tree cover within the site.

These conservation objectives and the underlying indicators were carefully selected to reflect the demands toward the PA network based on the post-2020 GBF as well as the current state of the literature addressing both the biodiversity and climate crises. The biodiversity objective combines information on the number, diversity and rarity of species across several higher taxa within the area to include different aspects of biodiversity.[47,49–52] Highlighting those sites that are of particular importance for biodiversity is in line with the first part of Action Target 3 of the post-2020 GBF.[9] The ecosystem integrity objective uses information on recent impacts on the site and the intactness of the local ecological communities, highlighting those sites that contain ecosystems that are still largely intact. This objective was included because remaining intact ecosystems are often not directly addressed by conservation efforts or international policy frameworks[21,53] but provide various key functions, such as acting as critical carbon sinks, stabilizing hydrological cycles, or providing crucial refuge for imperiled species, intact mega-faunal assemblages, or wide-ranging or migratory species.[21,54–59] The size objective is somewhat related to the ecosystem integrity objective, under the assumption that larger areas have a higher potential to support populations of target species and maintain functioning ecosystems in the long term.[60,61] The climate protection objective is related to Action Target 8 of the post-2020 GBF[9], which aims to minimize the impacts of climate change on biodiversity.

The final two objectives were included to assess sites not only based on their current importance for biodiversity, ecosystem functioning, and climate protection, but also based on the most major future threats toward biodiversity, i.e., projected future climate and land-use change. The five direct drivers of biodiversity loss with the largest impact, according to the 2019 Global Assessment Report by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, are changes in land and sea use, direct exploitation of organisms, climate change, pollution, and invasion of alien species.[1] The climatic and land-use stability objectives provide an indication of potential future changes within the site based on climate change responses (geographic range shifts) of the local flora and fauna within the region and give an indication of which sites might be under increasing pressure of land-use change in the region.

A key aspect in developing a transparent site-selection approach was to make results of different values-based objective weighting immediately accessible to a broader audience, including decision makers. We therefore developed an open-source spatial decision support tool to facilitate the priority-based area-selection process. The tool generates a ranking of sites globally as well as for each biogeographic realm based on the six conservation objectives, which are weighted individually by the user. Using sliders to allocate weights to the six conservation objectives, users can design their own conservation scenarios "on the fly" (examples see Figure 1) and directly visualize the resulting ranking. The tool allows a comparison of a far wider range of different conservation scenarios than the examples we give here to evaluate synergies and trade-offs among these and select sites for a more detailed investigation. The current version is publicly available (https://ll-evaluation-support-tool.shinyapps.io/legacy_landscapes_dst/) and restricted to the case study dataset, objectives, and indicators presented in the paper, but the flexible approach we use can be implemented easily to other datasets, objectives, and goals.

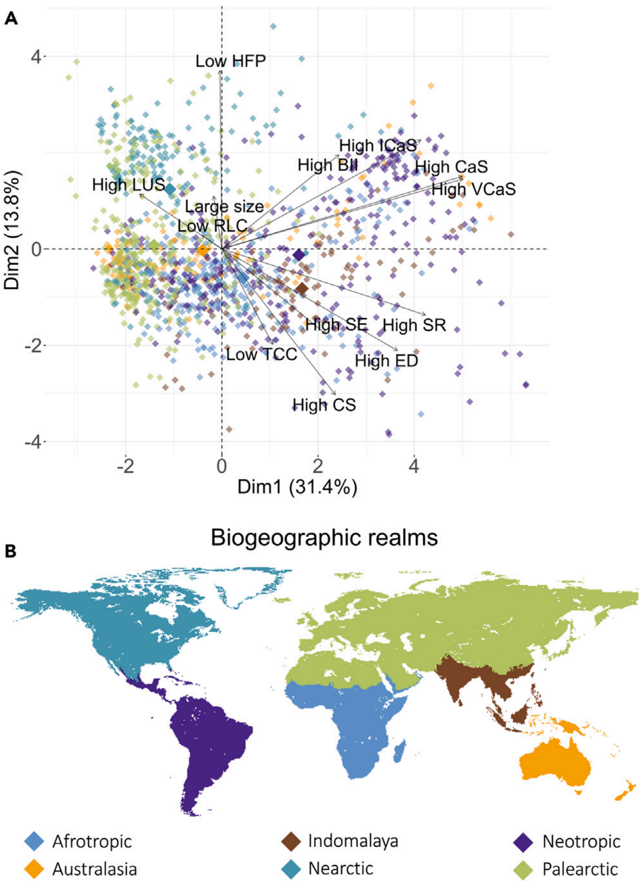

Figure 2. Trade-offs and synergies between the conservation indicators of individual sites

Shown are the first and second dimensions of a principal component analysis (PCA) that was performed across 1,346 sites and their variation in 13 indicator variables aggregated into six conservation objectives (order of indicator variables in the legend aligns with Figures 1 and 3; see these for matching variables to objectives) (A). The first and second PCA dimensions together explain 45.3% of the variation in the data. Each dot represents one site. The arrows represent the indicators, and the arrow length indicates the loading of each indicator onto the PCA dimensions (i.e., their correlation with each principal component). Opposite loadings indicate trade-offs between the variables (i.e., a site that has a high value in one of these variables has a low value in the other variable and vice versa). The individual sites (points) are colored by the biogeographic realm (B) in which they are located.[65] High SR, high species richness; High SE, high species endemism; High ED, high evolutionary diversity; High BII, high biodiversity intactness; Low HFP, low human footprint; Low RLC, low recent land-use change; High CaS, high manageable carbon storage; High VCaS, high vulnerable carbon storage; High ICaS, high irrecoverable carbon storage; Large Size, large size; High LUS, high land-use stability; High CS, high climatic stability; Low TCC, low tree cover change.

ILLUSTRATION OF THE SELECTION APPROACH: THE LEGACY LANDSCAPES FUND AS A CASE STUDY

The Legacy Landscapes Fund (LLF) is a recently established foundation that provides long-term funding for PAs[62]; it is useful in this context because it uses our six conservation objectives, operates on a global level, and mostly focuses on existing sites. This allowed us to run a case study across a significant set of PAs and other sites of interest across the globe in order to demonstrate how the newly developed decision support tool facilitates the flexible evaluation of potential priority sites for conservation and to explore the potential and limitations of this approach. We assessed synergies and trade-offs among areas according to the different objectives at a global scale as well as within biogeographic realms. Finally, we aimed to investigate how priority setting by different societal actors affects site selection by combining the multiple conservation objectives into broader conservation scenarios that weigh each objective according to user-specified priorities.

The case study dataset for the analysis contained 1,346 sites globally. These sites included formally protected areas of International Union for Conservation of Nature (IUCN) category I or II, listed Natural World Heritage Site (WHS), and registered Key Biodiversity Area (KBA) (see experimental procedures for details of dataset and methods).[63,64] A principal component analysis (PCA) applied to this dataset globally (Figure 2) and at the level of biogeographic realms (Figure 3) showed that the indicators belonging to each conservation objective tended to be closely aligned at both the global and the realm levels, with the only exception being the two climatic stability indicators across the Australian realm. For example, within the biodiversity objective, species richness (SR), species endemism, and evolutionary diversity were closely aligned at the global scale as well as at the biogeographic realm level, although the alignment between SR and the other two indicators was slightly less tight in the tropical realms (Figure 3).

Looking at the trade-offs and synergies among the objectives, we found that at the global scale the first and second PCA axes explained 31.4% and 13.8% of the variation in the data, respectively. These axes showed relatively clear trade-offs and synergies among the six different conservation objectives (Figure 3). The strongest global trade-off was found between current biodiversity and future land-use stability (Pearson's correlation coefficient $r [n = 1346] = -0.30$, $p < 0.01$). These two objectives are negatively correlated, as increasing land-use pressure is often projected to occur around sites with exceptionally high current biodiversity (e.g., deforestation of tropical forests for agriculture). The strongest global synergies were found between current biodiversity and future climatic stability ($r [n = 1{,}346] = 0.41$, $p < 0.01$) and current biodiversity and high climate protection potential based on the amount of manageable carbon stored in the site ($r [n = 1{,}346] = 0.58$, $p < 0.01$). This suggests that sites with exceptionally high biodiversity often coincide with areas of lower projected impacts of climate change on vertebrate communities and tree cover and with a high potential for climate protection through carbon storage. The identified global synergies and trade-offs between the different objectives were only partially consistent within realms, with patterns similar to the global analysis for the Afrotropical realm but notably different alignments in the Palearctic and Nearctic.

Finally, to investigate how priority setting by different societal groups can affect site selection, we compared the outcome of area selection under three different conservation scenarios. We used two extreme and one combined scenario to explore a broad range of values (Figure 1). The first scenario was a biodiversity scenario (biodiversity objective weighted by 100% and the other five objectives by 0%). The second was an ecosystem integrity scenario (ecosystem integrity 100%, all others 0%). The third scenario was a stakeholder-driven scenario that resulted from joint discussion during an expert workshop (LLF scenario) (Figure 1). At this

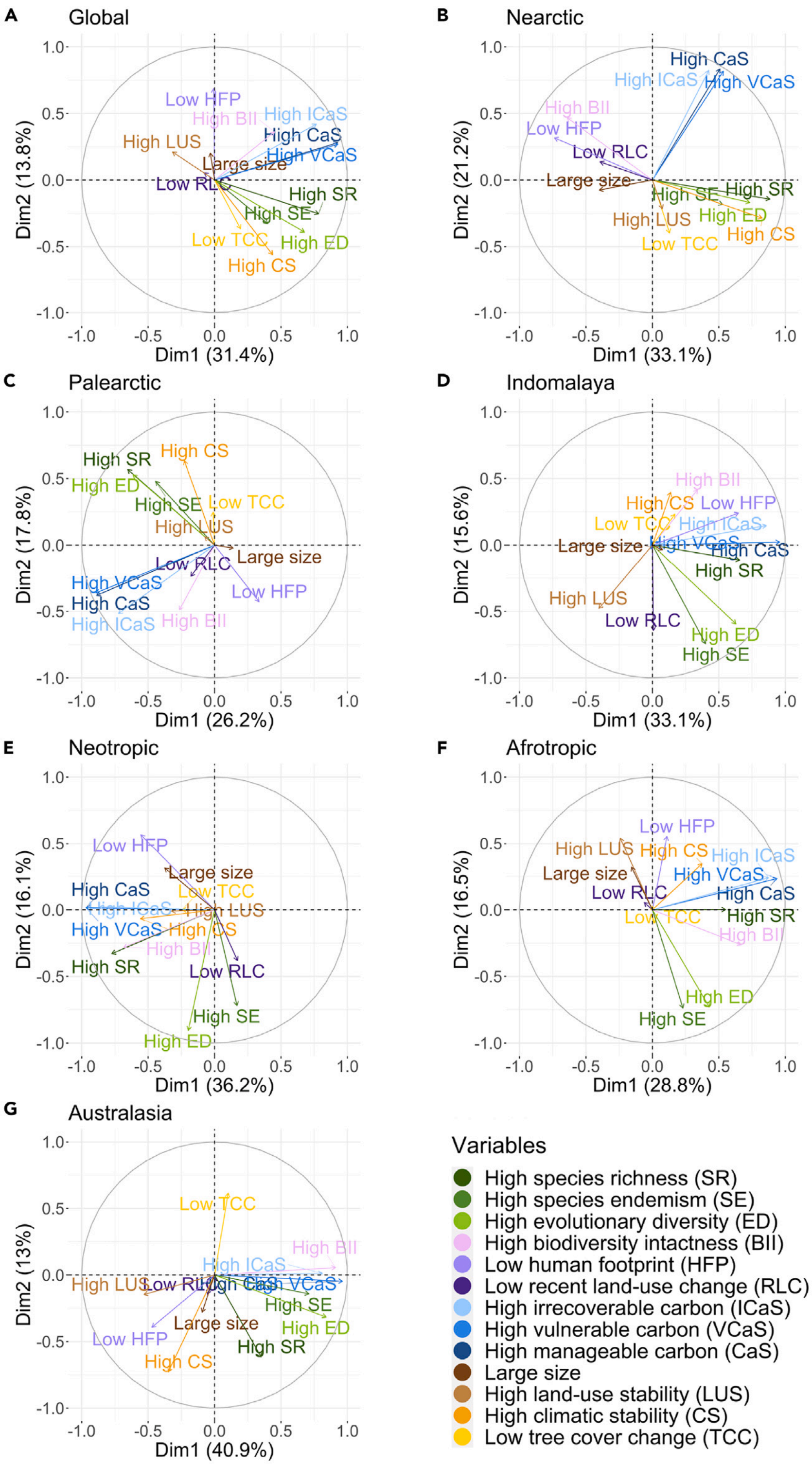

Figure 3. Trade-offs and synergies between the conservation indicators of individual sites at the global and realm levels

Shown are the first two axes of the principal component analysis (PCA) for all 1,346 sites included in the Legacy Landscapes case study globally (A) and for each individual realm (B–F). These analyses reveal trade-offs between the conservation objectives, indicated by variables mapping onto opposing ends of a principal component axis. Variable colors indicate conservation objectives as in Figure 1: biodiversity (shades of green), ecosystem integrity (shades of purple), climate protection (shades of blue), size (dark brown), land-use stability (light brown), and climatic stability (orange and yellow). PCA plots show the respective first two axes identified and the percentage of variation explained by each of the axes.

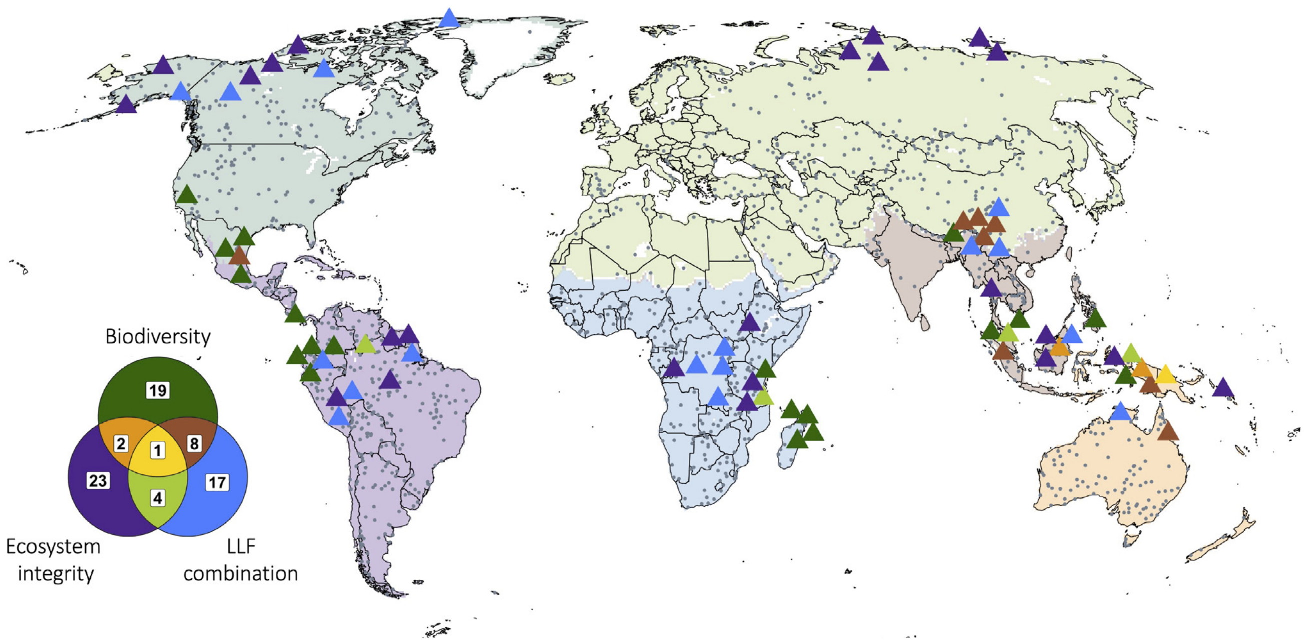

Figure 4. Spatial distribution of sites

Spatial distribution of sites highlighting the top five priority sites for each of the three example conservation scenarios: prioritizing biodiversity (dark green), prioritizing ecosystem integrity (purple), and the LLF scenario (Legacy Landscapes Fund, prioritizing a combination of all objectives that stresses high biodiversity, high ecosystem integrity, and large size; blue). The top five sites for all three scenarios (triangles) are shown per biogeographic realm (i.e., 30 top sites per conservation scenario in total). The colors correspond to the three different conservation scenarios and their overlap (if a site is in the top five for more than one objective), as shown in the Venn diagram. Only 14 of the top sites were selected under two scenarios (light green, brown, and orange), and one site was selected under all three scenarios (yellow). Gray points indicate sites included in the analysis but not selected under the top five. Top sites in close geographic proximity are spaced out for visualization and deviate from their exact spatial position. Map colors indicate the different biogeographic realms.

2-day online workshop, which was attended by 35 experts with a strong conservation background, we introduced the site-selection approach, further developed the indicators and objectives, and voted on the LLF scenario (see experimental procedures for more detail). This scenario reflects the main selection criteria for potential LLF sites (high biodiversity, ecosystem integrity, and size) but considers also the other objectives weighted according to lower priorities (biodiversity, ecosystem integrity, and size weighted with 25% each, climatic stability and land-use stability with 10% each, and climate protection with 5%).

Despite synergy between some objectives, we found that when comparing the top five sites selected for each of the three conservation scenarios within each biogeographic realm, there is little congruence among these scenarios (Figure 4). This implies that selecting sites based on their biodiversity will in most cases result in the protection of different sites compared to a selection based on high ecosystem integrity or the LLF scenario. Australasia has the highest overlap of top sites for the three different scenarios, with five sites being in the top five for at least two of the scenarios. The Nearctic, Neotropic, and Afrotropic realms have the least overlap among the top sites for the investigated scenarios, with only one shared site in the top five of at least two scenarios.

DISCUSSION

Our case study demonstrates that the selection of "best" sites for nature conservation depends largely on the relative weighting of different conservation priorities and is therefore heavily influenced by decision-maker values. This is supported by the clear trade-offs among the six conservation objectives at the realm and global scales (Figures 2 and 3) as well as the limited congruence among the top sites selected under the three different conservation scenarios (Figure 4). These results illustrate the opportunities and challenges faced by decision makers when selecting priority areas for nature conservation. Furthermore, they demonstrate the need for a global approach to nature conservation that involves multiple stakeholder groups and perspectives and a transparent decision-making process.

Here, we introduce an approach to select priority areas for biodiversity conservation at the global scale that separates (1) global biogeographic information on biodiversity, ecosystem services, and so forth from (2) a values-based prioritization of different conservation objectives in the decision-making process. This allows the trade-offs between conservation objectives to be understood and acknowledged explicitly and quantitatively. It thereby enables a first transparent evaluation of sites that reflects the varying priorities among different societal or conservation actors. Furthermore, the approach allows optimization of site selection toward more than one objective, which can significantly increase the efficiency of a PA network.[66] Additionally, the transient nature of conservation goals or new drivers of biodiversity loss, such as climate change, might result in the need to adjust prioritization in the future. Both arguments highlight the advantages of a flexible site-selection approach over the static selection of hotspots based on a small number of fixed objectives and indicators.

Our approach goes beyond existing studies that explore the spatial agreement of conservation objectives and presents optimized solutions through aligning several objectives by allowing the user to change the prioritization on the fly (Table 1). Instead of presenting a static conservation priority map, we present a dynamic result that ranks potential sites for protection based on user preferences. This approach puts the focus on the decision-making process and allows the exploration of trade-offs and synergies among different options. Rather than providing another method to set conservation priorities, our approach is complementary to the various approaches we found in the literature (Tables 1 and S1). It could, for example, be used to explore the differences, synergies, and trade-offs between any of the existing global prioritization maps across PAs.

Applying the tool to a specific conservation problem

For the LLF, the three conservation objectives of size, biodiversity, and ecosystem integrity are of high priority.[67] Applying the decision support tool to the assembled dataset revealed a trade-off between high biodiversity and high ecosystem integrity, clearly demonstrated in the comparison between the three conservation scenarios—high biodiversity, high ecosystem integrity, and the LLF scenario—which considers multiple conservation objectives. For the actual selection of sites, to be financed by the LLF, the decision support tool enabled an initial screening of potential sites globally. This allowed the LLF to evaluate the performance of individual sites under the desired conservation objectives and to compare different weightings before proceeding with the selection of the pilot sites. Here, the decision support tool was used in an integrative decision-making process which transparently separated biogeographic site screening from other criteria such as stakeholder consent, political commitment, and experience of the implementing NGO (see also below).

Applying the approach beyond the case study

Our approach and the newly developed tool can be easily extended to include a broader range of biogeographic datasets, additional conservation objectives, or additional sites into the analysis, making the tool widely applicable to a variety of site-selection tasks. Although the current setup of the tool already contains six objectives representing several broad conservation goals (i.e., safeguarding biodiversity or mitigating climate change), these are still to some extent geared toward the case study. To broaden the scope of the tool through additional objectives and opposing the focus on intact ecosystems used in our case study, priority setting could highlight areas that harbor a high amount of threatened biodiversity,[68] e.g., by including an additional objective based on the threat status of all occurring species (i.e., as provided in the IUCN Red List) in a site.[49,69,70] Another obvious and easy possibility to expand the current setup of the tool would be to allow further subsetting of the included sites. Currently the tool allows for an initial screening of sites at the level of biogeographic realms or at the global scale. Information such as the extent of a biogeographic realm or ecoregion that is already protected would need to be considered separately. Adjusting the tool to rank sites not only at the realm level but also at finer scales, for example at the ecoregion level, would allow users to prioritize sites in finer-scale under-represented categories.

Action Target 8 of the post-2020 GBF also calls for a well-connected PA network.[9] Connectivity is highly species specific and landscape dependent, and thus requires local and long-term studies on individual species.[71,72] Assessments on a scale such as the decision support tool shown here cannot yet reliably capture connectivity. Nonetheless, previous efforts have estimated the connectivity of global PA networks at a coarser scale, based for example on different levels of home range size in mammals[73] or even by modeling the movement of large animals throughout the landscape between PAs.[74] A first step to integrate connectivity into the decision support tool could be to use a distance matrix of sites from surrounding existing PAs. This could give a first rough indication of how well a site is embedded into the PA network and allow prioritization of connected sites over very isolated sites.

Caveats to consider when applying the tool

There are several core assumptions that need to be kept in mind when using the site-selection tool in the current setup. As currently designed, the tool is meant to allow the comparison of sites and different conservation objectives based on biogeographic variables, which are available at a global scale. This necessitates the use of relatively coarse-grained datasets (resolution here is mostly dependent on the biodiversity data). The biodiversity variables are calculated from global range maps of each terrestrial vertebrate species, which come at a coarse resolution, are of varying quality across species and taxa, and are therefore used for analysis at a 0.5° resolution; these cannot be used to derive accurate species lists for a given protected area.[75] Therefore, the included biodiversity variables give an indication of the biodiversity value of the region a site is located in rather than accurate values for the individual site.

Further, there is always a high level of uncertainty surrounding any future land-use and climate projections, which applies also to the models used to compute the indicators. Aside from specific model-related uncertainties, the projected future impacts will largely depend on socioeconomic decisions and climate mitigation efforts.[76] Nevertheless, we believe that the large-scale geographic patterns of variables included in the analysis remain robust to these uncertainties and allow for a comparison across sites at the chosen resolution.

The tool allows an initial screening of a large number of potential sites globally (or regionally) and can be extremely useful in creating prioritizations of PAs based on different objectives and indicators that can be applied flexibly. This tool, however, is only useful as a first step that allows a range of options to be explored as part of a much broader decision-making process. This decision-making process should include on-site assessments of additional parameters at a higher resolution (e.g., more detailed biological data acquired through surveys and observations) as well as non-biological characteristics. These socioeconomic factors could include, for example, the political legitimacy of the initiative, the involvement of local communities, and the presence of a supportive NGO. In the case of the pilot site selection for the LLF, these factors were considered in the next step that followed the use of the site evaluation tool.

Further, the decision support tool was designed to facilitate value-based discussions by enabling on-the-fly comparison of sites based on different biogeographic attributes. To allow easy handling of the decision support tool and thus enable a wider range of people to use it, weights can only be applied to the individual conservation objectives but not the underlying indicators. This results in limited possibilities to fine-tune the evaluation of sites. Furthermore, the tool does not facilitate the optimization of site networks, i.e., it does not assess different combinations of sites based on representativeness or cost efficiency. This might lead to unintended effects, such as several sites with similar biodiversity composition being in the top ranks, or the selection of sites where much more funding would be needed to achieve similar conservation outcomes compared to more cost-efficient sites.

Applying the tool within the post-2020 GBF

The ambition of the Aichi Biodiversity Targets has been increasingly criticized as being too modest to safeguard biodiversity in perpetuity.[6,7] Accordingly, the post-2020 GBF of the Convention on Biological Diversity calls for "at least 30 per cent of terrestrial, inland water and of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem functions and services, to be effectively conserved."[9] Thus it becomes increasingly important to identify new sites for conservation—and new ways of conserving—outside of the already delineated areas both on land and in the oceans.[8,77] The presented decision support tool could be extended to aid these efforts, either by adapting it to identify new sites or by expanding the case study dataset. A first possible extension would be the inclusion of the Indigenous and Community Conservation Areas and Other Effective Area-based Conservation Measures, which are increasingly being recognized as effective and potentially more inclusive conservation tools.[78]

Going beyond global priority setting, the post-2020 GBF aims to facilitate implementation primarily through activities at the national level. Furthermore, unlike in the LLF case study, a vast amount of conservation funding is not available at the global scale but rather at the national or regional level. Our approach could be used at the national or subnational level to help prioritize conservation decisions through facilitating transparent value-based discussion and supporting the implementation of the post-2020 GBF at this scale.[79] Applying the tool at the national or regional scale would open the possibility to add more finely resolved datasets to the conservation objectives that are not yet available at the global scale (e.g., species abundances or more specific land-use projections) and thus tailor the decision support tool to specific conservation actions.

An example of a relevant adjustment that may be possible at national scales could be the adjustment of the intended time frame, as the decision support tool with its inclusion of future projections (climatic and land-use stability) as well as the focus on intact ecosystems is currently geared toward longer time horizons. Highlighting sites where there is an urgent need to act (e.g., within a couple of years because of high conservation value in combination with high current pressure) would require the use of very different datasets with a much higher resolution. Working at regional or national scales would allow the inclusion of datasets on recent changes within a site that are not available or very heterogeneous at the global scale (e.g., population trends, recent deforestation rates, or the level of exploitation of natural resources).

In conclusion, the proposed approach facilitates a transparent initial screening of potential priority sites that allows the trade-offs between conservation objectives to be understood and acknowledged explicitly and quantitatively. It promotes the inclusion of multiple stakeholder positions, views, and preferences, and facilitates discourse and decision making while working toward the overarching conservation goals.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Alke Voskamp (alke.voskamp@senckenberg.de; alke.voskamp@posteo.net).

Materials availability

This study did not generate unique new materials.

Data and code availability

All codes needed to replicate the presented analysis are available from GitHub (https://github.com/Legacy-Landscapes/LL_analysis). The decision support tool is accessible via https://ll-evaluation-support-tool.shinyapps.io/legacy_landscapes_dst/. All codes for the decision support tool are available under https://github.com/Legacy-Landscapes/LL_Decision_Tool.

The case study dataset and analysis

To assess synergies and trade-offs among the different conservation objectives, we used the LLF as a case study to assemble a global dataset of sites. The LLF is a recently established foundation that provides long-term funding of 1 million US dollars per "legacy landscape" per year. Funding stems from public and private sources. It aims to protect areas of outstanding biodiversity over initially 15 years but with a vision to ensure funding in perpetuity.[67] The LLF is based on a strategic global site-selection approach and the strong long-term commitment of local NGOs, protected area authorities, and local communities "on the ground."[62] The initial requirements for sites to be considered by the LLF are outstanding biodiversity, a minimum size of 2,000 km^2, and a protection status as IUCN protected area category I or II for at least 1,000 km^2. Based loosely on these guidelines, we assembled a dataset and extracted site-specific values for each objective (Figure 1).

Processing the protected area data

The potential sites currently included in the analysis are PAs within IUCN category I or II, sites listed as a WHS,[64] or sites registered as a KBA.[63] There are various sites in the world where the WHSs or the KBAs overlap with the IUCN PAs. We resolved all such spatial conflicts by retaining the shapefile with the higher protection status where different shapefiles overlapped (IUCN > KBA > WHS). For example, WHSs that were embedded within an IUCN protected area as well as KBAs that overlapped with an IUCN protected area were excluded from the analysis. In some instances, there was only a partial overlap of either a KBA or WHS with an IUCN protected area or a KBA overlapped with an IUCN protected area but was considerably larger (Figure S1). For these cases we kept both shapefiles in the analysis. This was the case for 17 sites (Table S2).

We sampled all protected area polygons into a grid of 0.5° longitude × 0.5° latitude, deriving the percentage overlap of each polygon with the grid cells. To estimate the potential impacts of projected future land-use change around the PAs, we derived 50-km buffers around each protected area polygon and then sampled these into the grid as described above.

The conservation objectives data

The six conservation objectives were developed in a discussion process among the broader conservation community. We introduced our approach at a 2-day webinar which was attended by 35 experts with a strong conservation background. These included (1) conservation scientists, (2) international conservation NGOs, (3) the financial sector, and (4) policy sectors, in particular the German Federal Ministry for Economic Cooperation and Development (BMZ). These experts provided feedback on the objectives and indicators through a questionnaire (see supplemental information). They were asked to (1) report any missing objectives, (2) report any missing indicators that should be included in the objectives, and (3) rank the suggested objectives by their personal preferences.

Processing the conservation indicator datasets

The six different conservation objectives included in the decision support tool are biodiversity, ecosystem integrity, climatic stability, land-use stability, climate protection, and size. Each of these objectives consists of one or several underlying biogeographic indicators as follows.

Objective biodiversity

Indicator: Species richness. The SR for four taxa of terrestrial vertebrates was derived from BirdLife International (birds), IUCN (mammals, amphibians), or Global Assessment of Reptile Distributions (reptiles) range-map polygons, which were gridded to the 0.5° grid.[49–51] The species ranges were stacked to obtain species lists for each grid cell. The resulting species matrix was then merged with the site grid and the unique species across all grid cells within each site grid were summed up as the SR value for the site (the resulting map is shown in Figure S2). For the site selection, sites with a high SR are of high value, whereas sites with a low SR are of less value.

Indicator: Species endemism—corrected range-size rarity. To capture unique biodiversity, we included a measure for the number of range-restricted (endemic) species within a protected area, the so-called range-size rarity (RSR), which has been used as a proxy for species endemism.[52] This is derived by summing the species for each grid cell, including weights that reflect species' range sizes. Usually RSR is calculated by weighting each species by the inverse of its range extent (e.g., number of cells occupied globally) so that species within a given grid cell have larger weights if they occur in very few other grid cells.[80,81] The resulting values are highly correlated with SR, because the weighted species values are summed up per grid cell.[52] Therefore, we corrected for SR by dividing the weighted RSR value by the total number of species within the grid cell following Crisp et al.[52] (the resulting map is shown in Figure S3). Using this corrected RSR as a measure instead of the raw number of endemic species is of advantage because there is no arbitrary cutoff to define endemic species. Site-specific RSR values were derived for the four vertebrate taxa in the same way as SR values, by merging the species matrix (containing the species-specific RSR values for each grid cell) to the site grid, summing the RSR values of the unique species across all grid cells of the site. For the site selection, sites with a high RSR are of high value, whereas sites with a low RSR are of less value.

Indicator: Evolutionary diversity—phylogenetic endemism. Evolutionary diversity was included to evaluate how evolutionarily unique the species within a protected area are. Measures of phylogenetic diversity, such as Faith's PD, can give an idea of how much evolutionary history is stored within a set of species.[82] A high amount of evolutionary history has been linked to higher productivity and stability of ecosystems.[83,84] Evolutionary diversity was calculated using phylogenetic endemism (PE), which is a combined measure of phylogenetic diversity and uniqueness of a species community.[47] PE identifies areas with high numbers of evolutionarily isolated and geographically restricted species. In addition to the summed shared evolutionary history of a species assemblage, PE therefore incorporates the spatial restriction of phylogenetic branches covered by the assemblage.[47] PE was calculated following the method developed by Rosauer et al.[47] To derive the PE values, we used the phylogenetic supertree for all four terrestrial vertebrate taxa from Hedges et al.,[85] which was combined with the aforementioned species range-map data from IUCN and BirdLife International.[86] The number of species for which both distribution and phylogenetic data were available differed across taxa, but all analyses included high percentages of the globally known species in each taxon (Table S3). PE was derived for each 0.5° grid cell, after which the PE for each protected area was calculated as mean PE across all grid cells within the area polygon (the resulting map is shown in Figure S4). For the site selection, sites with a high PE are of high value, whereas sites with a low PE are of less value.

Objective ecosystem integrity

Indicator: Biodiversity intactness index. The biodiversity intactness index (BII) represents the modeled average abundance of present species relative to the abundance of these species in an intact ecosystem.[87] This means it gives an indication how much species abundances in an area have already changed due to anthropogenic impacts such as land-use change. We used the global map of the BII provided by Newbold et al.[88] (see Newbold et al.[89] for a detailed description of how the BII is derived). The values were extracted for each grid cell and grid cell values were weighted by their percentage overlap with the protected area polygon, then weighted mean BII values were derived for each protected area. For the site selection, sites with a low BII within the protected area are of lower value, whereas sites with a high BII are of higher value.

Indicator: Human footprint. As a measure of how pristine the PAs still are in general, a measure of the human footprint (HFP) within the area was included. Estimates of the HFP within PAs were derived using the data of Venter et al.[90] We used the standardized HFP that was provided by Venter et al. and includes data on the extent of built environments, cropland, pasture land, human population density, night-time lights, and the density of railways, roads, and navigable waterways. We aggregated the HFP layers to half-degree resolution, derived HFP values for each grid cell, weighted grid cells by their percentage overlap with the protected area polygon, and derived the mean HFP for each protected area. For the site selection, sites with a high HFP within the protected area are of lower value, whereas sites with a low HFP are of higher value.

Indicator: Recent land-use change. To derive past changes in the land cover of the protected area, we calculated the average percentage of the site altered from biomes (natural land cover classes) to human-dominated land cover classes (anthromes; i.e., urban/semi-urban areas and cultivated areas). The time series of fractions of land cover classes, ranging from 1992 to 2018, was obtained from the GEOEssential project.[91] The land cover classes used in this were derived from the European Space Agency Climate Change Initiative Land Cover and were available on a 30-km grid. We calculated the total percentage change from biomes to anthromes between the years 1992 and 2018 and aggregated the data into the half-degree grid. The summed changes for each protected area polygon were derived from the grid cell values weighted by the percentage overlap of grid cells and polygon. For the site selection, sites with a high percentage of land-use change between 1992 and 2018 are of lower value, whereas sites with a low percentage of land-use change are of higher value.

Objective climatic stability

Indicator: Projected biodiversity change. To assess the climatic stability of a protected area, we evaluated the potential impacts of climate change on the biodiversity within the site. Climate change is already driving observable shifts in species distributions, and it is well known that many taxa are shifting their ranges toward higher latitudes.[92,93] However, idiosyncratic species responses to climate change have also been observed.[94–96] These range shifts have the potential to reshuffle species assemblages,[48,97] which can have highly unpredictable impacts on the assemblage (e.g., changes in prey-predator balance or competition). We assume that species assemblages predicted to change only weakly in composition in the future or to experience very few species losses are under less risk from climate change than species assemblages projected to experience a lot of reshuffling. Under this assumption, we defined the inverse of projected turnover in species as an indicator for climatic stability, and calculated climatic stability for each protected area until 2050. The projected turnover is calculated for each of the four vertebrate taxa based on species-level range-map projections derived from species distribution models (SDMs).

The SDMs have been published previously (see Hof et al.[98] for a detailed account of the modeling methods) and are based on an ensemble of two modeling algorithms (Generalized Additive Models and Generalized Boosted Regression Models) and four different global climate models (MIROC5, GFDL-ESM2M, HadGEM2-ES, and IPSL-CM5A-LR). These models use the meteorological forcing dataset EartH2Observe, WFDEI, and ERA-Interim data, which were merged and bias-corrected for Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (EWEMBI[99]), as dataset for the current climatic conditions (from 1980 to 2009). As future climate dataset, they rely on bias-corrected global climate scenarios produced by ISIMIP phase 2b.[100] Here we used the projections assuming a medium dispersal scenario (allowing dispersal across a distance equal to half the largest radius of the range polygons of a species) and a medium representative concentration pathway of 6.0 (i.e., a medium scenario of global warming). Species with range extents of fewer than ten grid cells were excluded from the modeling. In total we had modeled distributions available for 22,652 vertebrate species (see Table S4) on the 0.5° grid. To derive species lists per site we applied species-specific thresholds that maximized the fit to the current data, using the true skill statistic (MaxTSS), to translate the projected probabilities of occurrence into binary presence/absence data.[101]

For each site, all species that were projected to occur currently and/or in future (2050) were extracted. Turnover was then calculated between the current and future species assemblage of a site, using the formula for Bray-Curtis dissimilarity[102]:

$$B_{ij} = \frac{2C_{ij}}{S_i + S_j}, \qquad \text{(Equation 1)}$$

where S_i and S_j are the species counts at the two points in time, and C_{ij} are the counts of species found in both sites (the resulting map is shown in Figure S5). For the site selection, sites with a high projected turnover as a consequence of global climate change are of low value, whereas sites with a low projected turnover are of high value.

Indicator: Projected tree cover change. We included the projected potential forest cover change from 1995 until 2050 based on the projected change in tree cover of the LPJ-GUESS process-based dynamic vegetation-terrestrial ecosystem model.[103] This variable captures changes in forest cover but not necessarily changes in other vegetation types, e.g., the desertification of grasslands and drylands. The projected changes in forest cover are driven by climate and CO_2 changes but do not include projected changes in land use. The climate input for the model was derived from the ISIMIP2b simulations (see detailed description above under "indicator: climatic stability of biodiversity"). The projected change in tree cover was provided as a percentage per grid cell.

The grid cell values were weighted by their percentage overlap with the protected area polygon, after which the weighted mean percentage change in tree cover was derived for each protected area. Both a strong decrease and a strong increase in tree cover could equal a risk for a site, e.g., a projected loss in tree cover could be a risk for a forest while a projected increase could be a risk for grasslands. Therefore, sites with a low projected change in tree cover, in either direction, are of higher value for the site selection, whereas sites with a high projected change in tree cover are of lower value.

Objective land-use stability

Indicator: Projected land-use change around the site. Projected land-use change was derived from the ISIMIP2b simulations of current and future land use for 1995 and 2050, based on the MAgPIE and REMIND-MAgPIE models,[104–106] using the assumptions of population growth and economic development as described in Frieler et al.[100] Land-use change models accounted for climate impacts (e.g., on crop yields) and were driven with the same climate model projections as the SDMs used to derive climatic stability (see above). The ISIMIP land-use scenarios provide percentage cover of six different land-use types (urban areas, rainfed crop, irrigated crop, and pastures, as well as rainfed and irrigated bioenergy crops) at a spatial resolution of 0.5°. We averaged the land-use change for each land-use type across the four global climate models. We then calculated a summed value of land-use change (cropland, biofuel cropland, and pastures) between the two different time periods (1995 and 2050) per grid cell. To obtain an estimate of the potential pressure that future land-use change could put on a protected area, we derived the mean and maximum values of the projected land-use change across all grid cells in the 50-km buffer zone around each protected area (see "processing the protected area data"). The grid cell values were weighted by their extent of overlap with the buffer zone to derive the final value for each site. For the site selection, sites with a high projected land-use change around the protected area are of low value, whereas sites with a low projected land-use change are of higher value.

Objective climate protection

Indicator: Manageable carbon. Here we used the estimated amount of manageable carbon as provided by Noon et al.[23] Manageable carbon is defined by Goldstein et al.[22] as an ecosystems carbon stock that is primarily affected by human activities that either maintain, increase, or decrease its size. This layer is derived from a comprehensive suite of carbon datasets across terrestrial, coastal, and freshwater ecosystems globally.[22] It includes the amount of carbon stored in the above and below-ground vegetation as well as soil organic carbon stocks up to 30-cm depth or up to 100 cm within inundated soil, as these depths are most relevant to common disturbances.[22] We aggregated the carbon data[23] to a 0.5° resolution and calculated the amount of manageable carbon storage in tons per grid cell. Aggregating the data to the same resolution as the other datasets before using it for the analysis is necessary to speed up data processing for the decision support tool. The grid cell values were weighted by their percentage overlap with the protected area polygon to derive the final mean manageable carbon storage value per site. For the site selection, sites with lower baseline carbon stocks are of lower climate protection value, whereas sites with higher baseline carbon stocks are of higher climate protection value.

Indicator: Vulnerable carbon. Vulnerable carbon is defined by Goldstein et al.[22] as the amount of manageable carbon, described above, that is likely to be released through typical land conversion in an ecosystem. Considered conversion drivers here were agriculture for grasslands, peatlands, and tropical forests; forestry for boreal and temperate forests; and aquaculture or development for coastal ecosystems.[22] Data for vulnerable carbon were processed as described above for manageable carbon. For the site selection, sites with higher vulnerable carbon stocks are allocated a higher suitability for long-term conservation than sites with lower vulnerable carbon stocks.

Indicator: Irrecoverable carbon. Irrecoverable carbon is defined as the amount of the vulnerable carbon, described above, which if it is lost through typical land conversion actions cannot be recovered over the following 30 years, even if human activities cease.[22] Data for vulnerable carbon were processed as described above for manageable carbon. For the site selection, sites with higher irrecoverable carbon stocks are allocated a higher suitability for long-term conservation than sites with lower irrecoverable carbon stocks.

Objective size

Indicator: Extent of the site. For the size conservation objective, we preselected sites that are larger than 2,000 km^2. Despite being a quite arbitrary threshold, the minimum size was set as a result of the LLF stakeholder debate based on the assumption that larger areas have a higher potential to support populations of target species and to maintain functioning ecosystems in the long term.[60,61] Even for areas above this threshold, the size of the site is still an important criterion under this reasoning, and we used the extent of the site polygon as variable/indicator of this. The area in km^2 was derived from the site polygons (see "processing the protected area data"). The IUCN sites and WHSs were provided in Mollweide projection. To calculate the area extent, the entire dataset was projected to Mollweide projection and km^2 were then measured in QGIS using the area measurement tool.[107]

Scaling and weighting the indicators for site evaluation

We calculated values for each indicator variable for each site included in the conservation decision support tool (see correlation matrix for indicators within the different objectives, Figure S7). For both summarizing the individual indicators into conservation objectives and weighing them in the decision support tool as well as for the PCA, these values need to be scaled. Therefore, all variables were scaled from 0 to 1, where high values have high priority and low values have low priority for conservation. For some of the variables the original data are opposite to this scale (e.g., for the HFP an area with a high value is of lower conservation value than a low value); therefore, we multiplied such variables by −1 after scaling them. The variables for which the scale was reversed were HFP, recent land-use change, land-use stability, and climate stability of species communities and tree cover change. For the change in tree cover we assumed that both high positive values (i.e., strong increase in tree cover) as well as high negative values (i.e., strong decrease in tree cover) are not desirable. Therefore, we changed the original variable into absolute values. The variable is then interpreted in the same way as all other variables with high values (1) being good and low values (0) being less desirable for conservation.

To aggregate indicators that belong to one conservation objective into a single variable, we averaged the scaled variables and rescaled the resulting values to range from 0 to 1. The three carbon storage variables that are included in the climate protection goal constituted the only variables that are nested (i.e., irrecoverable carbon is part of the vulnerable carbon stock, and vulnerable carbon is part of the baseline carbon stock in the site). Nevertheless, we treated the carbon stock variables in the same way as the other variables because we assumed that the different carbon variables are each of comparable priority. For example, the protection of irrecoverable carbon might arguably be as important for climate protection as the sole protection of manageable carbon. Taking the average across the three variables acknowledges these values. Assume that there are two sites, one with a high amount of manageable carbon but no irrecoverable carbon and one with lower manageable carbon but with a high amount of that being irrecoverable; these sites come out with a similar averaged value. Thus, although the second site has less carbon storage potential in total, some of it is of high importance for climate protection (see correlation matrix for carbon storage, Figure S8).

Principal component analysis of the included indicators

We investigated global synergies and trade-offs among the final set of conservation objectives using a PCA across all sites. To further explore whether synergies and trade-offs between the objectives were different in biogeographic regions of the world, we repeated the PCA separately for each of the six terrestrial biogeographic realms.[65] The analysis was conducted in R (version 4.1.1), using the "prcomp" function from the "stats" package.[108] All variables were scaled and shifted to be zero centered before the analysis. The PCA plots (Figure S6) were generated using the "fviz_pca" function of the "factoextra" package.[109]

Sensitivity analysis of the site rankings

We assessed the correlation between the scaled values that were calculated for each conservation objective for each site included in the analysis. As expected, based on the identified synergies and trade-offs in the PCA analysis, the Pearson correlation coefficients between the different conservation objectives were low (Figure S7). The highest correlation ($r = 0.58$) was found between the biodiversity and the climate protection objectives.

The correlation between the different indicators included within the conservation objectives varied between the objectives (Figure S8). Within the biodiversity (Pearson's $r > 0.20$ and <0.77) and the climate protection (Pearson's $r > 0.85$ and $r < 1$) objectives, the individual indicators tended to be more strongly correlated than within the ecosystem integrity (Pearson's $r > 0.01$ and $r < 0.08$) and climatic stability (Pearson's $r > -0.08$ and $r < 0.88$) objectives.

The conservation decision support tool allows the selection and weighting of the individual conservation objectives but does not offer a subweighting of the individual indicators included within an objective. To investigate how much the rankings of individual sites could vary if they were evaluated based on a single indicator instead of the combined objective values, we looked at the changes in rank positions across all sites included in the analysis (Figures S9–S11). For comparison, we also looked at the changes in ranking positions between the conservation objectives, evaluating sites based on one objective at a time. We found that the average rank change between the different conservation objectives was 435 rank positions (Figure S9). Looking at the changes in rank positions within the individual conservation objectives, we found that the magnitude of the average change in rank position differed strongly between the different objectives (Figures S10 and S11). While the average change across the three biodiversity indicators across all sites was 221 rank positions, the average change across the two climatic stability indicators was 377 rank positions. Although there is variation in the ranking positions between the individual indicators included within the conservation objectives, the changes in ranking positions between the conservation objectives is markedly higher.

The webinar

We introduced the site-selection approach at a 2-day online webinar, which was attended by 35 experts with a strong conservation background. During the workshop the different conservation objectives and indicator variables were presented and discussed. We used a questionnaire (Figures S12–S16) to determine any missing conservation objectives or indicators as well as to allow everyone to order the conservation objectives by their perceived importance. In total, 22 of the 35 attendants responded to the questionnaire.

The decision support tool

To make the analysis accessible to the broader conservation community and enable a rapid comparison of sites based on the user-specified prioritization of the different conservation objectives, we designed an interactive spatial decision support tool in which weightings can be modified (see Note S2 and Figures S17–S22 for detailed content of the app interface). The user interface for the tool was developed using R Shiny version 1.5.0.[110]

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.08.009.

ACKNOWLEDGMENTS

We thank all participants of the expert workshop for valuable discussions and input to the development of the decision support tool, and the Frankfurt Zoological Society staff in the project areas who tested the tool and helped to evaluate its use for conservation. We gratefully acknowledge the use of the Goethe-HLR HPC at the Center for Scientific Computing at Goethe University Frankfurt for some of the computationally heavy aspects of this work. We also thank BirdLife International for making the KBA data available as well as the ISIMIP and ISIpedia—the open climate-impacts encyclopedia funded by JPI Climate and the EU, grant number 690462—for their support and data availability. Furthermore, we thank the Temperatio Foundation for their financial support. S.A.F. was supported by the German Research Foundation DFG (FR 3246/2-2) and the Leibniz Competition of the Leibniz Association (P52/2017); A.N. was supported by European Union's Horizon 2020 research and innovation program under grant agreement no. 689443.

AUTHOR CONTRIBUTIONS

Conceptualization, A.V., S.A.F., V.K., C.S., and K.B.G.; methodology, A.V., S.A.F., and K.B.G.; feedback on methodology, all authors; software, A.V., T.N.B., and M.F.B.; writing – original draft, A.V., S.A.F., V.K., and K.B.G.; writing – review and editing, all authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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One Earth, Volume *6*

Supplemental information

Utilizing multi-objective decision support tools for protected area selection

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Note S1: Screened literature on global prioritization approaches

At the start of the project, we screened the available literature on global prioritization approaches, to identify a suitable tool that would allow to explore and compare the trade-offs between different conservation objectives flexibly. Although there are numerous prioritization approaches available based on various conservation objectives, none of them was applicable for the task at hand. The majority of approaches presented static maps on global priority areas for conservation based on one or more objectives, and only very few approaches considered weighing the included objectives (or variables included within the objectives) to obtain a consensus map across the different objectives. Table S1 provides a list of the global studies that we selected as highly relevant to our approach (i.e. not those with a focus on prioritizing a network of sites or identifying sites of high complementarity to an existing site network, but rather studies that resulted in priority maps across assemblages, sites, or some other spatial unit).

Table S1: Studies that present global prioritization maps based on one or multiple conservation objectives. The column objectives considered shows if the study is focused on a 'single' objective, which could be based on one or more variables (e.g. biodiversity measured based on several indicators like species richness, number of threatened species, etc.); on 'multiple' objectives which could be based on several variables (e.g. biodiversity, measured based on several indicators like species richness and number of threatened species, as well as ecosystem integrity, measured based on several indicators such as human footprint and intactness of species assemblages); or on 'multiple weighted' objectives which could be based on several variables and where the objectives (or the variables within the objectives) were not equally weighted.

#	Authors	Year	Title	# of objectives considered	Variables
1	Albuquerque et al.[1]	2015	Global patterns and environmental correlates of high-priority conservation areas for vertebrates	single	vertebrate richness complementarity
2	Allan et al.[2]	2022	The minimum land area requiring conservation	multiple	key biodiversity areas, ecologically intact areas, protected areas

			attention to safeguard biodiversity		
3	Allan et al.[3]	2017	Temporally inter-comparable maps of terrestrial wilderness and the Last of the Wild	single	remaining wilderness
4	Belote et al[4].	2020	Mammal species composition reveals new insights into Earth's remaining wilderness	multiple	intactness mammal communities, human footprint
5	Beyer et al.[5]	2020	Substantial losses in ecoregion intactness highlight urgency of globally coordinated action	single	habitat intactness
6	Brooks et al.[6]	2004	Coverage provided by the global protected area system: Is it enough?	single	species richness, threatened species, protection coverage
7	Brooks et al.[7]	2006	Global biodiversity conservation priorities	multiple	high biodiversity threat, low biodiversity threat
8	Brum et al.[8]	2017	Global priorities for conservation across multiple dimensions of mammalian diversity	multiple	mammal phylogenetic diversity, mammal functional diversity, mammal trait diversity
9	Buchanan et al.[9]	2011	Identifying priority areas for conservation: A global assessment for forest-dependent birds	single	contribution to forest bird distribution
10	Buhlmann et al.[10]	2009	A Global Analysis of Tortoise and Freshwater Turtle Distributions with Identification of Priority Conservation Areas	single	turtle and tortoise richness, turtle and tortoise protection
11	Butchart et al.[11]	2015	Shortfalls and Solutions for Meeting National and Global Conservation Area Targets	multiple	species coverage, ecosystem coverage, key biodiversity areas, gross domestic product
12	Cantu-Salazar et al.[12]	2013	The performance of the global protected area system in capturing vertebrate geographic ranges	single	richness of under protected vertebrates
13	Cardillo et al.[13]	2006	Latent extinction risk and the future battlegrounds of mammal conservation	single	richness latent extinction risk in mammals
14	Carrara et al.[14]	2017	Towards biodiversity hotspots effective for conserving mammals with small geographic ranges	multiple	richness range restricted species, richness range restricted evolutionary diversity, richness range restricted threatened species
15	Ceballos and Ehrlich[15]	2006	Global mammal distributions biodiversity hotspots and conservation	multiple	mammal species richness, mammal endemic species richness, mammal threatened species richness

16	Chen and Peng[16]	2017	Evidence and mapping of extinction debts for global forest-dwelling reptiles, amphibians and mammals	multiple	extinction depth mammals, amphibians and reptiles, extinction risk mammals, amphibians and reptiles, richness mammals, amphibians and reptiles
17	Cimatti et al.[17]	2021	Identifying science policy consensus regions	multiple	63 different conservation priority maps
18	Daru et al.[18]	2019	Spatial overlaps between the global protected areas network and terrestrial hotspots of evolutionary diversity	multiple	phylogenetic diversity, phylogenetic endemism, EDGE
19	Di Marco et al.[19]	2019	Wilderness areas halve the extinction risk of terrestrial biodiversity	multiple	vertebrate persistence, plant persistence, wilderness
20	Di Marco et al.[20]	2012	A novel approach for global mammal extinction risk reduction	single	extinction risk reduction opportunity
21	Dinerstein et al.[21]	2020	A global safety net to reverse biodiversity loss and stabilize earth climate	multiple	species rarity, distinct species assemblages, rare phenomena, carbon storage, wildlife corridors
22	Freudenberger et al.[22]	2013	Nature conservation Priority-setting needs a global change	multiple, weighted	16 variables including carbon storage, vegetation density, species richness vascular plants, functional richness, forest cover loss and human footprint
23	Funk et al.[23]	2010	Ecoregion prioritization suggests an armoury not a silver bullet for conservation planning	multiple	species richness, endemism, endangerment and threat, ecoregions
24	Girardello et al.[24]	2019	Global synergies and trade-offs between multiple dimensions of biodiversity and ecosystem services	multiple, weighted	taxonomic, phylogenetic and functional diversity birds and mammals, carbon sequestration, pollination potential and groundwater recharge
25	Goldstein et al.[25]	2020	Protecting irrecoverable carbon in Earth's ecosystems	single	manageable carbon, vulnerable carbon, irrecoverable carbon
26	Gonçalves-Souza et al.[26]	2020	Habitat loss extinction and conservation effort in terrestrial ecoregions	multiple	projected extinction risk, protected area coverage
27	Grenyer et al.[27]	2006	Global distribution and conservation of rare and threatened vertebrates	multiple	bird, mammal and amphibian species richness, endemic richness and threatened richness

28	Gumbs et al.[28]	2020	Global priorities for conservation of reptilian PD in the face of human impacts	multiple	reptile phylogenetic endemism, human impact
29	Hanson et al.[29]	2020	Global Conservation of species niches	single	species niches
30	Hidasi-Neto et al.[30]	2015	Global and local evolutionary and ecological distinctiveness of terrestrial mammals	multiple	ecological and evolutionary distinctiveness mammals, threat status
31	Hoekstra et al.[31]	2005	Confronting a biome crisis Global disparities of habitat loss and protection	single	habitat conversion, habitat protection
32	Howard et al.[32]	2020	A global assessment of the drivers of threatened terrestrial species richness	single	threatened species richness
33	Jenkins et al.[33]	2013	Global patterns of terrestrial vertebrate diversity	multiple	vertebrate richness, endemism and threat
34	Jetz et al.[34]	2014	Global Distribution and Conservation of Evolutionary Distinctness in Birds	single	evolutionary distinctiveness birds, threat status, protection coverage
35	Jung et al.[35]	2021	Areas of global importance for conserving terrestrial biodiversity, carbon and water	multiple	carbon stock, threatened species, water quality
36	Kier et al.[36]	2009	A global assessment of endemism and species richness across island and mainland regions	single	bird, mammal. Amphibian, reptile and vascular plant species richness and endemism
37	Kullberg et al.[37]	2018	Using KBAs to guide effective expansion of the global PA network	single	protection coverage threatened vertebrates, key biodiversity areas
38	Lamoreuxet al.[38]	2006	Global tests of biodiversity concordance and the importance of endemism	single	bird, mammal, amphibian and bird species richness and endemism
39	Loiseauet al.[39]	2020	Global distribution and conservation status of ecologically rare mammal and bird species	single	species richness, ecologically rare species richness, threatened species
40	Mazel et al.[40]	2014	Multifaceted diversity-area relationships reveal global hotspots of mammalian species trait and lineage diversity	multiple	mammal species richness, mammal functional diversity, mammal phylogenetic diversity
41	McDonald et al.[41]	2018	Conservation priorities to protect vertebrate endemics from global urban expansion	multiple	vertebrate endemism, current land cover, urban expansion
42	Myers et al.[42]	2000	Biodiversity hotspots for conservation priorities	multiple	endemic species richness, habitat loss
43	Mittermeier et al.[43]	2003	Wilderness and biodiversity conservation	multiple	wilderness, species richness vascular plants, species richness terrestrial vertebrates

44	Mokany et al.[44]	2020	Reconciling global priorities for conserving biodiversity habitat	single	assemblage intactness, human footprint
45	Moran et al.[45]	2017	Identifying species threat from global supply chains	single	biodiversity footprint, threatened species richness
46	Naidoo et al.[46]	2008	Global mapping of ecosystem services and conservation priorities	multiple	carbon sequestration, carbon storage, freshwater provision, grassland production of livestock
47	Olson et al.[47]	2002	The global 200: Priority ecoregions for global conservation	multiple	species richness, endemic species richness, unusual higher taxa, unusual ecological phenomena, evolutionary phenomena, habitat rarity
48	Orme et al.[48]	2005	Global hotspots of species richness are not congruent with endemism or threat	multiple	bird species richness, bird species endemism, bird threatened species richness
49	Pelletier et al.[49]	2018	Predicting plant conservation priorities on a global scale	single	threatened plant species richness
50	Pollock et al.[50]	2017	Large conservation gains possible for global biodiversity facets	multiple	mammal and bird species richness, phylogenetic diversity and functional diversity
51	Pouzols et al.[51]	2014	Global PA expansion is compromised by projected land-use and parochialism	multiple	species richness, current protection coverage, projected future land-use
52	Riggio et al.[52]	2020	Global human influence maps reveal clear opportunities in conserving Earths remaining intact terrestrial ecosystems	single	anthromes, human footprint, Low impact areas, Global human modification
53	Rodriguez et al.[53]	2004	Global gap analysis Priority regions for expanding the global protected-area network	multiple	species richness mammals, amphibians, freshwater turtles, tortoises and threatened birds, protected areas
54	Roll et al.[54]	2017	The global distribution of tetrapods reveals a need for targeted reptile conservation	single	species richness reptiles, species richness terrestrial vertebrates
55	Rosauer et al.[55]	2017	Phylogenetically informed spatial planning is required to conserve the mammalian tree of life	single	mammalian phylogenetic diversity, species richness
56	Safi et al.[56]	2013	Global Patterns of Evolutionary Distinct and Globally Endangered Amphibians and Mammals	multiple	evolutionary distinctiveness amphibians and mammals, threat status amphibians and mammals,

57	Schipper et al.[57]	2008	The status of the worlds land and marine mammals: Diversity, threat and knowledge	multiple	terrestrial and marine mammal species richness, endemic species, threatened species and phylogenetic diversity
58	Soto Navarro et al.[58]	2020	Mapping co-benefits for carbon storage and biodiversity to inform conservation policy and action	multiple	species richness–area of habitat, rarity-weighted richness–area of habitat, mean species abundance, biodiversity intactness index, biodiversity habitat index, above- and below ground terrestrial carbon storage,
59	Stuart et al.[59]	2004	Status and Trends of Amphibian Declines and Extinctions Worldwide	multiple	species richness, declining species, enigmatic species, habitat loss, over exploitation
60	Veach et al.[60]	2017	Species richness as criterion for global conservation area placement leads to large losses in coverage of biodiversity	multiple	species richness vertebrates, threatened species richness vertebrates, endemic species richness vertebrates
61	Venter et al.[61]	2014	Targeting global protected area expansion for imperilled biodiversity	multiple	area protected, opportunity cost, number of species protected
62	Voskamp et al.[62]	2017	Global patterns in the divergence between phylogenetic diversity and species richness in terrestrial birds	single	species richness birds, phylogenetic diversity birds
63	Watson et al.[63]	2018	Protect the last of the wild	single	remaining wilderness
64	Yang et al.[64]	2020	Cost-effective priorities for the expansion of global terrestrial protected areas Setting post 2020 global and national targets	multiple	crisis ecoregions, biodiversity hotspots, endemic bird areas, key biodiversity areas, centres of plant diversity, global 200s, and intact forest landscapes, human footprint, human modification, low human impact areas

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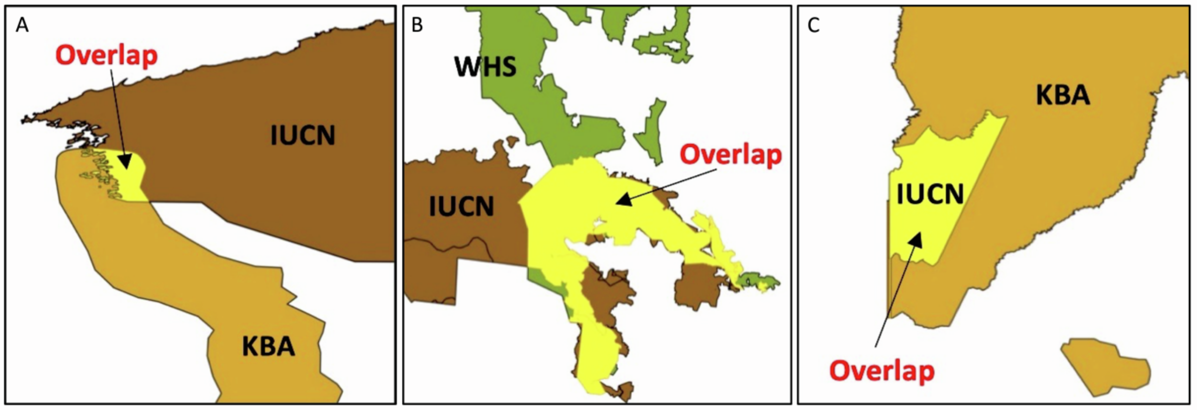

Fig. S1: Examples of marginal, partial and full overlap of two shapefiles. A shows a KBA (orange) that has marginal overlap with an IUCN site (brown). B shows a WHS site (green) that partially overlaps with an IUCN site but is kept because it is considerably larger than the area already covered by the IUCN site. C shows an IUCN site that is embedded within a KBA, here too the KBA is kept because it is considerably larger than the IUCN site.

Table S2: Number of sites that had partial, marginal or full overlap with another site included in the dataset.

Overlapping sites	Type of overlap	Number of occasions
IUCN + KBA	marginal	8
IUCN + KBA	partial	2
IUCN + KBA	embedded	1
IUCN + WHS	marginal	3
IUCN + WHS	embedded	1
WHS + KBA	marginal	2
Total		**17** (1.3% of sites included)

Table S3: The number of species in each class of terrestrial vertebrates for which phylogenetic data was available, and the number of species that were included in the analyses for species richness and endemism but which are missing in the phylogenetic endemism analysis. We also give the total number of species with distribution data and the corresponding percentage of known species represented in each taxon, following the respective taxonomy.

Taxa	Species w. phylogenetic + distribution data	Species w. distribution data only	Total	%
Birds	8296	1360	9656	86
Mammals	4867	113	4980	98
Amphibians	6051	145	6196	98
Reptiles	8801	1263	10064	87

Table S4: The number of species in each class of terrestrial vertebrates for which species distribution models could be built and which were included in the analyses for climate stability of biodiversity. The total species number is the number of species with range maps, we also give the corresponding percentage of species with range maps models could be built for (cf. Table S3).

Taxa	Species with SDM	Species without SDM	Total	%
Terrestrial birds	8986	896	9882	91
Terrestrial mammals	4307	968	5275	82
Amphibians	3063	3317	6380	48
Reptiles	6296	3768	10,064	60

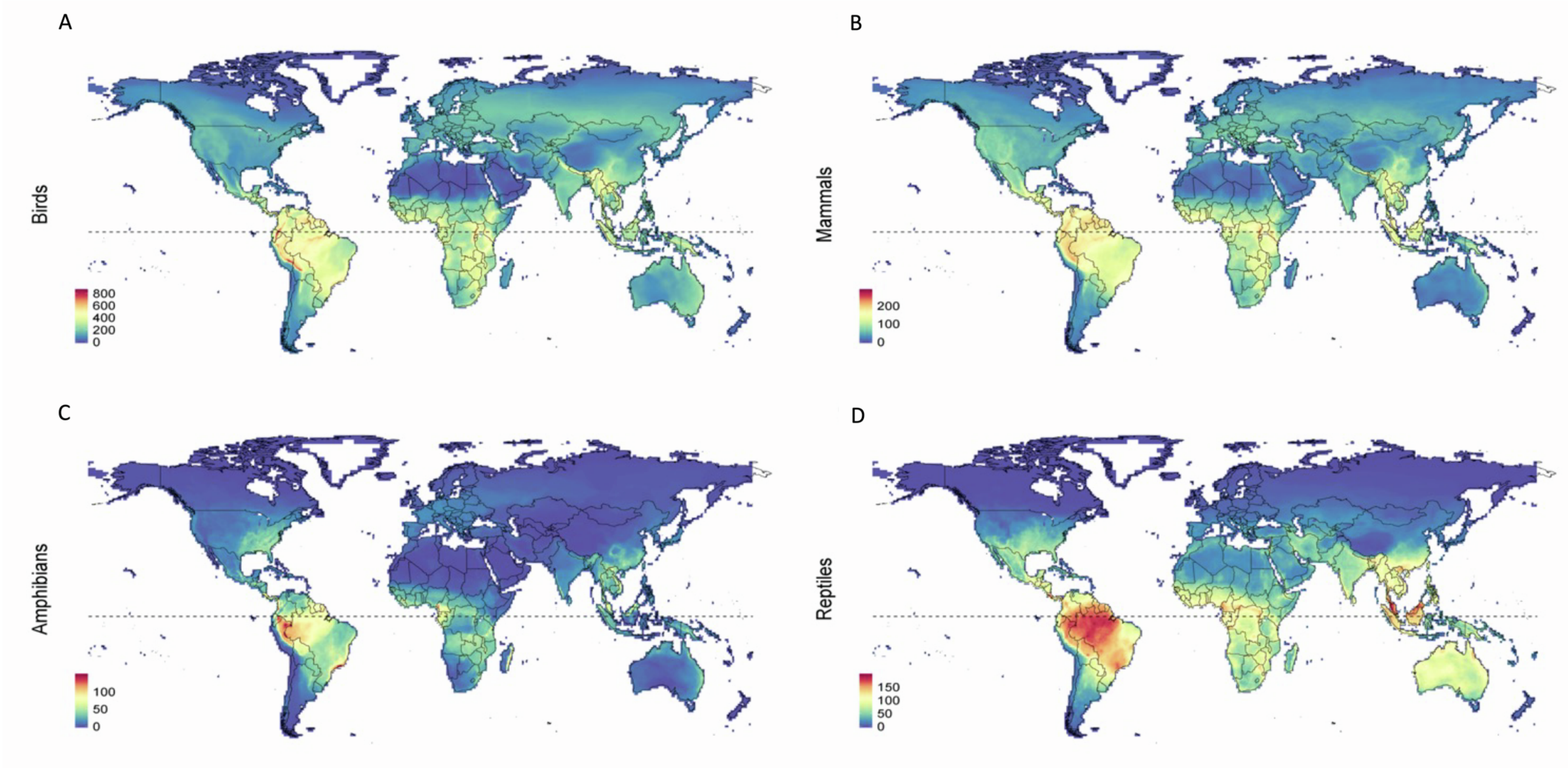

Fig. S2: Global species richness for all four taxa of terrestrial vertebrates (A birds, B mammals, C amphibians and D reptiles), calculated on a 0.5-degree grid. *Note that the colour scale extent differs between the different taxa.*

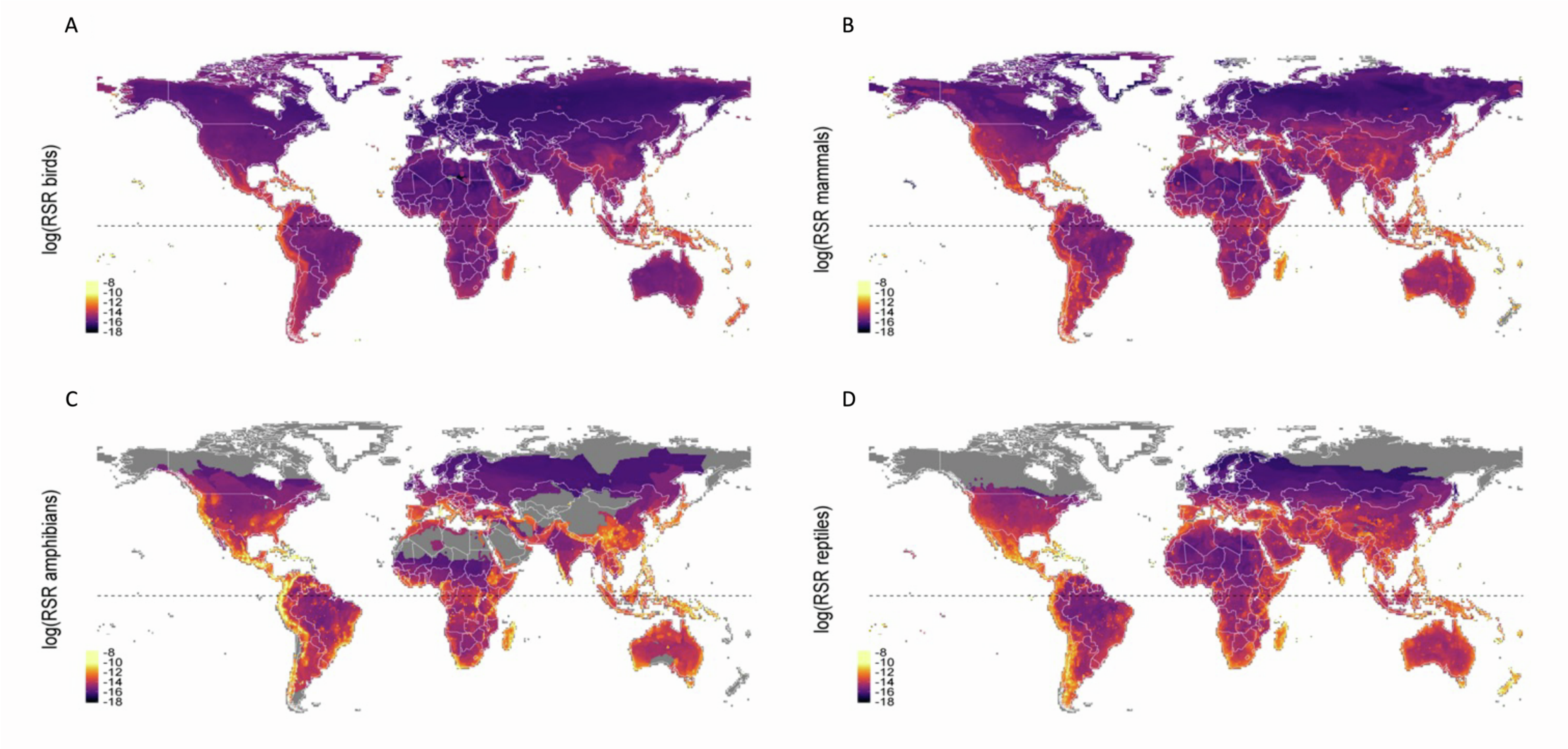

Fig. S3: Global corrected range size rarity for all four taxa (A birds, B mammals, C amphibians and D reptiles), calculated on a 0.5-degree grid. Corrected range size rarity is the number of species weighted by their inverse range size and divided by the total number of species, shown here on a logarithmic scale. *Note that the scale differs between the different taxa.*

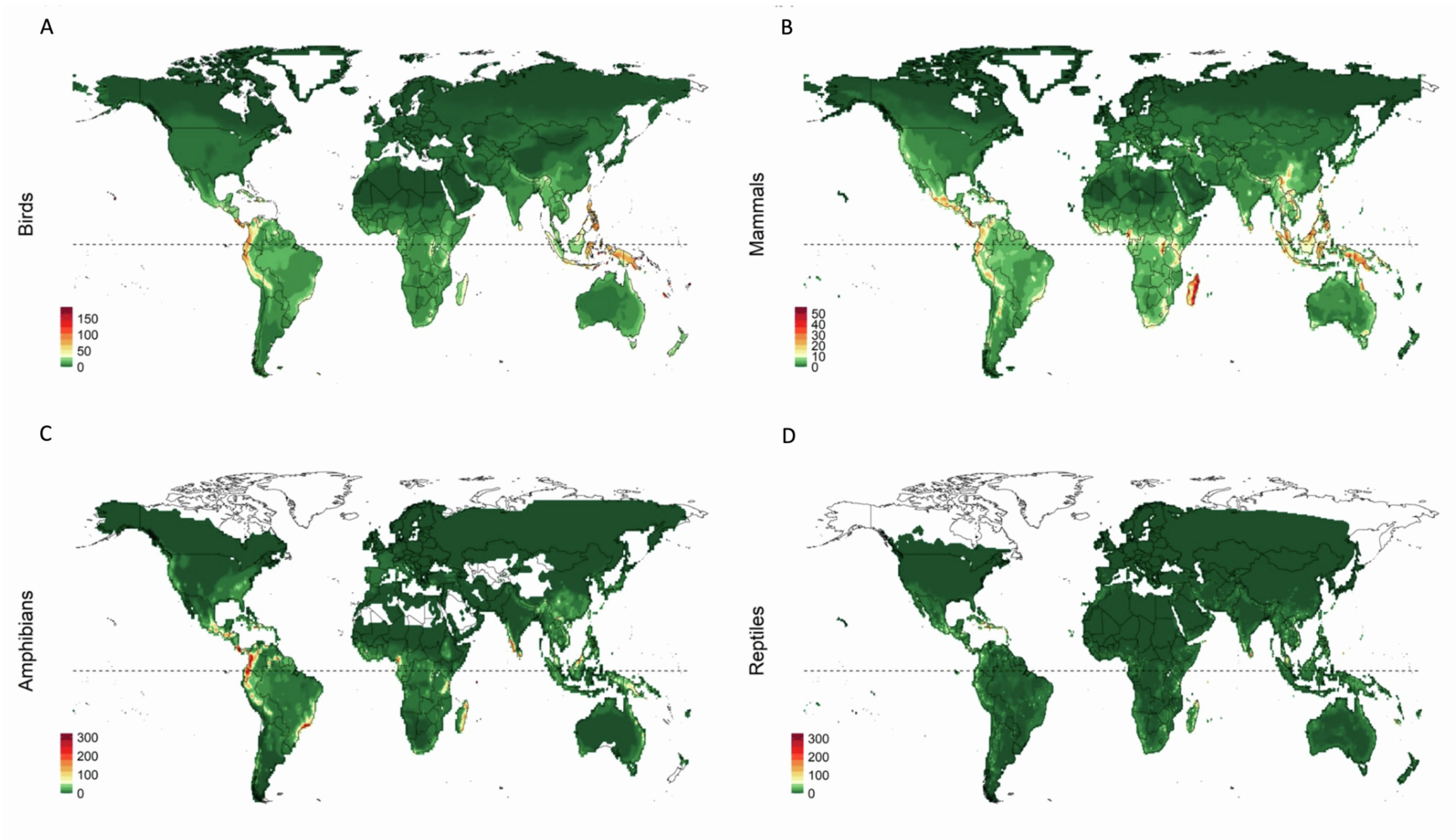

Fig. S4: Global patterns of phylogenetic endemism for all four taxa (A birds, B mammals, C amphibians and D reptiles), calculated on a 0.5-degree grid. Phylogenetic endemism is calculated by summing the shared evolutionary history of a species assemblage and combining it with information on the range extent of the individual species. *Note that the scale differs between the different taxa.*

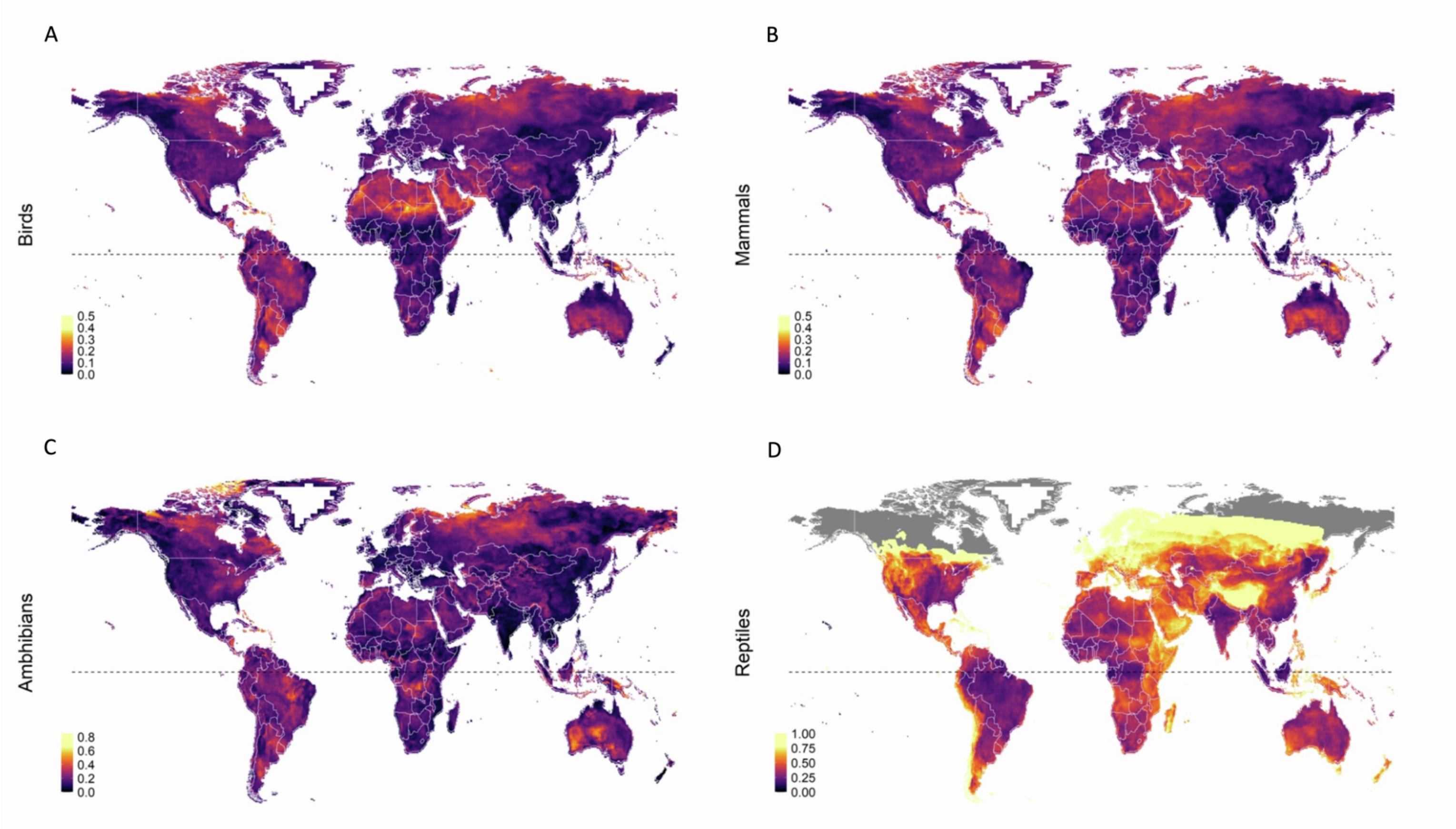

Fig. S5: Projected assemblage-level turnover values under climate change for all four taxa (A birds, B mammals, C amphibians and D reptiles), calculated on a 0.5-degree grid. Turnover ranges from 0 (low) to 1 (high) and was calculated between the projected current species compositions (1995, average climate projections from 1980 – 2009) and the projected future species compositions (2050, average climate projections 2035 - 2064) under a medium emission scenario (RCP 6.0) and assuming a medium dispersal scenario. *Note that the scale differs between the different taxa*

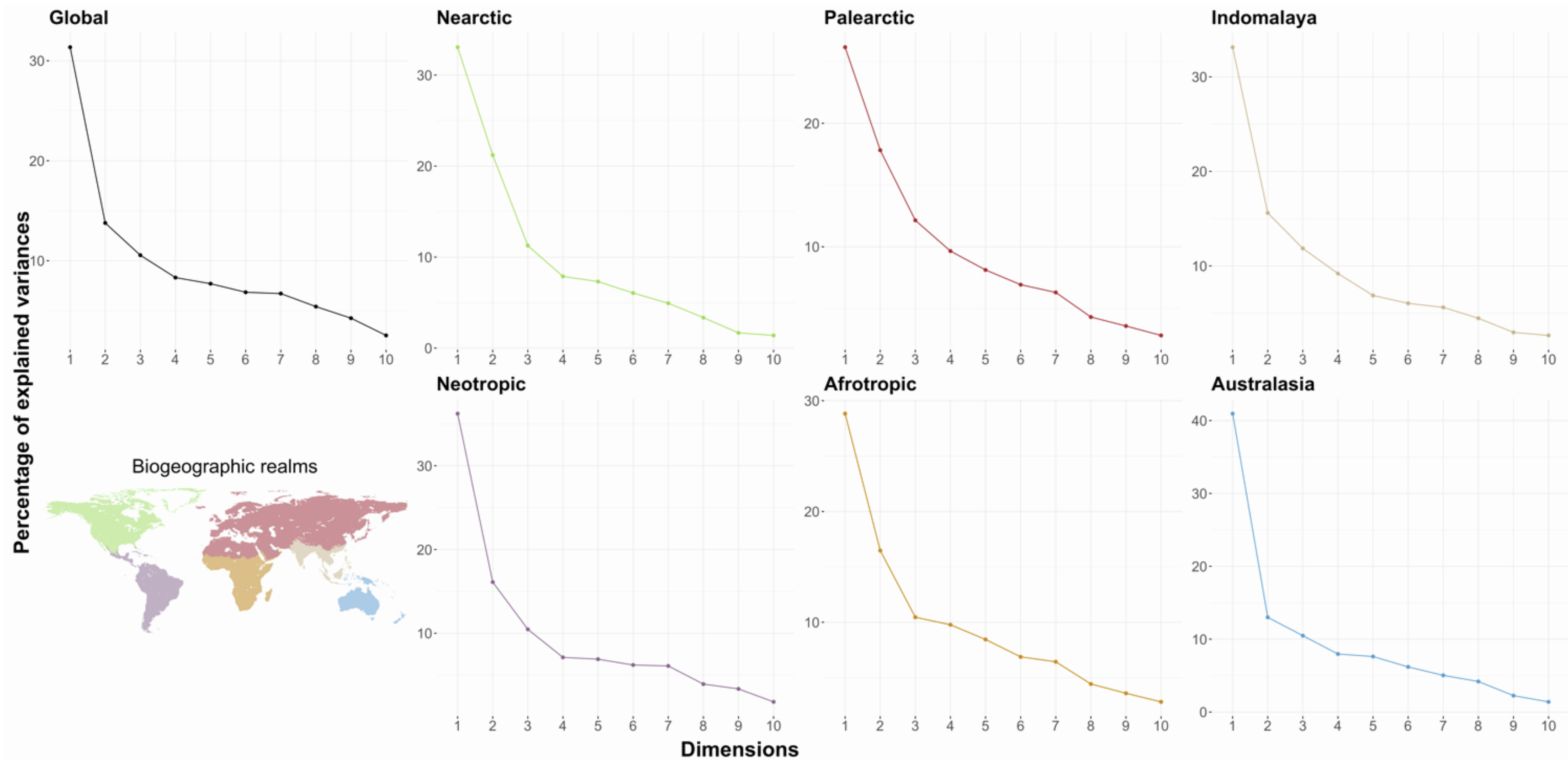

Fig. S6: The percentage of variance explained across the different dimensions of the principal components analysis, shown for the global PCA and the realm-wise PCAs.

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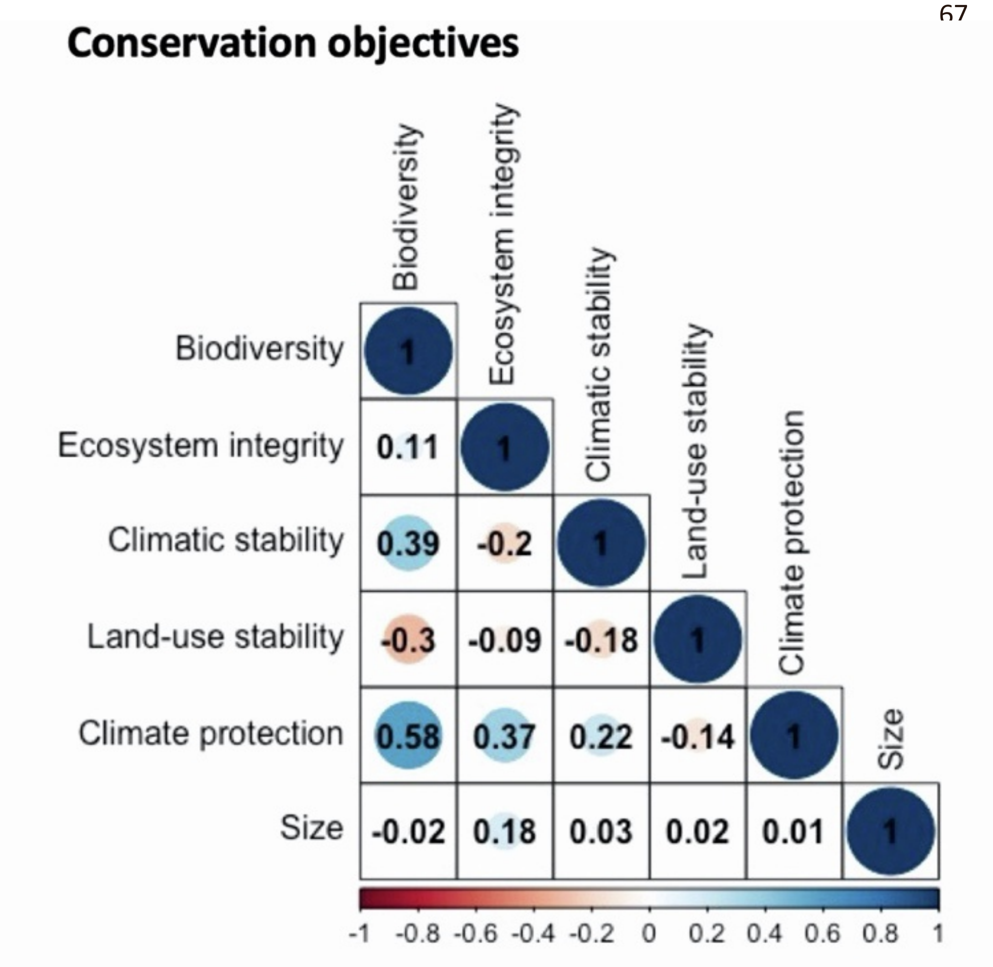


86 **Fig. S7:** Correlation matrix of the different conservation objectives included in the conservation

87 decision support tool, n=1347.

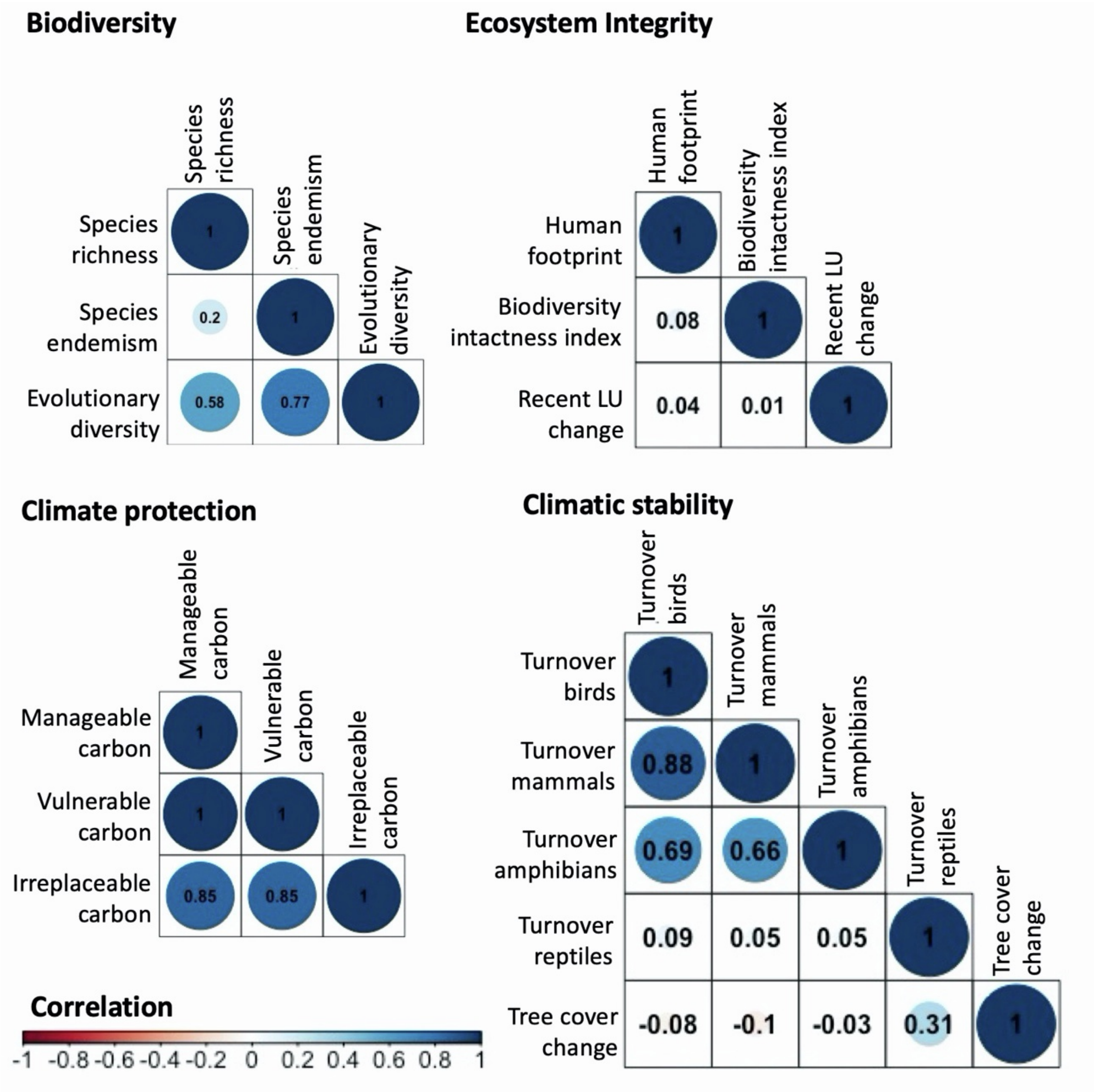


Fig. S8: Correlation matrix of the different indicators included in the biodiversity, ecosystem integrity, climate protection and climatic stability, n=1347.

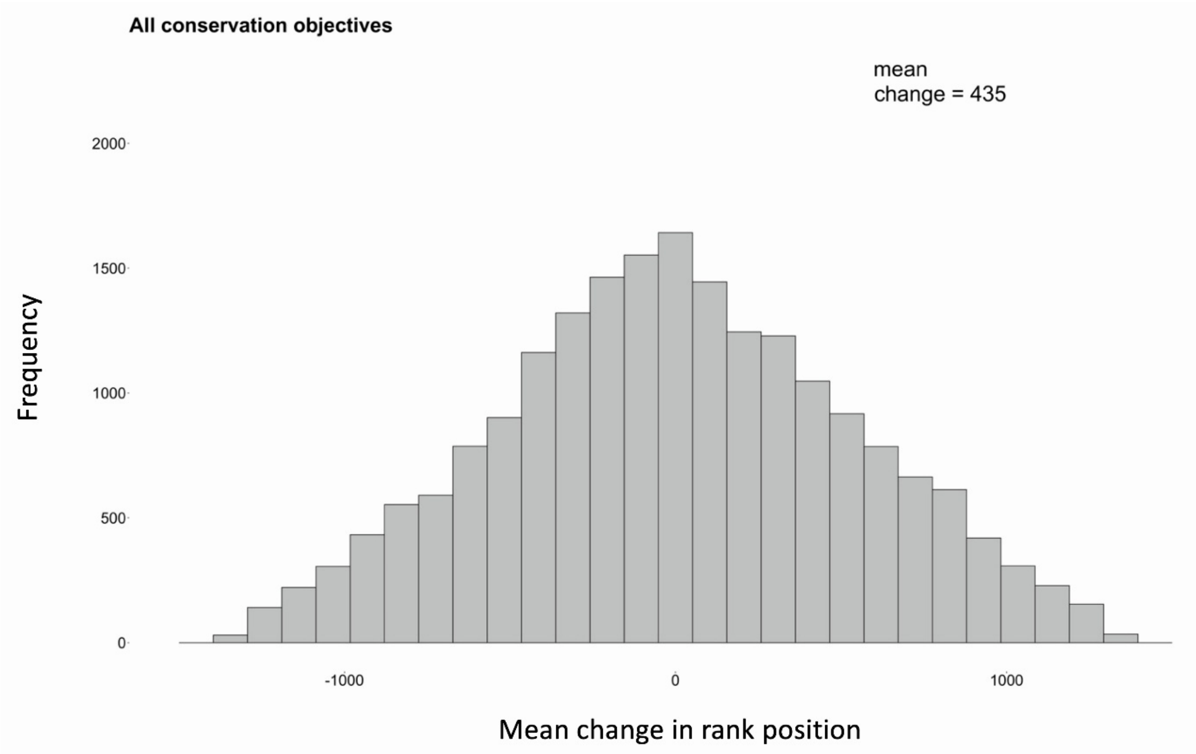


Fig. S9: Mean change in rank positions across all sites for the six different conservation objectives. To assess the mean change in rank position, all sites were ranked for each conservation objective individually and the average change in rank position per site was compared across the individual rankings.

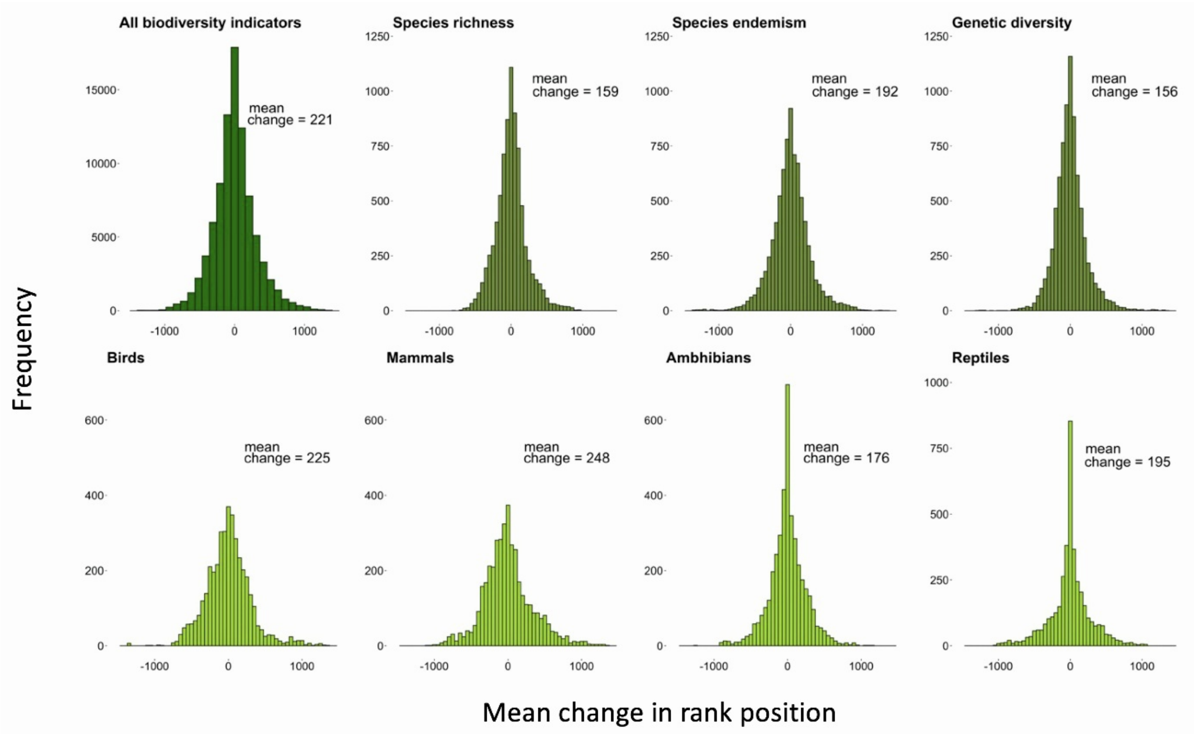


Fig. S10: Mean change in ranking position across all sites compared for all biodiversity indicators, for the three individual biodiversity indicators across all taxa and for the four taxa compared across all biodiversity indicators. To assess the mean change in rank position, all sites were ranked for each indicator and taxa individually and the average change in rank position per site was compared across the individual rankings (i.e. To assess the average change in rank position for species richness (SR) only, four rankings were compared: SR birds; SR mammals; SR; amphibians and SR reptiles. Subsequently the average change in rank position per site was calculated and plotted).

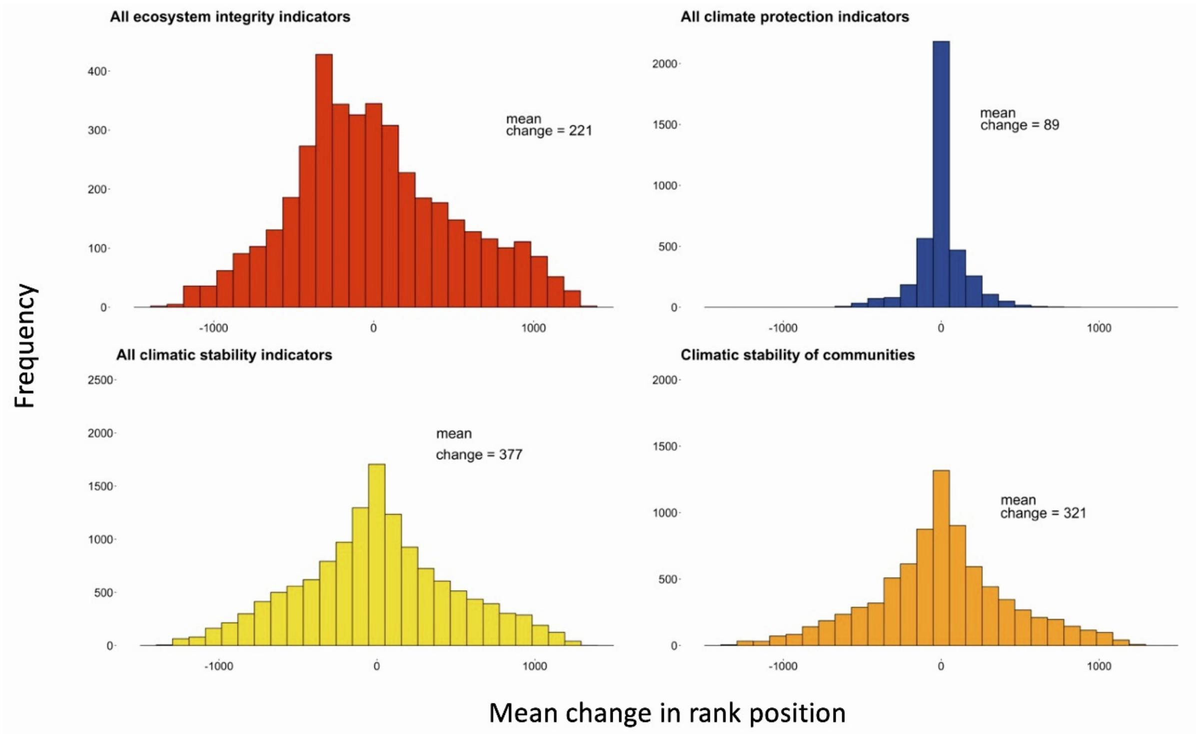


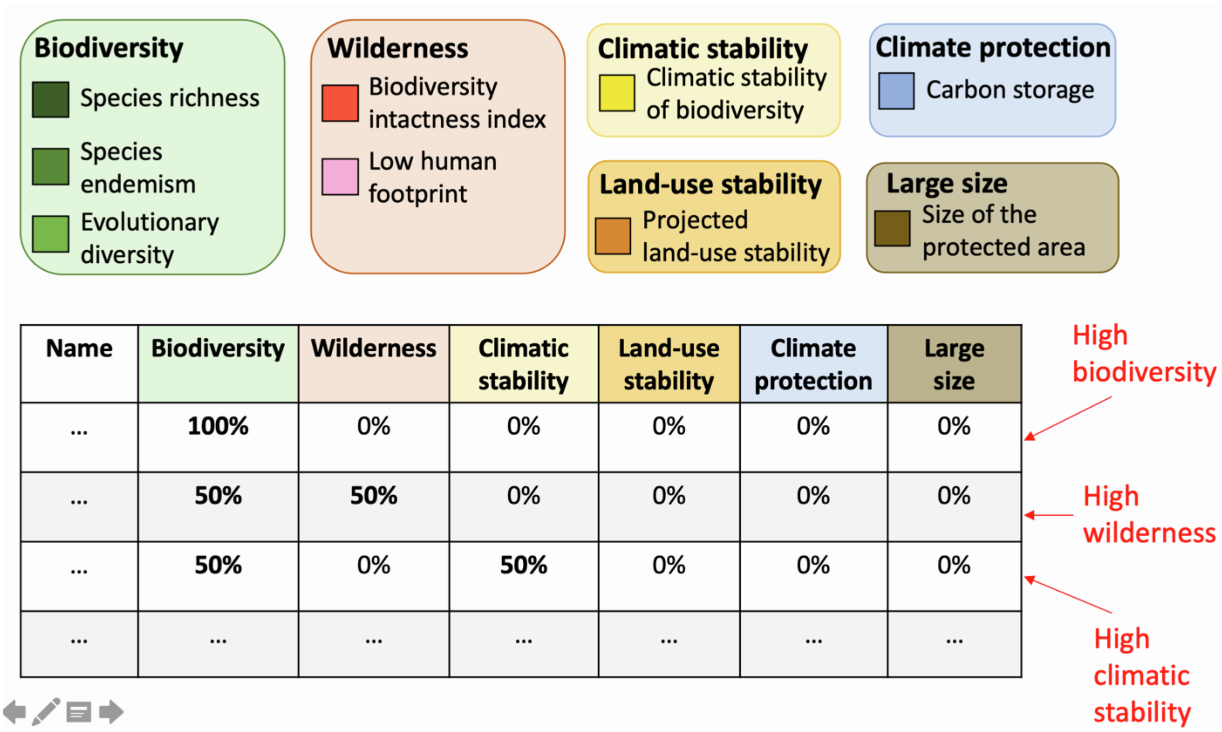
Fig. S11: Mean change in ranking position across all sites compared for all ecosystem integrity, climate protection and climatic stability. For climate stability the change in rank position across all indicators (climatic stability of species communities and change in forest cover) is shown in the bottom left graph and the change in rank position for climatic stability of species communities, considering the four included taxa individually, in the bottom right graph.

Conservation priority setting

Please fill in the table below with a weighting of the different conservation strategies we introduced in the webinar session today. The weighting should be given from the perspective of your work sector. The weights should be allocated in the Legacy Landscapes context rather than based on other goals (e.g. regional or local development goals).

Weights allocated to the different conservation strategies should sum up to 100%. See example table in *Figure1*.

By filling in this questionnaire, you agree that the data will be analyzed in anonymous form for a scientific publication.



Name	Biodiversity	Wilderness	Climatic stability	Land-use stability	Climate protection	Large size
…	**100%**	0%	0%	0%	0%	0%
…	**50%**	**50%**	0%	0%	0%	0%
…	**50%**	0%	**50%**	0%	0%	0%
…	…	…	…	…	…	…

Figure 1: Example weighting table

Question 1. Please fill in the weighting table from the perspective of your work sector, using percentages. Please use 5 percent intervals (e.g. 5%, 10%, 15%). If you filled in ‘Other’, please specify below the table.

Biodiversity	Wilderness	Climatic stability	Land-use stability	Climate protection	Large size	*Other*

If you filled in 'Other' please specify:

Question 2. Please (briefly) explain the motivation behind your weighting:

Question 3. Do we miss any important indicators within the six different conservation objectives (see Figure 1)? Please list:

Question 4. Do we miss any (macro ecological) conservation objectives in the Legacy Landscapes context (see Figure 1)? Please list:

Question 5. Which is the main work sector you would assign yourself to? Please choose one:

Academia:

NGO:

Consultancy:

Government:

Other:

If other please specify:

Question 6. Please identify your work place nationality (If you like to):

Question 7. Please identify your gender (m/f/d) (If you like to):

Fig. S12: The Questionnaire used during the workshop

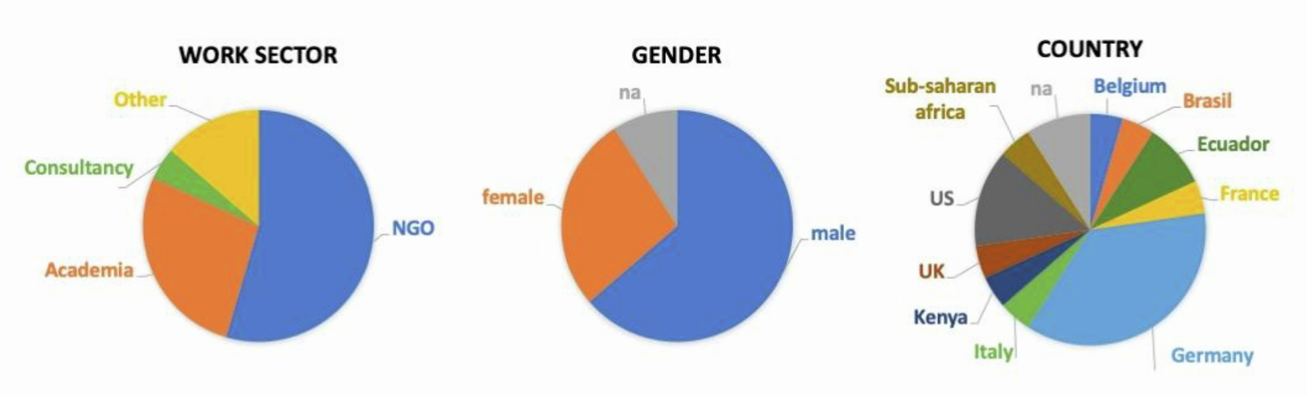


Fig. S13: Anonymous participant data for all workshop attendants who responded to the questionnaire.

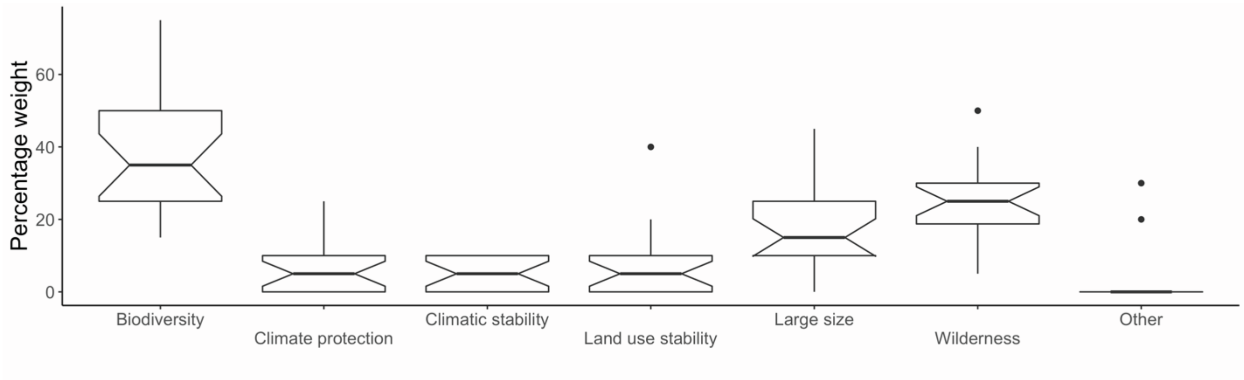


Fig. S14: Responses to Q1 by all attendants who filled in the questionnaire. Weights were allocated in 5 percent intervals to the individual objectives. Combined weights for all conservation objectives allocated per person summed up to 100 percent. Other included governance, ecosystem loss rate and socio-economic factors.

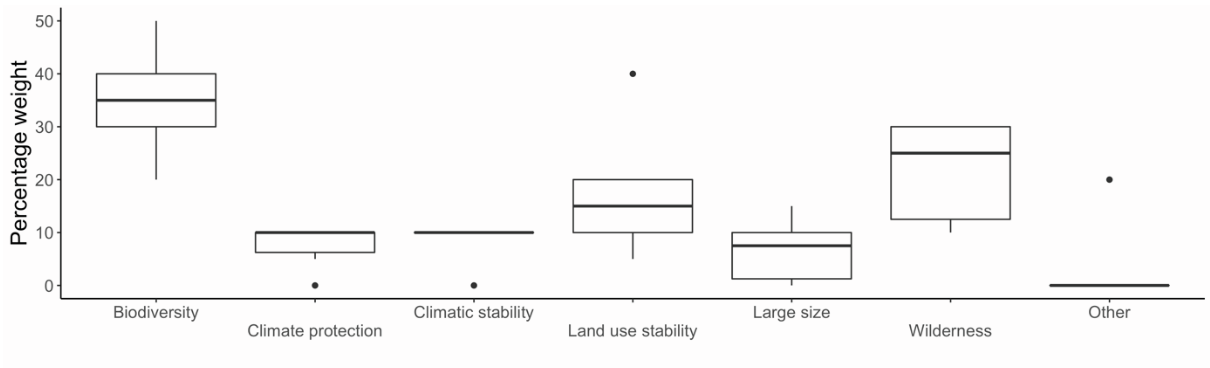


Fig. S15: Responses to Q1 by all attendants who described they work sector as academia. Weights were allocated in 5 percent intervals to the individual objectives. Combined weights for all conservation objectives allocated per person summed up to 100 percent (Other included socio-economic factors).

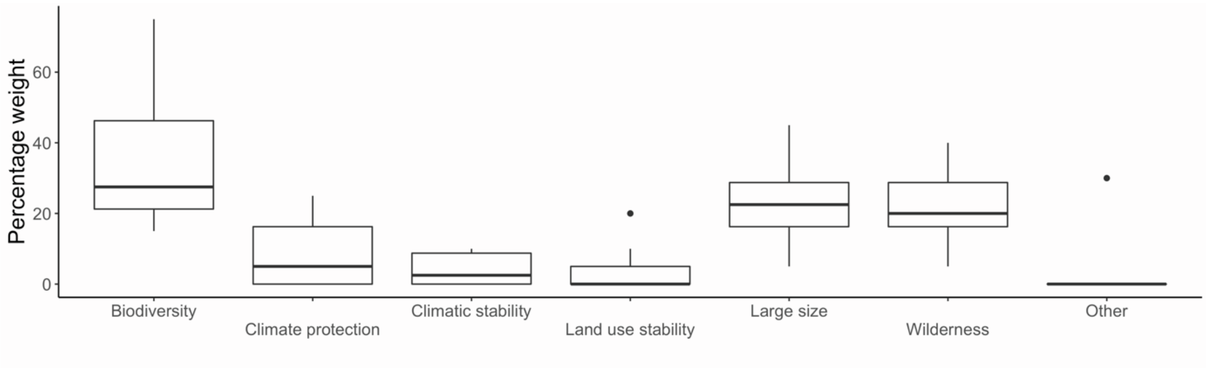


Fig. S16: Responses to Q1 by all attendants who described their work sector as NGO. Weights were allocated in 5 percent intervals to the individual objectives. Combined weights for all conservation objectives allocated per person summed up to 100 percent (Other included governance and ecosystem loss rate).

Note S2: The decision support tool

The decision support tool was developed to allow easy access to the different biogeographic datasets. It consists of four tabs and a settings panel on the left-hand sites which are described below:

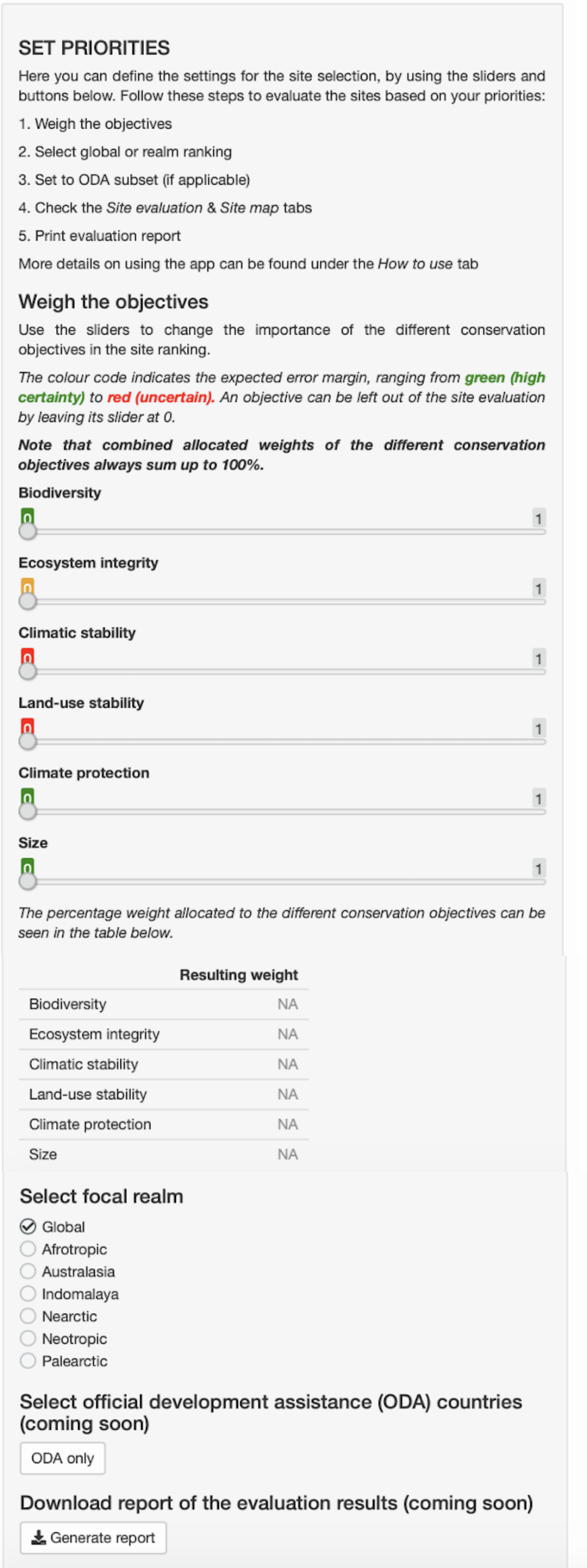


Fig. S17: The settings panel. The brief step by step instruction at the top gives a summary on how to use the conservation decision support tool. The sliders allow users to manually adjust the weighting of the individual conservation objectives (top).

The resulting allocated percentages can be seen in the tables below the sliders (center).

Below the weights table the user can select if sites should be selected globally or for a specific realm. With the "Select focal realm" button users can choose between evaluating sites globally or for one specific realm (bottom). The "Select official development assistance" button allows us to subset if all sites should be included in the evaluation or if only sites located in ODA countries should be included (bottom). The "Generate report" button allows downloading the generated evaluation based on the manually set weights and the selection of region and sites (bottom).

Setting global priorities for longterm conservation

Background | Conservation objectives | Site evaluation | Site map | How to use

The decision support tool

The establishment and maintenance of protected areas (PAs) is viewed as a key action in delivering post 2020 biodiversity targets and reaching the sustainable development goals. PAs are expected to meet a wide range of objectives, ranging from biodiversity protection to ecosystem service provision and climate change mitigation. As available land and conservation funding are limited, optimizing resources by selecting the most beneficial PAs is therefore vital.

This decision support tool enables a flexible approach to PA selection on a global scale, which allows different conservation objectives to be weighted and prioritized. It is meant to facilitate a first evaluation of the potential of PAs for long term conservation before following up with detailed on the ground assessments of the candidate sites.

The current version of the decision support tool contains a set of 1347 PAs. The included PAs were selected as a case study subset based loosely on the criteria of the Legacy Landscapes Fund.

Legacy Landscapes Fund

Legacy Landscapes is a new international public-private initiative, led by the German Government, to develop and implement a conservation and financing strategy for the safeguarding of selected protected areas. The Legacy Landscapes Fund has a terrestrial focus and will significantly contribute to the post-2020 Biodiversity-Framework of the COP 15 at the CBD in 2021.

The Legacy Landscapes Fund concept is based on three pillars:

1. Permanent, stable and performance-based **funding** ensured by a combination of private donors and public funds of about one million $ per site per year.

2. Effective and efficient **management** that will be caried out in cooperation with national authorities, local communities and an NGO, with the annual disbursement of funds being controlled by an independent platform, and based on the fulfillment of certain indicators, the key performance indicators.

3. Strategic site selection, based on the **biogeography** of the site.

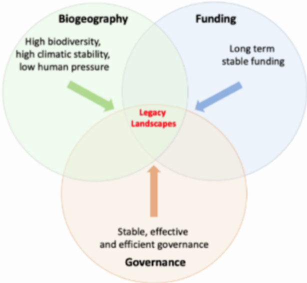


Figure 1: The three cornerstones of the Legacy Landscapes Fund concept

This decision support tool has been developed in cooperation between the Frankfurt Zoological Society and the Senckenberg Biodiversity and Climate Research Centre to support the selection of suitable sites for the Legacy Landscapes Fund. The tool enables the comparison of potential sites based on macro-ecological variables and thus falls under the Biogeography cornerstone of the Legacy Landscapes Fund concept. It facilitates the ranking of sites based on their performance across six different conservation objectives:

Biodiversity, Ecosystem integrity, Climatic stability, Land-use stability, Climate protection and Size.

Contact
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FRANKFURT ZOOLOGICAL SOCIETY

SENCKENBERG
world of biodiversity

Senckenberg Biodiversity and Climate Research Centre

Frankfurt Zoological Society

Fig. S18: The "Background" tab of the conservation decision support tool. Here the user finds a brief introduction to the tool and its purpose.

Background | Conservation objectives | Site evaluation | Site map | How to use

The conservation objectives

Six conservation objectives were selected to enable the comparison of protected areas and evaluate their potential for long term conservation based on macroecological data. The objectives were chosen to allow a first assessment based on the size of the site, the biodiversity it contains, its intactness and its potential for future persistence. Each of the conservation objectives is measured based on one or more macro-ecological variables as described below:

Biodiversity: includes the richness, endemism and evolutionary diversity of species comprising four different taxa (mammals, birds, reptiles and amphibians)

Ecosystem integrity: includes the Biodiversity Intactness Index (BII), the human footprint and the observed change from biome to anthrome (change from natural to human modified landcover) in the area over the past 20 years

Climatic stability: includes the projected impacts of climate change on the stability of ecological communities (mammals, birds, reptiles and amphibians) and the change in tree cover by the mid of the century under a medium warming scenario

Land-use stability: includes the projected change in land-use in the buffer zone around the site

Climate protection: includes the amount of baseline, vulnerable and irrecoverable carbon storage within the site, indicating the contribution of the site to climate protection by binding carbon dioxide.

Size of the site: is the extent of the site in km2

The six different conservation objectives can be combined into different conservation goals as laid out in the figure below. Using the sliders on the left the conservation objectives can be combined by allocating a weight to each objective. Objectives allocated a weight of 0 are excluded from the weighting. The resulting ranking based on the selected objectives and the allocated importance (weight) can be seen in the ***Site evaluation*** tab. The location of the top scoring sites can be seen in the ***Site Map*** tab.

Details on the included variables and data sources and can be found in the text box at the bottom of the page.

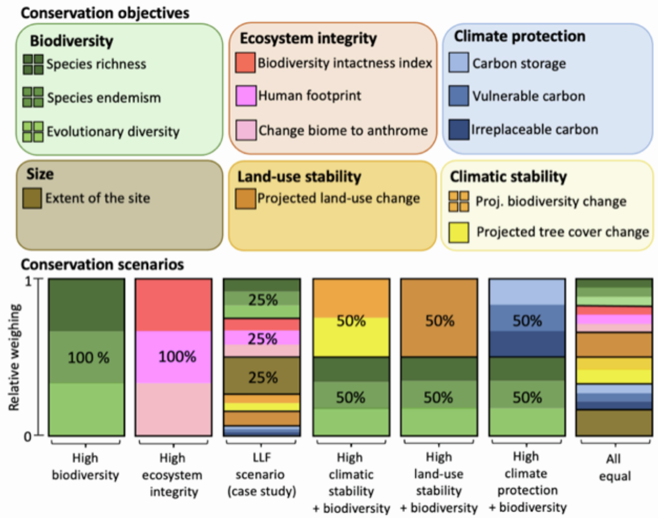
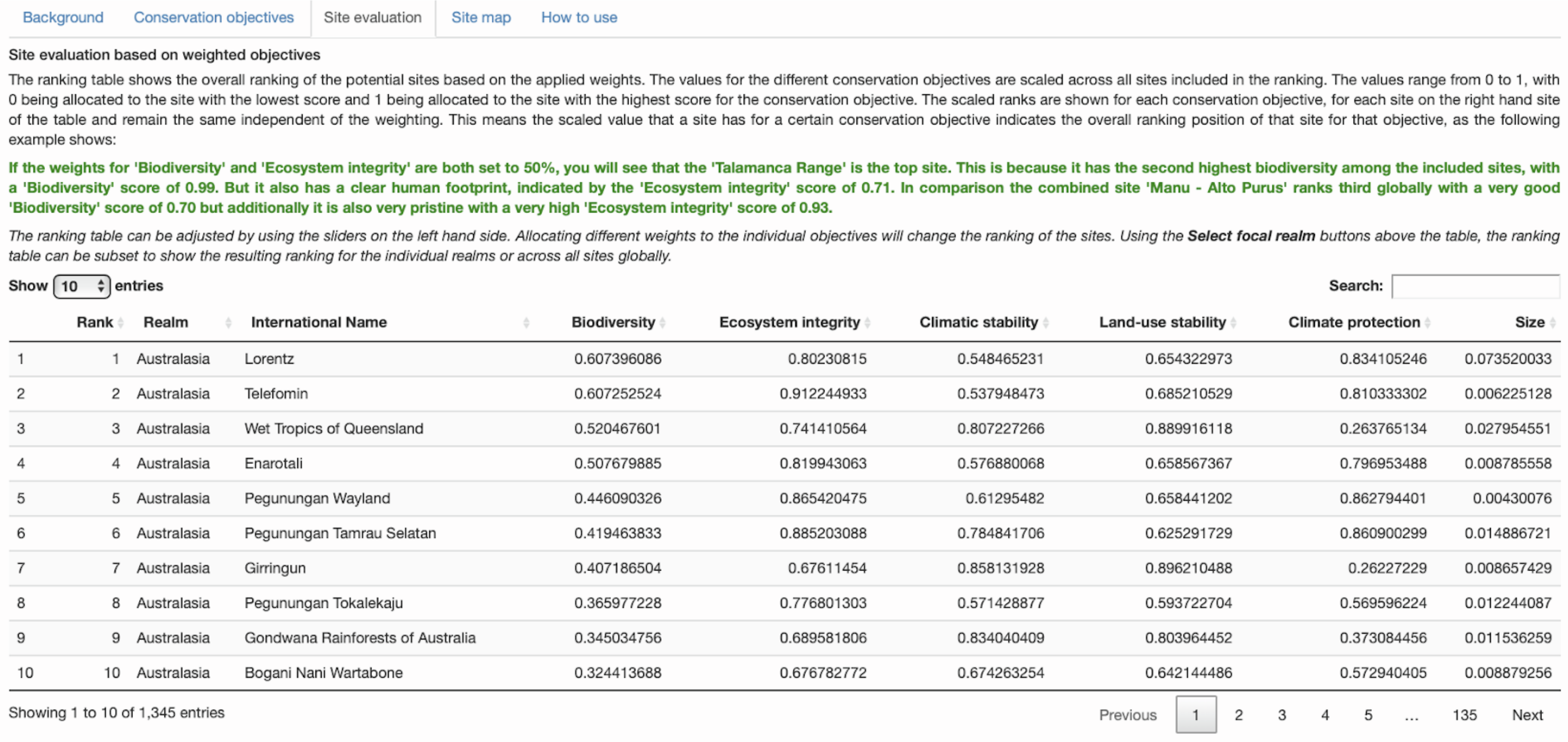


Figure 2: Conservation objectives and strategies The six different conservation objectives Biodiversity, Ecosystem integrity, Climatic stability, Land-use stability, Climate protection and Size can be combined into different conservation scenarioes. These conservation scenarioes allow to weigh the different conservation objectives against each other, to set priorities when evaluating sites for conservation.

Fig. S19: The "Conservation objectives" tab gives the user an overview over the six conservation objectives included in the conservation decision support tool and the indicators they consist of. At the bottom of the tab the user can find a PDF that explains the included data in greater detail (the content of the PDF can be found below under *Details on the conservation objectives*).



Background | Conservation objectives | Site evaluation | Site map | How to use

Site evaluation based on weighted objectives

The ranking table shows the overall ranking of the potential sites based on the applied weights. The values for the different conservation objectives are scaled across all sites included in the ranking. The values range from 0 to 1, with 0 being allocated to the site with the lowest score and 1 being allocated to the site with the highest score for the conservation objective. The scaled ranks are shown for each conservation objective, for each site on the right hand site of the table and remain the same independent of the weighting. This means the scaled value that a site has for a certain conservation objective indicates the overall ranking position of that site for that objective, as the following example shows:

If the weights for 'Biodiversity' and 'Ecosystem integrity' are both set to 50%, you will see that the 'Talamanca Range' is the top site. This is because it has the second highest biodiversity among the included sites, with a 'Biodiversity' score of 0.99. But it also has a clear human footprint, indicated by the 'Ecosystem integrity' score of 0.71. In comparison the combined site 'Manu - Alto Purus' ranks third globally with a very good 'Biodiversity' score of 0.70 but additionally it is also very pristine with a very high 'Ecosystem integrity' score of 0.93.

The ranking table can be adjusted by using the sliders on the left hand side. Allocating different weights to the individual objectives will change the ranking of the sites. Using the ***Select focal realm*** *buttons above the table, the ranking table can be subset to show the resulting ranking for the individual realms or across all sites globally.*

Show 10 entries | Search:

	Rank	Realm	International Name	Biodiversity	Ecosystem integrity	Climatic stability	Land-use stability	Climate protection	Size
1	1	Australasia	Lorentz	0.607396086	0.80230815	0.548465231	0.654322973	0.834105246	0.073520033
2	2	Australasia	Telefomin	0.607252524	0.912244933	0.537948473	0.685210529	0.810333302	0.006225128
3	3	Australasia	Wet Tropics of Queensland	0.520467601	0.741410564	0.807227266	0.889916118	0.263765134	0.027954551
4	4	Australasia	Enarotali	0.507679885	0.819943063	0.576880068	0.658567367	0.796953488	0.008785558
5	5	Australasia	Pegunungan Wayland	0.446090326	0.865420475	0.61295482	0.658441202	0.862794401	0.00430076
6	6	Australasia	Pegunungan Tamrau Selatan	0.419463833	0.885203088	0.784841706	0.625291729	0.860900299	0.014886721
7	7	Australasia	Girringun	0.407186504	0.67611454	0.858131928	0.896210488	0.26227229	0.008657429
8	8	Australasia	Pegunungan Tokalekaju	0.365977228	0.776801303	0.571428877	0.593722704	0.569596224	0.012244087
9	9	Australasia	Gondwana Rainforests of Australia	0.345034756	0.689581806	0.834040409	0.803964452	0.373084456	0.011536259
10	10	Australasia	Bogani Nani Wartabone	0.324413688	0.676782772	0.674263254	0.642144486	0.572940405	0.008879256

Showing 1 to 10 of 1,345 entries

Previous 1 2 3 4 5 … 135 Next

Fig. S20: The "Site evaluation" tab shows the evaluation results based on the set weights and selected region and type of sites (ODA or not) in a table. Sites are ranked from performing best to least under the respective settings.

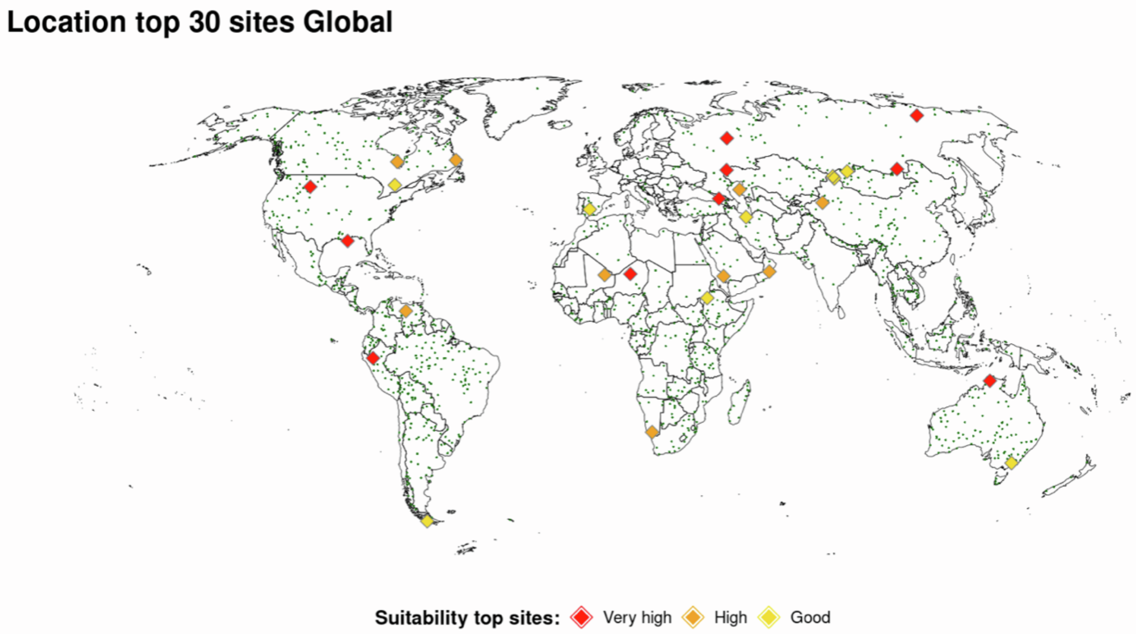
Background | Conservation objectives | Site evaluation | Site map | How to use

Location of the selected sites

The map shows the location of the top sites ranked by their suitability based on the applied weights across the six conservation objectives. Depending on the selection the map shows either the top 30 sites globally or the top 10 sites for a selected biogeographic realm. For full table of all sites see the ***Site evaluation*** tab

The small green points show the locations for all sites included in the analysis. The large red, orange and yellow points show the location of the top sites with red indicating the sites of highest suitability.

*The choice of biogeographic realm can be changed by using the **Select focal realm** button in the panel on the left.*



The country boarders displayed in this map are derived from Natural Earth (version 4.1.0) and do not imply the expression of any opinion concerning the legal status of any country, area or territory or of its authorities, or concerning the delamination of its boarders.

Fig. S21: The “Site map” tab shows the spatial distribution of the top 30 sites based on the set weights and selected region and type of sites (ODA or not).

Background | Conservation objectives | Site evaluation | Site map | How to use

Using the decision support tool for site evaluation

A short step by step instruction can be found at the top of the side panel on the left. Following these instructions the sites included in the decision support tool can be compared based on six different conservation objectives:

Biodiversity: includes the richness, endemism and evolutionary diversity of species comprising four different taxa (mammals, birds, reptiles and amphibians)

Ecosystem integrity: includes the Biodiversity Intactness Index (BII), the human footprint and the observed change from biome to anthrome (change from natural to human modified land cover) in the area over the past 20 years

Climatic stability: includes the projected impacts of climate change on the stability of ecological communities (mammals, birds, reptiles and amphibians) and the change in tree cover by the mid of the century under a medium warming scenario

Land-use stability: includes the projected change in land-use in the buffer zone around the site

Climate protection: includes the amount of baseline, vulnerable and irrecoverable carbon storage within the site, indicating the contribution of the site to climate protection by binding carbon dioxide.

Size of the site: is the extent of the site in km2

A more detailed description of the six conservation objectives and the included indicators can be found at the bottom of the ***Conservation objectives*** tab.

Interpreting the evaluation results

The different conservation objectives are underly different sources of uncertainty, which need to be taken into account when using the decision support tool and interpreting the evaluation results. See text box below for a brief description of the uncertainty associated with each conservation indicator.

Fig. S22: At the bottom of the tab the user can find a PDF with more detailed instructions and information on how to interpret the results and the uncertainty around the different objectives (the content of the PDF can be found below under *How to use the conservation decision support tool*)

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User manual decision support tool

To help users understand the datasets underlying the decision support tool and enable them to use the tool to evaluate sites for conservation, the tool includes a brief description of the included data and a user manual.

Details on the conservation objectives

The site data

The sites currently included in the conservation decision support tool are all registered sites under either one or more of the following criteria:

- a protected area from the global world database in protected areas [65] that is listed by the International Union for Conservation of Nature (IUCN) in either category I or II,
- a natural World Heritage Site (WHS),
- a Key Biodiversity Area (KBA).

The shapefiles for the IUCN protected areas as well as the World Heritage Sites were derived from protected planet [65]. The Shapefiles for the KBAs were derived from BirdLife International [66].

The conservation objectives data

The six different conservation objectives which are included in the decision support tool are biodiversity, ecosystem integrity, climatic stability, land-use stability, carbon storage and size. Each of these objectives consists of one or several underlying macro-ecological indicator variables. See below for a detailed description of the variables included within each of the six conservation objectives and how these variables are derived (*Shorter and simpler explanations can be found under the tab "**How to use**"*).

Biodiversity

The biodiversity objective includes three different variables, the total number of species, the degree of endemism and the evolutionary diversity of the species occurring in the region the site is located in.

<u>*Species richness*</u>

The species richness, for four taxa of vertebrates, is derived from range maps for virtually all species of the four terrestrial vertebrate taxa: from the BirdLife International for birds [67], the IUCN for mammals and amphibians [68], and from GARD for reptiles [54].

Sites with a higher species richness are allocated a higher suitability for long-term conservation than sites with a lower species richness.

<u>Endemism</u>

To capture biodiversity that is unique to a region, a measure for the prevalence of range restricted (endemic) species within the region is used. Species endemism is estimated by calculating weighted range size rarity, which is the sum of the inverted range extents of all species, divided by the number of species occurring in a site [69].

Sites with a higher rate of species endemism are allocated a higher suitability for long-term conservation than sites with a lower rate of species endemism.

<u>Evolutionary diversity</u>

Evolutionary diversity is included to have an estimate of how evolutionary unique the species within a region are. Measures of evolutionary diversity can give an idea of how much evolutionary history is stored within a set of species. A high amount of evolutionary history might imply a high feature diversity across the species within the region and could, arguably, make a community more resilient to disturbance. Evolutionary diversity is calculated using phylogenetic endemism (PE), which is a combined measure of evolutionary history and the uniqueness of a species community. PE identifies regions with high numbers of evolutionary isolated and geographically restricted species. In addition to summing the shared evolutionary history of a species assemblage, PE also incorporates the spatial restriction of phylogenetic branches covered by the assemblage [70].

Sites with a higher evolutionary diversity are allocated a higher suitability for long-term conservation than sites with a lower evolutionary diversity.

Ecosystem Integrity

The ecosystem integrity objective includes three different variables, the biodiversity intactness index (BII), the human footprint in and around the site and the change from biome to anthrome in the past two decades.

Biodiversity intactness index (BII)

The BII presents the modeled average abundance of present species, relative to the abundance of these species in an intact ecosystem [71]. This means the index gives an indication of how much species abundances in a region have already changed due to anthropogenic impacts e.g. land-use change. For the BII we are using the global map of the Biodiversity Intactness Index calculated by Newbold et al (2016).

Sites with a higher estimated biodiversity intactness are allocated a higher suitability for long-term conservation than sites with a lower biodiversity intactness.

Human footprint

As a measure of how pristine the sites still are, a measure of the human footprint within the region is included. Estimates of the human footprint within sites are derived from the standardised human footprint layer by Venter et al (2016), which includes data on the extent of built environments, crop land, pasture land, human population density, night-time lights, railways, roads and navigable waterways.

Sites with a lower human footprint are allocated a higher suitability for long-term conservation than sites with a higher human footprint.

Land-use change

To derive past changes in the land cover of a site we calculated the average percentage change across the site from biomes (natural vegetation cover) to anthromes (human-modified land cover such as rainfed cropland, irrigated cropland, mosaic cropland, mosaic natural vegetation and urban areas). The fraction of land cover classes time series, ranging from 1992 – 2018, was obtained from the GEOEssential project [72].

Sites with a lower percentage of land-use change are allocated a higher suitability for long-term conservation than sites with a higher percentage of land-use change.

Climatic stability

The climatic stability objective consists of two different variables: the projected stability of animal biodiversity and the projected tree cover change under future climate change.

Climatic stability of biodiversity

To estimate the climatic stability of a site we are looking at the potential impacts of climate change on the biodiversity within the site. Climate change is driving shifts in species distributions and it is well established that many taxa are shifting their ranges towards higher latitudes and elevations. But also, idiosyncratic species responses to climate change have been observed. These heterogeneous range shifts have the potential to reshuffle species assemblages, which can have highly unpredictable impacts on species interactions and ecosystem functions (e.g., changes in prey predator relationships or competition). We assume that species assemblages that are not predicted to change a lot in future or experience large species losses are under less risk from climate change than species assemblages that experience a lot of reshuffling. Therefore, we include projected turnover in species under future climate change as an indicator for the climatic stability of biodiversity. Projections of species ranges are derived from species distribution models (see Hof et al 2018 for a detailed description of the modelling). For each site all species that are projected to occur there currently and/or in future (2050) are extracted. The turnover is then calculated between the current and future species assemblage of a site, using the formula for Bray Curtis dissimilarity [73].

Sites with higher climatic stability (i.e., a lower projected turnover in species) are allocated a higher suitability for long-term conservation than sites with a lower climatic stability.

Forest cover change

We included the projected change in tree cover derived from the LPJ-GUESS process-based dynamic vegetation-terrestrial ecosystem model [74]. The climate input for the model was derived from the ISIMIP2b simulations, described above under climatic stability of biodiversity. The projected change of tree cover is calculated as the average percentage change projected to occur within the site.

Sites with a lower change in the projected tree cover are allocated a higher suitability for long-term conservation than sites with a higher change in projected tree cover.

Land-use stability

To assess the potential impacts of projected future land-use change we used predictions of the change in pastures, croplands and biofuel croplands in the buffer zone around the sites (50 km buffer), excluding the site itself.

<u>*Projected land-use change*</u>

Projected land–use change is derived from simulations of current and future land-use, based on global land-use change models, using the assumptions of population growth and economic development as provided by ISIMIP2b and described in Frieler et al. (2017). The used land-use change models [75,76] account for climate impacts (e.g., on crop yields) and were driven with the same climate input as the species distribution models used to derive climatic stability of biodiversity (see above). The land-use scenarios provide percentage cover of six different land-use types (urban areas, rainfed crop, irrigated crop, pastures, as well as rainfed and irrigated bioenergy crops). We averaged annual land-use data for each of two different time periods (1995 and 2050), across the four GCMs (see above under Climatic stability), and calculated a combined value of average land-use change for the buffer zone around each site.

Sites with a lower projected increase in land-use in the buffer zone are allocated a higher suitability for long-term conservation than sites with a higher projected increase in land-use in the buffer zone.

Carbon storage

The carbon storage objective includes three different variables, using the three dimensions of ecosystem carbon stocks as defined by Goldstein et al. (2020). These include the amount of manageable carbon stocks that currently exist but could be influenced in principle by human actions, the amount of vulnerable carbon stocks that currently exist and will be released if land-use changes and the amount of irrecoverable carbon stocks in a site.

<u>*Manageable carbon*</u>

As an indicator for the climate protection capacity, we used the estimated amount of manageable carbon as provided by Noon et al (2021). This layer includes the amount of carbon stored in the above and below ground vegetation as well as soil organic carbon stocks up to 30 cm depth, or up to 100 cm within inundated soil, as these depths are most relevant to common disturbances [25]. We derived the average amount of carbon in t per ha for each site.

Sites with higher baseline carbon stocks are allocated a higher suitability for long-term conservation than sites with lower baseline carbon stocks.

<u>*Vulnerable carbon*</u>

Vulnerable carbon is defined by Goldstein et al (2020) as the amount of the manageable carbon, described above, that is likely to be released through typical land conversion in an ecosystem. We derived the average amount of vulnerable carbon in t per ha for each site.

Sites with higher vulnerable carbon stocks are allocated a higher suitability for long-term conservation than sites with lower vulnerable carbon stocks.

<u>*Irrecoverable carbon*</u>

Irrecoverable carbon is defined as the amount of the vulnerable carbon, described above, that if it is lost through typical land conversion actions, cannot be recovered over the following 30 years [25]. We derived the average amount of irrecoverable carbon in t per ha for each site.

Sites with higher irrecoverable carbon stocks are allocated a higher suitability for long-term conservation than sites with lower irrecoverable carbon stocks.

Large size

For the extent of the area, we preselected sites that are larger than 2000 km^2, based on the precondition that Legacy Landscapes should have a minimum size to maintain a viable ecosystem.

<u>*Extent of the site*</u>

The area in km^2 is derived from the site polygons provided by protected planet [65] or the Key Biodiversity Area (KBA) database [66].

Larger sites are allocated a higher suitability for long-term conservation than smaller sites.

How to use the conservation decision support tool

The conservation decision support tool is meant to facilitate global or realm wise comparisons of sites based on macroecological datasets. The spatial scale of the included datasets enables the user to compare a vast number of sites globally based on the six different conservation objectives. Nevertheless, two important points need to be kept in mind when using the decision support tool and interpreting the evaluation results.

Large-scale comparison, not local assessment

Firstly, due to the coarse resolution of most globally available datasets the decision support tool facilitates a first evaluation of the included sites but *should not be used for local assessments*. This means that for the selection of specific areas for conservation and the practical implementation of nature conservation on the ground requires further evaluation steps that a tool like this cannot cover. These further steps should involve an on-site assessment based on additional parameters at a higher resolution (e.g. more detailed biological data acquired through surveys and observations). For a final decision, it is also crucial to consider non-biological characteristics, ranging from available infrastructure, NGO presence, political situation, access to the site and potential funding possibilities to socio-economic factors.

Underlying data uncertainty varies among objectives

Secondly, the different indicator datasets included within the six conservation objectives come with different levels of uncertainty and error margins, which affects the resulting ranking. These varying error margins should be kept in mind when interpreting the results. For example, a ranking of sites based exclusively on the biodiversity objective is less prone to errors, because the global patterns of species richness and diversity are well-known and unlikely to change substantially in the near future at the used spatial scale. In contrast, the climatic stability objective is based on modelling of future biodiversity responses to climate change, which are sensitive to human societal and political decisions and need to be regularly updated with ongoing developments and new knowledge; therefore, the ranking of sites based exclusively on the climatic stability objective is more prone to errors and could change in the future. *We have therefore colour-coded the sliders for the individual objectives in the panel on the left based on the expected error margin, ranging from* ***green*** *(high certainty) via* ***yellow*** *(intermediate* *certainty) to* ***red*** *(uncertain). An objective can be left out entirely of the site evaluation by leaving its slider at 0.* Below we briefly describe the underlying main sources of uncertainty that should be considered with each conservation objective.

Biodiversity objective: ***Low error margin***

This objective consists of three conservation indicators:

- species richness is the number of species occurring in the region the site is located in and is derived from species range polygons provided by BirdLife International (birds [67]), IUCN (mammals, amphibians [68]) or GARD (reptiles [54]).
- endemism is the range size rarity across all species occurring within the site.
- evolutionary diversity is calculated using phylogenetic endemism (PE), which is a combined measure of evolutionary history and the uniqueness of a species community. PE identifies areas with high numbers of evolutionary isolated and geographically restricted species.

The base data for these indicators are globally available species range maps for virtually all species in the four classes of terrestrial vertebrates (mammals, birds, reptiles, and amphibians) and, for evolutionary diversity, phylogenies that describe how species are related to each other. The observed indicator patterns are well-known and therefore stable at the global scale and unlikely to introduce high amounts of uncertainty into the site evaluation, although we acknowledge that the individual species range maps are only rough representations of where species actually occur and should therefore not be used for local assessments. Similarly, some uncertainty exists in the phylogenetic tree. Due to the coarse nature of the range maps, the resulting species numbers for the individual sites should be interpreted as the number of species occurring within the region where the site is located, not as the exact number of species known to occur within the site.

Ecosystem integrity objective: ***Intermediate error margin***

The ecosystem integrity objective includes three conservation indicators with differing error margins:

- The biodiversity intactness index (BII) connects modelled land-use pressures on biodiversity with locally observed biodiversity data from the PREDICTS project. There are several sources of uncertainty associated with this modelling approach, including the quality of the underlying biodiversity data and the modelling approach itself. We therefore consider the error margin for this conservation indicator as higher compared to e.g. the indicators included in the biodiversity or size objective, but not as high as the completely modelled indicators such as climatic stability. Details on the BII can be found in Newbold et al 2016.

- The human footprint (HFP) within the sites was estimated using the data of Venter et al (2016). The standardized HFP provided by the source data includes the extent of built environments, cropland, pasture land, human population density, night-time lights, railways, roads and navigable waterways. Data included in the footprint dates partially back to 2009 and might not reflect recent developments within and around the actual sites. Therefore, we consider the error margin for this indicator to be higher compared to e.g. the indicators included in the biodiversity or size objective, but not as high as the completely modelled indicators such as climatic stability.
- The biome to anthrome change over the last 20 years measures the conversion of natural ecosystems to different human-dominated land-use categories. This indicator is derived from satellite pictures, which are classified into biome and anthrome classes [72]. From these classes, the percentage change in class coverage across the image pixels falling into each site is then calculated. This indicator has a low error margin, as it is unlikely to introduce high amounts of uncertainty into the site evaluation.

Climatic stability objective: ***High error margin***

The climatic stability objective includes two conservation indicators with high error margins:

- projected change in biodiversity until 2050 modelled under a medium emission pathway (IPCC scenario RCP 6.0 [77]) and associated level of global warming
- projected change in tree cover until 2050 modelled under a medium emission pathway (IPCC scenario RCP 6.0 [77]) and associated level of global warming

Both indicators are based on models, which come with various sources of uncertainty, including the underlying biodiversity data, the chosen model type and the climatic drivers and associated models (details on can be found here [74,78]). Projected change in biodiversity is the turnover in species community compositions between today and 2050 based on species-specific distribution models for virtually all species of the four classes of terrestrial vertebrates (mammals, birds, reptiles, and amphibians) projected onto modelled future climatic conditions. Projected change in tree cover is measured as the percentage change between today and 2050 based on a global dynamic vegetation model that was run for modelled present and future climatic conditions. These projections give an estimate where the impacts of climate change are expected to be severe and which areas might be less affected, but they come with high levels of uncertainty and models are constantly updated as they are based on human societal behaviour and political decisions. We thus expect a relatively high error margin for the climatic stability objective compared to the other objectives.

Land-use stability objective: ***High error margin***

The land-use stability objective is based on one conservation indicator:

- percentage of projected land-use change in a buffer zone around each site (50 km buffer from site margin) until 2050 modelled under a medium emission pathway (IPCC scenario RCP 6.0 [77]) and associated level of land-use conversion [e.g. from pasture to cropland].

The underlying modelled data are matching those for the conservation indicators included in the climatic stability objective. These models come with several sources of uncertainty and additionally depend on the applied assumptions of population growth and economic development (details on the methods and potential sources of uncertainty can be found here [75,76]). The projected changes in land-use give an indication where circumstances might be beneficial for a future increase in land-use potentially adding additional pressures on sites, but these projections are highly uncertain and need to be constantly updated as they are based on human societal behaviour and political decisions. The expected error margin for the land-use stability is thus expected to be high.

Carbon storage objective: ***Low error margin***

The carbon storage objective consists of three different measures of carbon storage as a conservation indicator:

- baseline carbon, i.e. the amount of carbon stored in the above and below ground as well as the soil organic carbon of an ecosystem.
- vulnerable carbon is defined as the amount of (baseline) carbon that is likely to be released through typical land conversion in an ecosystem.
- irrecoverable carbon, is defined as the amount of carbon, that if it is lost through typical land conversion actions, and that cannot be recovered over the following 30 years.

All three measures are derived from the same data source [79] and measure carbon storage because this effectively removes the greenhouse gas carbon dioxide (CO2) from the atmosphere, thus protecting the current climate system from global warming effects. The baseline carbon estimates for the underlying dataset have been derived from various sources and combine the best estimates available. Whilst the amount of vulnerable and irrecoverable carbon strongly depend on the estimates of carbon lost through land conversion and recovery time, the overall spatial patterns of carbon storage are well-known and likely to be stable. The expected error margin for the carbon storage objective is thus expected to be comparatively low, contrary to the climatic and land-use stability objectives which depend on complex modelled datasets.

Size objective: ***Low error margin***

The only conservation indicator for the size objective is the size of the sites. This is directly calculated from shapefiles provided by the World Database on Protected Areas [65] and BirdLife International [66] and has an expected low error margin. As the calculated size depends on the accuracy of the shapefiles, this accuracy might therefore slightly affect the site evaluation for some included sites, but the errors are likely to be minor.

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