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Perspective

Utilizing multi-objective decision support tools for protected area selection

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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

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, 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

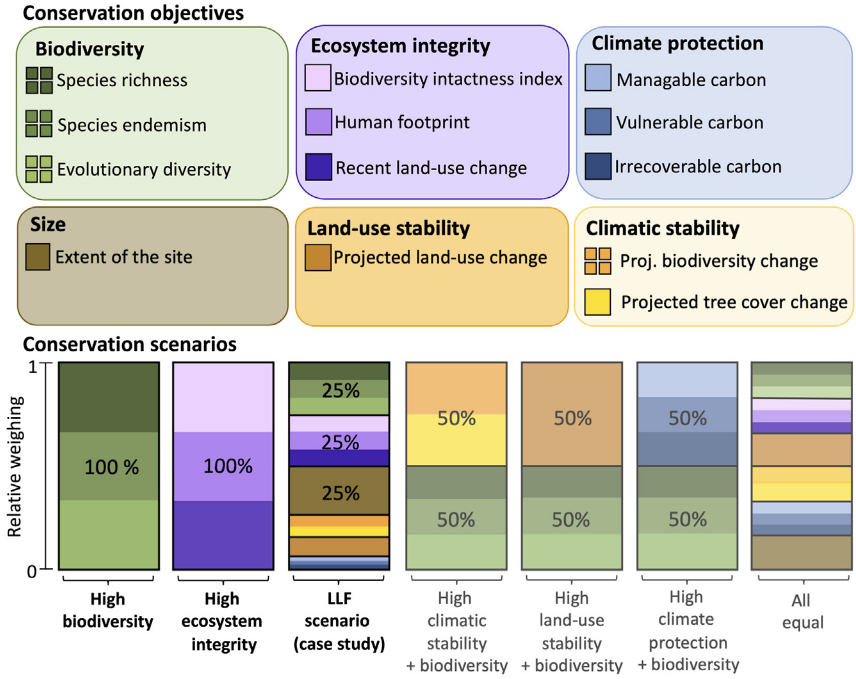

Figure 1. The included conservation objectives

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.

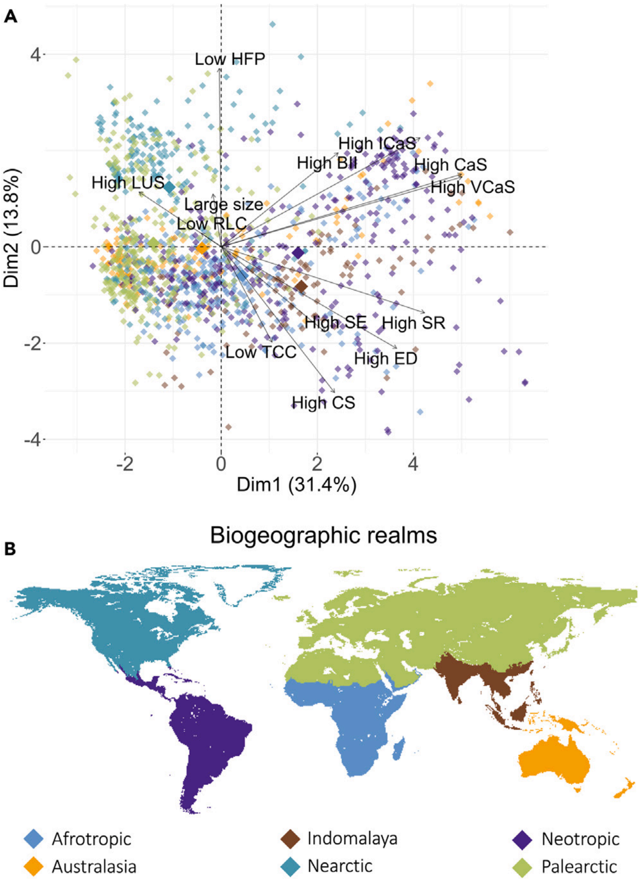

Figure 2. Trade-offs and synergies between the conservation indicators of individual sites

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

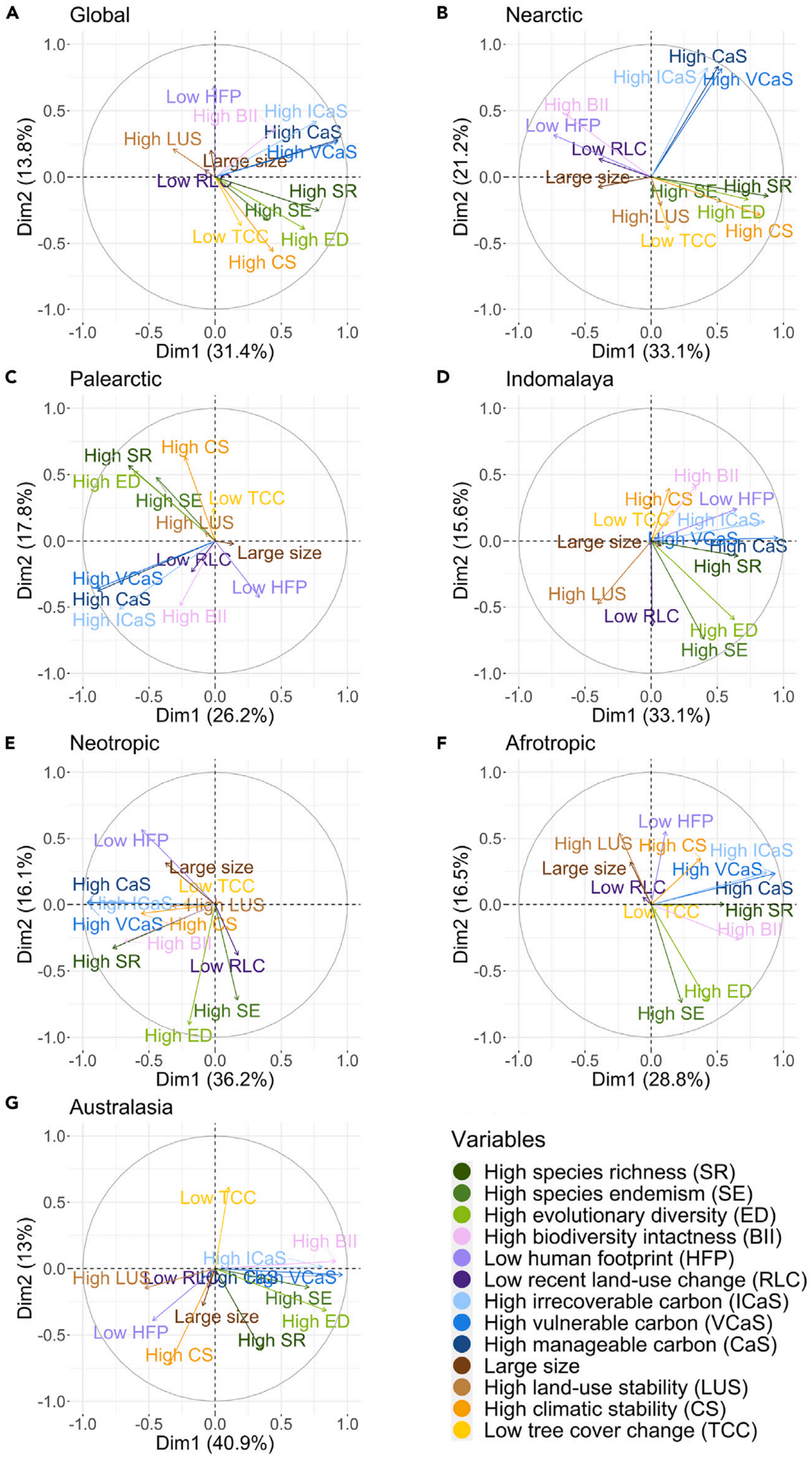

Figure 3. Trade-offs and synergies between the conservation indicators of individual sites at the global and realm levels

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.

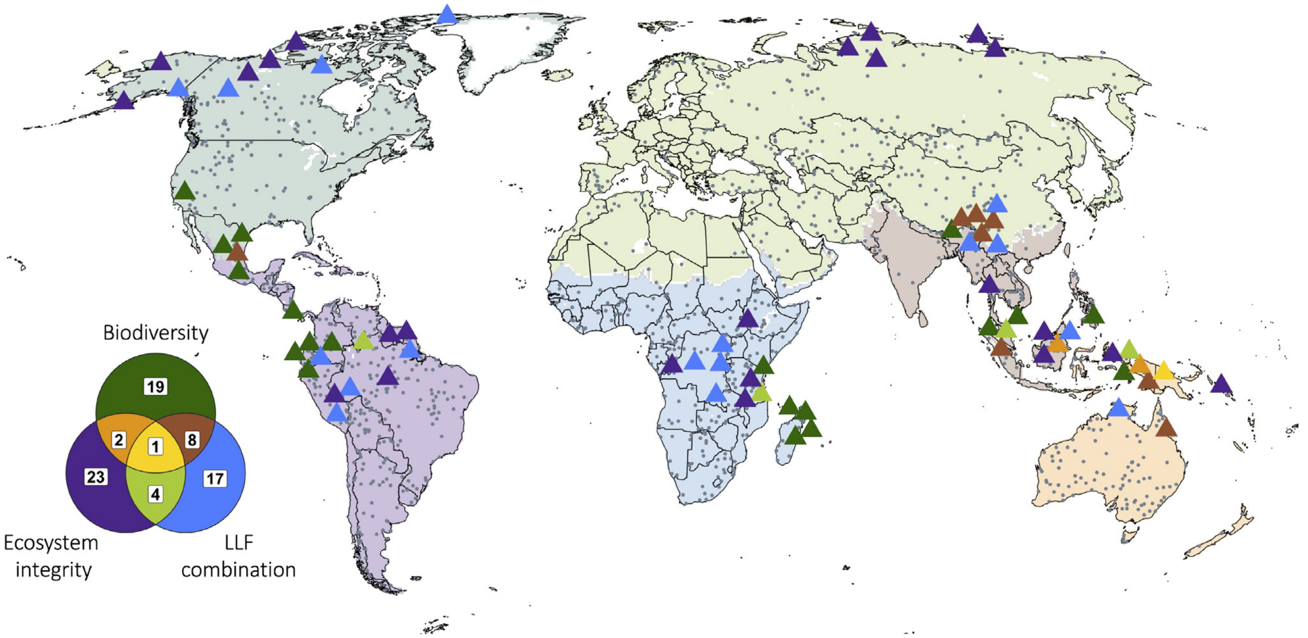

Figure 4. Spatial distribution of sites

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.

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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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