## Title

Areas of global importance for conserving terrestrial biodiversity, carbon, and water

## Author list

Martin Jung1 ([jung@iiasa.ac.at](mailto:jung@iiasa.ac.at)), Andy Arnell2, Xavier de Lamo3, Shaenandhoa García-Rangel2, Matthew Lewis1,4, Jennifer Mark2, Cory Merow5, Lera Miles2, Ian Ondo6, Samuel Pironon6, Corinna Ravilious2, Malin Rivers7, Dmitry Schepashenko1,8, Oliver Tallowin2, Arnout van Soesbergen2, Rafaël Govaerts6, Bradley L. Boyle9, Brian J. Enquist9, Xiao Feng10, Rachael Gallagher11, Brian Maitner9, Shai Meiri12, Mark Mulligan13, Gali Ofer12, Uri Roll14, Jeffrey O. Hanson15, Walter Jetz16,17, Moreno Di Marco18, Jennifer McGowan19, D. Scott Rinnan16,17, Jeffrey D. Sachs20, Myroslava Lesiv1, Vanessa M. Adams21, Samuel C. Andrew22, Joseph R. Burger23, Lee Hannah24, Pablo A. Marquet25,26,27,28,29, James K. McCarthy30, Naia Morueta-Holme31, Erica A. Newman9, Daniel S. Park32, Patrick R. Roehrdanz24, Jens-Christian Svenning33,34, Cyrille Violle35, Jan J. Wieringa36, Graham Wynne37, Steffen Fritz1, Bernardo B.N. Strassburg38,39,40,41, Michael Obersteiner1,42, Valerie Kapos2, Neil Burgess2, Guido Schmidt-Traub43 and Piero Visconti1 ([visconti@iiasa.ac.at](mailto:visconti@iiasa.ac.at))

**Affiliations**

1 Biodiversity and Natural Resources Program (BNR), International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria

2 UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), 219 Huntingdon Road, Cambridge CB3 0DL, United Kingdom

3 Food and Agriculture Organization of the United Nations (FAO), Viale delle Terme di Caracalla, 00153, Rome, Italy.

4 Department of Zoology, University of Cambridge, Downing Street, Cambridge CB2 3EJ, United Kingdom

5 Department of Ecology and Evolutionary Biology, University of Connecticut, CT 06269, USA

6 Royal Botanic Gardens, Kew, Richmond TW9 3AE, United Kingdom

7 Botanic Gardens Conservation International, Richmondy TW9 3BW, United Kingdom

8 Siberian Federal University, Krasnoyarsk 660041, Russia

9 Department of Ecology and Evolutionary Biology, University of Arizona, Tucson, AZ 85721, USA.

10 Department of Geography, Florida State University, Tallahassee, FL, 32306, United States.

11 Department of Biological Sciences, Macquarie University, North Ryde, NSW 2019, Australia

12 School of Zoology, Faculty of Life Sciences, Tel Aviv University, Tel Aviv 6997801, Israel

13 Department of Geography, King’s College London, London WC2B 4BG, United Kingdom

14 Mitrani Department of Desert Ecology, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Midreshet Ben-Gurion 8499000, Israel

15 CIBIO/InBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos da Universidade do Porto, 4485-661 Vairão, Portugal

16 Department of Ecology and Evolutionary Biology, Yale University, New Haven, CT, 06520, USA

17 Center for Biodiversity and Global Change, Yale University, New Haven, CT, 06520, USA

18 Department of Biology and Biotechnologies, Sapienza University of Rome, viale dell'Università 32, 6 I-00185 Rome, Italy

19 The Nature Conservancy, 4245 Fairfax Drive, Arlington, VA, 22203, USA

20 Columbia University, New York, NY 10027, USA

21 School of Geography, Planning and Spatial Sciences, University of Tasmania, Hobart TAS 7005, Australia

22 CSIRO Land and Water, Canberra, Australian Capital Territory, Australia

23 Department of Biology, University of Kentucky, Lexington, KY, 40506, USA

24 Betty and Gordon Moore Center for Science, Conservation International, 2011 Crystal Dr, Arlington, VA 22202, USA.

25 Departamento de *Ecología*, Facultad de Ciencias Biológicas, Pontificia Universidad *Católica* de Chile, CP 8331150, Santiago, Chile

26 Instituto de *Ecología* y Biodiversidad (IEB), Santiago, Chile

27 Centro de Cambio Global UC, Facultad de Ciencias *Biológicas*, Pontificia Universidad Católica de Chile, CP 8331150, Santiago, Chile

28 The Santa Fe Institute, 1399 Hyde Park Road, Santa Fe NM 87501, USA

29 Instituto de Sistemas Complejos de Valparaíso (ISCV), Artilleria 470, Valparaíso, Chile

30 Manaaki Whenua – Landcare Research, Lincoln 7640, New Zealand

31 Center for Macroecology, Evolution and Climate, GLOBE Institute, University of Copenhagen, Universitetsparken 15, build. 3, DK-2100 Copenhagen Ø, Denmark

32 Department of Biological Sciences, Purdue University, West Lafayette, Indiana, 47907 USA

33 Center for Biodiversity Dynamics in a Changing World (BIOCHANGE), Department of Biology, Aarhus University, Ny Munkegade 114, DK-8000 Aarhus C, Denmark

34 Section for Ecoinformatics and Biodiversity, Department of Biology, Aarhus University, Ny Munkegade 114, DK-8000 Aarhus C, Denmark

35 CEFE, Univ. Montpellier, CNRS, EPHE, IRD, Univ. Paul Valéry Montpellier 3, Montpellier, France

36 Naturalis Biodiversity Center, Darwinweg 2, Leiden, The Netherlands

37 World Resources Institute, London, UK

38 Rio Conservation and Sustainability Science Centre, Department of Geography and the Environment, Pontifical Catholic University, 2453900, Rio de Janeiro, Brazil

39 International Institute for Sustainability, Estrada Dona Castorina 124, 22460-320, Rio de Janeiro, Brazil

40 Programa de Pós Graduacão em Ecologia, Universidade Federal do Rio de Janeiro, 21941-590, Rio de Janeiro, Brazil

41 Botanical Garden Research Institute of Rio de Janeiro, Rio de Janeiro, Brazil

42 Environmental Change Institute, Centre for the Environment, Oxford University, South Parks Road Oxford OX1 3QY

43 UN Sustainable Development Solutions Network, 19 Rue Bergère, 75009 Paris, France

## Abstract

To meet the ambitious objectives of biodiversity and climate conventions, the international community requires clarity on how these objectives can be operationalized spatially, and multiple targets can be pursued concurrently. To support goal setting and implementation of international strategies and action plans, spatial guidance is needed to identify which land areas have the potential to generate the greatest synergies between conserving biodiversity and nature’s contribution to people (NCP). Here we present results from a joint optimization that maximizes improvements in species conservation status, carbon retention, and water quality regulation, and ranks terrestrial conservation priorities globally. We found that selecting the top-ranked 30% and 50% of terrestrial land area would conserve respectively 60.7% and 85.3% of the estimated total carbon stock, 66% and 89.8% of all clean water, in addition to meeting conservation targets for 57.9% and 79% of all species considered. Our data and prioritization furthermore suggests that adequately conserving all species considered (vertebrates and plants) would require giving conservation attention to ~70% of the terrestrial land surface. If priority was given to biodiversity only, managing 30% of optimally located land area for conservation may be sufficient to meet conservation targets for 81.3% of the terrestrial plant and vertebrate species considered. Our results provide a global assessment of where land could be optimally managed for conservation. We discuss how such a spatial prioritisation framework can support the implementation of the biodiversity and climate conventions.

## Main text

### Introduction

Biodiversity and nature’s contributions to people (NCP) are in peril, requiring increasing conservation efforts to avert further decline[1,2](https://www.zotero.org/google-docs/?sDjp8M). Existing global biodiversity conservation targets were not met by 2020[3](https://www.zotero.org/google-docs/?wTggJD) and the world is falling short of mobilizing the full climate mitigation potential of nature-based solutions, which it is estimated could provide around a third of the mitigation target specified under the Paris Agreement[4](https://www.zotero.org/google-docs/?uWTu2o). A new Global Biodiversity Framework is scheduled to be adopted in 2021 by the Convention on Biological Diversity (CBD) in Kunming, China[5](https://www.zotero.org/google-docs/?7hO0w1), and there are growing calls to integrate nature-based solutions into climate mitigation strategies[6](https://www.zotero.org/google-docs/?qmpbbl).

Targets for site-based conservation actions, hereafter ‘area-based conservation targets’, are given particular emphasis in the draft Global Biodiversity Framework[5](https://www.zotero.org/google-docs/?SyZ1ER). Target 2 calls for the protection and conservation of at least “30 % of the planet *through a well connected and effective system of protected areas and other effective area-based conservation measures with the focus on areas particularly important for biodiversity”.* This proposal somewhat integrates calls made by conservation advocates to conserve 30% of land and the oceans[7](https://www.zotero.org/google-docs/?tWyx3Q), with proposals putting emphasis on targeting conservation outcomes, rather than conservation area. This is to ensure that, by 2030, areas of global conservation importance for biodiversity are maintained or restored[8](https://www.zotero.org/google-docs/?5baLEg).

The Sustainable Development Goals (SDGs), and decisions under the United Nations Framework Convention on Climate Change (UNFCCC) [and](https://www.unccd.int/) CBD emphasize that habitat conservation and restoration should contribute simultaneously to biodiversity conservation and climate change mitigation[5](https://www.zotero.org/google-docs/?odGz07). In particular, the draft Target 7 of the Global Biodiversity Framework post-2020 calls for “*increased contributions to climate change mitigation, adaptation and disaster risk reduction from nature-based solutions [...] minimizing any negative impacts on biodiversity*..“ Recent global-scale spatial analyses of conservation priorities for biodiversity and carbon have overlaid areas of value for both features, effectively treating the two goals as being pursued separately (e.g.[7,9](https://www.zotero.org/google-docs/?DBtIsh)). However, multi-criteria spatial optimization approaches applied to conservation and restoration prioritisation have shown that carbon sequestration could be doubled, and the number of extinctions prevented tripled, if priority areas were jointly identified[10,11](https://www.zotero.org/google-docs/?HG4cRg). As yet, there are no comparable optimization analyses that identify areas of global terrestrial conservation importance for biodiversity and NCP.

A number of recent studies have attempted to map spatial conservation priorities on land[12](https://www.zotero.org/google-docs/?W75AUd), relying on spatial conservation prioritisation (SCP) methods[13–16](https://www.zotero.org/google-docs/?troPek). However, these approaches are limited, in that: they (*i*) have restricted geographic extent[17](https://www.zotero.org/google-docs/?UrVCnA) or focus on only a subset of global biodiversity, notably lacking reptiles, invertebrates, and plant species, which show considerable variation in areas of conservation importance compared to other taxa [18,19](https://www.zotero.org/google-docs/?DJhZxf); (*ii*) focus on species representation which is not directly correlated with reducing extinction risk, as per international biodiversity targets, and often ignoring other dimensions of biodiversity, e.g. evolutionary distinctiveness[20,21](https://www.zotero.org/google-docs/?iY12Kr); (*iii*) do not investigate the extent to which synergies between biodiversity and NCP, such as carbon sequestration or clean water regulation[22](https://www.zotero.org/google-docs/?k4SyQ1), can be maximised[17](https://www.zotero.org/google-docs/?vaJi6U); and (*iv*) they use a-priori defined measures of importance, such as intactness[23,24](https://www.zotero.org/google-docs/?JN94A2), or arbitrary area-based conservation targets, such as 30% or 50% of the Earth[7,25](https://www.zotero.org/google-docs/?0Qhl7l) instead of objectively delineating the potential value for biodiversity and NCP across the whole world irrespective of such constraints.

The aim of this study is to identify areas of global conservation importance for biodiversity - here focussing on species conservation - jointly with two NCP, carbon storage and water quality regulation. Ensuring the highest ranked areas retain their present conservation value in the next decade would greatly contribute to achieving global species conservation targets, harnessing climate change mitigation potential of natural ecosystems, and maintain their water quality regulation potential.

We define ‘conservation management’ as any set of site-based actions appropriate for the local context (considering pressures, tenure, land-use, etc.), that is commensurate with retaining the potential value of these areas for the features of conservation interest (e.g. species, habitat types, soil or biomass carbon, clean water). For instance, conservation management may equate to monitoring and surveillance (when the present conditions and ongoing and projected pressures do not require active management), establishing legal protection, establishing other area-based conservation measures such as community-managed forests[26](https://www.zotero.org/google-docs/?pYaHrL), or incentives such as payment for ecosystem services. We make no assumptions about the type of local management required, its feasibility and costs, or the counterfactual outcome with an alternative form of management, and therefore our prioritization is based on the upper limit of the value of these areas for achieving global conservation targets.

We obtained fine-scale range maps for the world’s terrestrial vertebrates as well as the largest sample of vascular plant range data ever considered in global species-level analysis, comprising ~41% of all accepted plant species names. To capture intraspecific variation, we considered each part of a species range occurring in geographically separate biomes as a separate feature with its own target, thus splitting each species into as many biodiversity features as the biomes in which the species occurs. For NCP we use the latest global spatial data on above- and below-ground biomass carbon, and vulnerable soil carbon, as well as the volume of potential clean water by river basin. We applied a multicriteria spatial optimization framework to investigate synergies between these features and explore how priority ranks change depending on how much weight is given to biodiversity, carbon sequestration or water quality regulation. We investigated the impact that accounting for vascular plants has on the geography of global conservation priorities. We furthermore tested the implications of setting biome-specific species targets, as opposed to the more common approach of setting global species targets. Finally, we examined whether the highest ranks vary if species evolutionary distinctiveness and threat status were considered.

### Results

We found large potential synergies between managing land for biodiversity conservation, storing soil and biomass carbon, and maintaining clean water quality regulation. Managing the top-ranked 10% of land, i.e. those areas with the highest priority, to achieve these objectives simultaneously (Fig. 1, Extended Data Fig. 1), has the potential to achieve conservation targets for 42.5% of all species considered, including about 33.7% of all known plant species, as well as conserving 26% of the total carbon and 22.1% of the potential clean water globally. Areas with the greatest global biodiversity importance notably include the mountain ranges of the world, large parts of Mediterranean biomes and South-East Asia (Extended Data Fig. 2a). Overall they were comparable to previous expert-based delineations of conservation hotspots[27](https://www.zotero.org/google-docs/?8e4xVX), while also highlighting additional areas of conservation importance for biodiversity, such as Western Central Africa, Papua New-Guinea, Western Tibetan Plateau and East Australian rainforest (Extended Data Fig. 2a). The Eastern Canada area, the Congo Basin and Papua New Guinea were among the top-ranked 10% areas for global carbon storage (Extended Data Fig. 2b, 3a), while the Eastern United States of America, the Congo, European Russia and Eastern India were among the areas with the greatest conservation importance for water quality regulation (Extended Data Fig. 2c, 3b). Overall, when jointly optimizing for biodiversity, carbon and water, top-ranked areas were distributed across all continents, latitudes and biomes (see Supplementary Information for averaged priority ranks per country).

Synergies and trade-offs depend on the relative preference given to conservation of terrestrial biodiversity, carbon storage and water quality regulation (Fig. 2a). We explored an array of conservation variants with a range of possible outcomes: at one extreme, priority is equally given to conserving biodiversity and carbon (Fig. 2b). At the other extreme are variants that prioritize conserving only biodiversity and water (Fig. 2c). Intermediate options include giving equal weighting to all three features; this weighting scheme yielded the best outcome in terms of numbers of species targets achieved (Fig. 2a), and in terms of average target shortfall across species and NCPs (Extended Data Fig 10), and was therefore chosen to visualize spatial priorities (Fig. 1). Similar to earlier assessments[9,28,29](https://www.zotero.org/google-docs/?aLC1Ec), we found synergies between the conservation of biodiversity and carbon storage (Fig. 2b, Extended Data Fig. 10). Additionally, we discovered similar synergies for biodiversity and water quality regulation (Fig. 2c, Extended Data Fig 10). Trade-offs between biodiversity versus carbon and water were dependent on conservation preferences (relative weights in the optimization analyses) and particularly high when given less than 50% preference to either NCP relative to species conservation (Fig. 2, Extended Data Fig. 10).

Conserving the top-ranked 10% of land areas for biodiversity and carbon only (equally weighted), can protect up to 22.8% of the global total carbon and 27% of all species, while maintaining 16% of all global water quality regulation as a co-benefit (Fig. 2b). In contrast, conserving the top-ranked 10% of land for biodiversity and water only (equally weighted) can protect 20% of water and 24.7% of all species (Fig. 2a), while maintaining 15% as a carbon co-benefit (Fig. 2c). The implications of assigning different relative preferences to conserving NCP magnify with increasing amounts of land area managed for conservation. The range of carbon conserved is 15% to 25% when conserving 10% of land and 47.1% to 61.4% when conserving 30%. The range of clean water conserved is 16% to 21.5% and 50% to 65.4% with 10% and 30% of land conserved, respectively (Fig. 2a).

Our results suggest that there is ample scope for achieving co-benefits from conserving these three features, if explicit targets for each are considered, areas of conservation value for each feature are identified through multi-criteria spatial optimization, and the range of relative preference given to each feature is comprehensively explored.

The amount of land necessary to exclusively protect global biodiversity continues to be debated[15,30,31](https://www.zotero.org/google-docs/?1NODXu). When splitting conservation targets across each biome, and in the absence of any socio-economic constraints, costs and ignoring other NCP than water and carbon, improving the conservation status for all vertebrate and plant species that we considered would require at least ~70% of global land area to be managed for conservation (Fig. 3a). This is robust to the number of species included in the analyses, provided that they are a representative subset (see Methods).

Optimally placing areas managed for conservation on 30% of the world's land area is already sufficient to conserve 81.3% of all species considered in this analysis (disregarding the additional contribution of existing protected areas and ignoring socio-economic constraints and costs and other NCP). Across the remaining species, the average target shortfall (see Methods) was 4.4%. Currently protected areas (PAs) are potentially sufficient to achieve conservation targets for 11.6% of the species analysed (Fig. 3b, Extended Data Fig. 4). However, multi-criteria spatial planning aided with explicit targets and optimization algorithms, could build on the highly inefficient set of existing PAs to reach a global 30% coverage, and achieve conservation targets for an additional 71.6% while leaving the average shortfall for remaining species to 7.2% (Fig. 3b). Therefore, there is an efficiency gap of ~10% between re-designing global conservation efforts and optimally building on existing efforts. While we do not recommend de-designations owing to other factors behind protected area establishment not considered in this analysis, the critical state of the world biodiversity suggest that ad-hoc conservation efforts are no longer an option, and target-based conservation planning, using methods like ours, should be applied at all levels if we are to reverse global biodiversity trends.

When jointly optimizing for biodiversity, carbon and water (Fig. 3a), we found that selecting the top-ranked 30% and 50% of terrestrial land areas, which are popular proposals for area-based conservation targets[7](https://www.zotero.org/google-docs/?4ssksQ), would conserve 60.7% and 85.3% of the estimated total carbon stock and 66% and 89.8% of water quality regulation, in addition to achieving conservation targets for 57.9% and 79% of all species considered, with a remaining average shortfall of 14.1% and 6.9% (Fig. 3b).

When optimizing conservation efforts for biodiversity only, we found that the groups that benefited the most (i.e. had the most rapid target accumulation curves) were amphibian and plant species (Fig. 3c,d) and threatened species (Fig. 3e,f). For plant species this is consistent with previous work on the spatial aggregation of centres of plant diversity and endemicity[32](https://www.zotero.org/google-docs/?KRzQKj). Threatened species tend to have smaller range sizes and smaller absolute area targets than other groups and are inherently prioritized with budgets ≤ 30% of land area.

When assigning global-level, rather than biome-level targets for each species, we found that current PAs conserve 16.2% of all species. However, an optimally placed 30% of land area achieved a similar level of biodiversity performance to the biome-level analysis: conserving 76.6% of all species with an average target shortfall across the remainder of species of 5.3% (Extended Data Fig. 9). Differences in accumulation curves among taxonomic groups were generally larger if species ranges were not split by biome, especially so for threatened species, indicating that fragmented parts of their range likely occur across multiple biomes (Extended Data Fig. 9).

Our analysis included, for the first time in a global prioritisation analysis, a representative subset of plant range data totalling ~41% of described vascular plant species[32](https://www.zotero.org/google-docs/?gmQ4fZ) (Fig. 4). Incorporating data on plants resulted in spatial shifts in areas of importance for conservation compared to analysis where plants are ignored, particularly in the western United States of America, west-central and South Africa, south-west Australia, central Brazil, as well as northern Europe and central Asian steppes and mountains (Fig. 4a). Overall, we found that montane and temperate forest and shrubland biomes gained relative importance when considering plants, whereas tropical biomes, flooded grasslands and mangroves lost relative importance (Fig. 4b). The inclusion of plants however reduced the number of conservation targets achieved across vertebrate species (-11.2% at 10% area budget, average across all budgets was -4.75%, Fig. 4c).

Areas of conservation importance can vary spatially if species are given different weights, prioritising for instance the protection of threatened or more evolutionarily distinct species[20,21](https://www.zotero.org/google-docs/?H7jQB0). We tested the implication of prioritising the improvement of conservation status for vertebrate species by weighting them by current IUCN Red List threat category or evolutionary distinctiveness. We found that doing so has only small inefficiency implications compared to prioritisation without these weights, with 0.7% fewer species conservation targets achieved when prioritising threatened vertebrate species and 1.7% fewer when prioritising evolutionarily distinct vertebrate species under a 10% of land area budget. Yet, overall spatial patterns of the top-ranked 10% of land areas of conservation importance were comparable, with only minor differences, notably highlighting the importance of New Zealand and the Brazilian Amazon for conserving threatened vertebrate species, the Mediterranean Basin, north-western USA, Florida and fringes of the Amazon Basin for conserving evolutionarily distinct vertebrate species (Extended Data Fig. 8). These results highlight that threatened or more evolutionary distinct vertebrate species are well covered by prioritization across all species[33](https://www.zotero.org/google-docs/?LoMsBQ), and their full conservation can be achieved at minimal extra cost.

### Discussion

How much area and where it should be managed for conservation is one of the key questions underpinning global biodiversity convention decisions and conservation planning discussions[5,31](https://www.zotero.org/google-docs/?cOH1hy). Our analyses suggest that even ambitious objectives such as ‘Half Earth’[25](https://www.zotero.org/google-docs/?nNeS7m) or ‘30 by 30’[7](https://www.zotero.org/google-docs/?4ecw0g) are insufficient to ensure that the conservation status of species is improved (Fig. 3). However, managing the top-ranked 30% of land areas in terms of their value for biodiversity conservation, as identified here, can maintain or bring over 81.3% of the world's terrestrial species (most vertebrates and a representative sample of plant species) to a non-threatened conservation status, with further increases in area offering minor additional returns (Fig. 3). An extra 20% of the total land area, in addition to the 30% of land area selected for biodiversity, could be dedicated to carbon storage as a contribution to climate regulation[7](https://www.zotero.org/google-docs/?AtlxYW) and sustainable management of natural resources. This would improve the status of 79% of all species considered to be non-threatened, which is comparable to the high-end ambition of draft goal A of the CBD Global Biodiversity Framework, to reduce the number of species threatened with extinction by 50% by 2030 and bring that number close to zero by 2050[1](https://www.zotero.org/google-docs/?w0KP9d). This also underscores the value of accompanying strict protection with spatial planning of land and sea uses to achieve conservation objectives, as stated in Target 2 of the CBD Global Biodiversity Framework. However, our analysis shows that considerable co-benefits can already be achieved by managing an optimally placed 30% of land area, if conservation of biodiversity, carbon and water are jointly planned for with spatial optimization approaches (Fig. 2).

Similarly to other studies, our analyses are sensitive to the data and methods applied [7,14,16,17](https://www.zotero.org/google-docs/?fuQtky), but, given the expanded taxonomic coverage to plants and reptiles, and the explicit accounting of taxonomic uncertainties (Extended Data Fig. 1), we believe our work provides a more robust systematic exploration of uncertainties of global priority areas for conservation than has been achieved so far.

Our work focussed on finding priority areas of global conservation importance, thus complementing recent efforts to prioritize transformed areas for habitat restoration, which also found similar co-benefits between restoring habitats for species conservation and carbon sequestration[11](https://www.zotero.org/google-docs/?gVHkmP). The ranked priority map is intended to provide broad spatial guidance to decision makers and opportunities for establishing international conservation programs and funding for biodiversity, carbon and water regulation, but is not intended to replace detailed national or sub-national planning. Harnessing these co-benefits will require integrated land-use plans at national to sub-national level that include both conservation and restoration management actions alongside productive and extractive activities, to maximize environmental and socio-economic benefits. The specific forms of management required will be highly contextual and will depend on local anthropogenic pressures, land tenure, governance, costs and opportunities for all relevant local stakeholders. Areas of conservation importance that require strict protection and active management, e.g. where narrow-ranging and threatened species occur, might be suitable for protected area expansion[34](https://www.zotero.org/google-docs/?vRSb1y). Other effective area-based conservation measures[26](https://www.zotero.org/google-docs/?XnMiwP), such as watershed management initiatives or community-managed forests, might be more suitable in areas where the upper limits of biodiversity, carbon and water values benefits are high but threats to species conservation remain low.

Our analyses impose no constraints on feasibility or on equity among countries[35](https://www.zotero.org/google-docs/?3HhU6M), resulting in over half the territory of some countries falling in the top-ranked 10% land areas of global conservation importance for biodiversity, carbon and water quality regulation, reflecting known patterns of unevenness among countries in species richness, endemicity and NCP provision (Fig. 1). We stress that, when considering implementations of conservation management, beneficial outcomes that maximize both human livelihood benefits as well as achieving biodiversity targets are necessary if conservation is to be successful. There is furthermore a need for fair resourcing of such management actions to offset the financial burden on some, predominantly tropical, countries[35,36](https://www.zotero.org/google-docs/?VCVMKS), while strengthening national institutions and governance. Existing funding mechanisms should further explore opportunities to synergistically benefit both biodiversity and NCP, as has been shown in the case of carbon[28](https://www.zotero.org/google-docs/?E9WQkX). Future synergistic prioritization efforts should particularly focus on considering both conservation and restoration[37](https://www.zotero.org/google-docs/?2k3NhA) and consider integrated scenarios of the projected future distribution of biodiversity, carbon and water, to support countries in identifying and planning conservation actions at finer scale to maximize the achievement of national and global targets and identify resilient green development pathways.

Our work also reveals research and data gaps in determining the potential value of conserving global terrestrial biodiversity and NCP. We chose carbon and water, but there are others we did not consider[22](https://www.zotero.org/google-docs/?CE3eqp) such as food provisioning or non-material contributions, including those for Indigenous communities. Similarly, many aspects of species diversity remain under-represented - although we consider a significant portion of plant species on Earth, and we developed a framework to account for spatial bias in conservation planning resulting from incomplete taxonomic coverage - we acknowledge the need to expand available data on other groups such as freshwater, soil, and invertebrate species[38,39](https://www.zotero.org/google-docs/?QmC7vx). We also only investigated the influence of evolutionary history and threat status on vertebrate, but not plant species, for whom hotspots of evolutionary history might differ, thus requiring comprehensive extinction risk assessments and phylogenies of plants at the species level, and ignored other aspects such as species functional role and rarity[40](https://www.zotero.org/google-docs/?0BVBoK).

Despite overall similarity between areas of conservation importance for vertebrate and plant species[18,19,41](https://www.zotero.org/google-docs/?4utu4m), many hotspots of plant endemism, particularly in temperate biomes (Fig. 4b), can be overlooked if focussing on vertebrate species alone, highlighting the need to account for plant species in spatial analyses of conservation and restoration priorities (Fig. 4c).

Our analyses highlight global land areas whose conservation can maximize synergies across conventions (e.g. CBD, UNFCCC) and some SDGs, particularly goals 3, 13 and 15. As identified by our global joint optimization, proposed conservation targets, such as ‘30 by 30’ or Half Earth, could be able to conserve most species and NCP globally, if the broad areas with highest importance from our analysis are managed for conservation. Particularly, our integrated maps could support international initiatives such as the 2021-2030 Strategic Plan of the CBD and the EU Biodiversity strategy and help government and non-government actors in translating these strategies into societal negotiations, actions and policies. Meeting the SDGs requires real, transformative commitments that are yet to be enacted[1](https://www.zotero.org/google-docs/?wi0ue6), however, by maximizing synergies in efforts and resources, a pathway towards effective biodiversity conservation can be laid out for the next decade.

## Methods

### Biodiversity data

We used the best available global species range data (overview in Supplementary Table 1), including all extant terrestrial vertebrates and a representative proportion (~41%) of all accepted species in the World Checklist of Vascular Plants[42](https://www.zotero.org/google-docs/?yIcZ10). Extant mammal (5,685 species) and amphibian (6,660) species range data were obtained from the International Union for Conservation of Nature Red List database (IUCN ver. 2019-2[43](https://www.zotero.org/google-docs/?AdKXpd)), while bird (10,953) range maps were obtained from Birdlife International[44](https://www.zotero.org/google-docs/?2XcsAZ). Data on the reptile ranges were obtained from the IUCN database when available (6,830 species), otherwise from the Global Assessment of Reptile Distributions (GARD) database (3,755[45](https://www.zotero.org/google-docs/?JQeJJw)). We obtained native plant range maps (193,954 species) from a variety of sources, including IUCN, Botanic Gardens Conservation International (BGCI) and the Botanical Information and Ecology Network (BIEN). The IUCN and BGCI data contains expert-based range maps and alpha-hulls (see Supplementary Information), while the BIEN data consists mainly of herbarium collections, ecological plots and surveys[32,46–53](https://www.zotero.org/google-docs/?kRBKud), that we used to construct conservative estimates of species ranges using species distribution models (SDMs). We used version 4.1 of BIEN, which includes data from RAINBIO[54](https://www.zotero.org/google-docs/?cTlval), TEAM[55](https://www.zotero.org/google-docs/?O5PjvH), The Royal Botanic Garden and Domain Trust Sydney, Australia, and NeoTropTree[56](https://www.zotero.org/google-docs/?sQUdOK). Additional plant plot data from a number of networks and datasets have been included in BIEN and a full listing of the herbaria data used can be found in the extended acknowledgements and online (<http://bien.nceas.ucsb.edu/bien/data-contributors/all/>). In cases where multiple data sources were available for the same plant species, we preferentially used expert-based range maps to characterize a species' spatial distribution. A full description of the preparation and processing of the plant data can be found in the Supplementary Information.

All vertebrate range maps were pre-processed following common practice[57](https://www.zotero.org/google-docs/?Gfj81y) by selecting only those parts of a species’ range where 1) it is extant or possibly extinct, 2) where it is native or reintroduced and 3) where the species is seasonally resident, breeding, non-breeding, migratory or where the seasonal occurrence is uncertain. We acknowledge that these ranges can contain some areas where the species is possibly extinct.

#### Suitable habitat refinement

Where data on species habitat and elevational preferences were available, we refined each species’ range to obtain the area of habitat (AOH) in which the species could potentially persist[58,59](https://www.zotero.org/google-docs/?aGAXFB). Data on species habitat preferences and suitable elevational range were obtained from the IUCN Red List database[43](https://www.zotero.org/google-docs/?Y3Jkc8) and, for an additional 1,452 reptile species in the GARD database, habitat preferences were compiled from an extensive literature search. For seasonally migrating birds and mammal species we ensured that separate habitat refinements were conducted for permanent and seasonally occupied areas of their range, that is, the breeding and non-breeding range. Whenever habitat or elevation preferences were not available for a given species, we used the full range, excluding only areas considered to be artificial habitat type classes, such as arable or pasture land, plantations and built-up areas. We note that this could exclude areas suitable for some generalist species. We do acknowledge that taxonomic biases can exist in the information on habitat preferences for some species which can be a limitation to our approach. For the AOH refinement we used a newly-developed global map (see Supplementary Information) that follows the IUCN habitat classification system, thereby avoiding crosswalks between habitat preferences and land cover maps[60](https://www.zotero.org/google-docs/?zzL1JK). This data product integrates the best available land cover and climate data, while also using newly developed land-use data such as data on global forest management[61](https://www.zotero.org/google-docs/?w0TKZL). Finally, per species range, we calculated the proportional amount (> 0-100%) of suitable habitat in each grid cell to include in the prioritisation analysis. Development of the habitat type map and all AOH refinement was performed in Google Earth Engine[62](https://www.zotero.org/google-docs/?cKCIMB).

#### Global representativeness

There is considerable bias and variability in the completeness of biodiversity records globally, particularly for plant species[32,63](https://www.zotero.org/google-docs/?g8OZG5).To estimate the amount of geographic bias in completeness of range data among plants, we first estimated the proportion of species for which we had range data relative to the number of species known to occur in the World Checklist of Vascular Plants[42](https://www.zotero.org/google-docs/?CXIZHY). This checklist provides for each accepted species name its native regions from the World Geographical Scheme for Recording Plant Distributions (WGSRPD,[65](https://www.zotero.org/google-docs/?R0a3YE)). We used geographic delineations for 50 WGSRPD level 2 regions[65](https://www.zotero.org/google-docs/?YvEHqi), excluding Antarctica and mid-Atlantic islands (Saint Helena and Ascension) for which we had no plant records. For 48 of the 50 WGSRPD regions we had range data for over >10% of all listed native plants (the exception being islands in the South-West and South-Central Pacific), relative to the maximum number of species described in a region. This proportion of species varied from 11% in islands of the North Pacific up to 100% in the Russian far east (mean 60.1% ∓ 24.5 SD). For 44 of these 50 regions we had range data for >40% of described plants in those regions.

Having identified 10% as a minimum common denominator of completeness across most regions, we then used an iterative heuristic algorithm to identify ‘representative’ sets of plant species. This was done by (1) identifying the number of species that approximate a 10% threshold per WGSRPD level 2 region, (2) calculating random samples that approximated these 10% of species from each WGSRPD level 2 region, and (3) accounting for the fact that some species occur across multiple regions, resampling species at random if necessary. To test if this approach yielded sets representative of biogeographic patterns of the full dataset, we compared the spatial patterns of scaled vertebrate species richness to the 10% sets of these species for each WGSRPD level 2 regions, random subsets of 10% of all vertebrates and for all vertebrates combined. We performed the test on vertebrates because we had range maps for ~95% of terrestrial vertebrates described, therefore allowing us to assess if our subsampling to representative sets can replicate “true” patterns in species richness obtained with a complete sample of species in a taxonomic group. Compared to a full vertebrate dataset, spatial patterns of scaled species richness were approximately identical across those sets (WGSRPD: Kendall 𝛕 = 0.954; Random: Kendall 𝛕 = 0.957), suggesting that this sampling approach can account for incomplete spatial coverage (Extended Data Fig. 5a).

We also checked if the frequency distribution of range sizes within our subsets matched the range size distribution of the entire set, using mammals as a test group, and found very modest differences between the full set and multiple subsets (Extended Data Fig. 5b). Having confirmed that this procedure recreates correct biogeographical patterns of conservation priorities and does not alter the range-size distribution (Extended Data Fig. 5), we proceeded to create 10 subsets of ~10% of plant species known to occur in each WGSRPD level 2 region and ten non-overlapping subsets of 10% of vertebrate species for all of our analyses. We found little difference among representation curves regardless of whether multiple representative subsets or all mammal species were included in the SCP, although there was greater efficiency in the latter (Extended Data Fig. 6).

### Carbon data

We used spatial estimates of the density of above-ground and below-ground biomass carbon and vulnerable soil carbon[9](https://www.zotero.org/google-docs/?UxR2AI). Estimates for above-ground carbon (AGC) were created by selecting the best available carbon maps[66,67](https://www.zotero.org/google-docs/?tatow9) for different types of vegetation classes, identified spatially using the Copernicus Land Cover map in 2015[68](https://www.zotero.org/google-docs/?R2een5). We used Santoro *et al.* as a baseline for a global carbon biomass map[67](https://www.zotero.org/google-docs/?pYHQIA), as it is the most recent global AGC map (2017), its spatial resolution aligns with that of the Copernicus Land Cover map (100m) and it is accompanied by an error layer describing the uncertainty of each grid cell’s AGC estimate[67](https://www.zotero.org/google-docs/?0fIsJT). In addition, we used more detailed estimates of above-ground biomass for the following land cover classes: African “open forest” and “shrubland”[69](https://www.zotero.org/google-docs/?gkcyk4), global “herbaceous vegetation” and “moss and lichen”[70](https://www.zotero.org/google-docs/?jMi19F) and “cropland” and “bare/sparse vegetation” land-cover classes[71](https://www.zotero.org/google-docs/?XWSHza). To map below-ground carbon, we applied corrected root-to-shoot ratios[72](https://www.zotero.org/google-docs/?DB5dgh) obtained from the Intergovernmental Panel on Climate Change (IPCC) technical guidance documents[73](https://www.zotero.org/google-docs/?zmpTA6). A newly developed forest management layer[61](https://www.zotero.org/google-docs/?q9i8eu) was used to update biomass density, by averaging estimates from 2010[66](https://www.zotero.org/google-docs/?wvywvS) and 2017[67](https://www.zotero.org/google-docs/?SQnzaw) in the most dynamic tree-covered classes (e.g. short rotation plantations, agroforestry).

The map of vulnerable soil organic carbon was created following IPCC Guidelines for National Greenhouse Inventories to estimate emissions and removals associated with changes in land use[73](https://www.zotero.org/google-docs/?2G6pHe). Vulnerable soil organic carbon was defined as those carbon stocks that could potentially be lost during the coming 30 years as a result of land use. We used recently published data on baseline soil organic carbon stocks[74](https://www.zotero.org/google-docs/?7LCfcf), and vulnerable stocks were estimated separately for mineral and organic soils. Organic soils were defined as those soils with ≥ 5% probability of being Histosols according to USDA soil order taxonomy[75](https://www.zotero.org/google-docs/?2d1l2l). All other soils were considered to be mineral soils. A 30cm depth was used to estimate vulnerable carbon stocks on mineral soils, while 200cm depth was used for organic soils. IPCC change factors (mineral soils) and emission factors (for organic soils) were used to estimate vulnerable soil organic carbon stocks according to IPCC land cover categories and climate zones. To be consistent with biomass carbon estimations, we created a crosswalk between the Copernicus global land cover map[61](https://www.zotero.org/google-docs/?vtPtan) and IPCC land cover classes. The newly developed forest management layer[61](https://www.zotero.org/google-docs/?G2BGmz) was used to refine vulnerable carbon stock estimates for mineral soils, whilst managed forest with organic soils were excluded from this assessment given that due to drainage, these areas would often be more suitable for restoration than for conservation action. Finally, all global carbon estimates were reprojected and aggregated (arithmetic mean) to 10 km to match the biodiversity data in scale.

### Water data

For capturing water quality regulation, we used estimates of potential clean water provision calculated by WaterWorld[76](https://www.zotero.org/google-docs/?ZqhCjs) and Co$ting Nature[77](https://www.zotero.org/google-docs/?LSxW4F). The WaterWorld model uses a long-term climatology (1970-2015), long-term average Leaf Area Index (LAI) over the same period and the Copernicus land cover map[68](https://www.zotero.org/google-docs/?IFQm7q) as baseline to be consistent with other assets in this analysis. We calculated for each grid cell the volume of water available, as the accumulated water balance from upstream based on rainfall, fog and snowmelt sources minus actual evapotranspiration. Second, clean water was assessed using the Human Footprint on Water Quality (HFWQ) index, which is a measure of the extent to which water runoff is from contaminating human land uses and diluted by passing through Natural ecosystems. It estimates pollution from both point (urban, roads, mining, oil and gas) and nonpoint (unprotected cropland, unprotected pasture) sources. The HFWQ index is calculated by aggregating the downstream runoff from polluting and non-polluting land uses and expressing the former runoff as a proportion of the total runoff. WaterWorld has not been validated with discharge at global scale but validations for various regions around the world showed good model performance for annual runoff based on the same climatology[78,79](https://www.zotero.org/google-docs/?29fpX1). The index is calculated by assigning an associated pollution (or dilution) intensity (as a proportion of grid cell) to each land-use class (default values from[77](https://www.zotero.org/google-docs/?QKDDFp)). The potential water quality regulation service is calculated for each cell as the inverse of the HFWQ (i.e. 100 - HFWQ), in other words clean water provided by the grid cell. For the analysis we ranked each grid per level 3 river basin [80](https://www.zotero.org/google-docs/?LguJtT) to determine their relative importance in delivering clean water within the basin.

### Prioritisation analysis

We determined global areas of conservation importance, quantified as maximum value in the present state, to be managed for conserving biodiversity, carbon and water by using a spatial conservation prioritisation approach (SCP[81](https://www.zotero.org/google-docs/?Fgledm)). We divided the world into 10 km (see Supplementary information for justification of scale) resolution ‘planning units’ (PUs, grid cells on the terrestrial land-surface excluding Antarctica), in which ‘features’ are distributed (all species, plus carbon stocks and water quality regulation), each of which had specific conservation targets allocated to it (next section). For each 10 km PU we calculated the amount of suitable habitat for each species whose range intersected that PU. We also calculated the total carbon (tC) and normalized ranks (0-1) of cubic Megametres of water (Mm³). All PUs had a cost c equivalent to the amount of land within them (), which we calculated from Copernicus land-cover data[68](https://www.zotero.org/google-docs/?IZgVGx). We did not use socio-economic conservation cost estimates as they are only relevant when prioritizing specific conservation actions that incur those costs, rather than identifying areas of conservation importance more broadly. Moreover, available global opportunity and management cost data may inadequately capture the spatial heterogeneity in these costs [82,83](https://www.zotero.org/google-docs/?3Ov16O), with lower costs seen in areas more suitable for less profitable activities, such as subsistence or small-holder farming[82](https://www.zotero.org/google-docs/?Ww1dAT) and in areas with lower governance scores, which in turn may reduce the feasibility and effectiveness of conservation interventions[84,85](https://www.zotero.org/google-docs/?AK0SBW). We do highlight however that conservation planning with the aim of implementing concrete actions needs to consider return on investment and appropriate counterfactual. As global budget (B) we set different percentages of the terrestrial land surface area starting at 10%, then increasing by 10% increments until all targets were met.

#### Target setting

One of the most impactful decisions in SCP frameworks is the definition of feature targets. In the past, many studies set targets for species representation according to rules[34,86,87](https://www.zotero.org/google-docs/?SN6UtZ) or area-based policies (e.g. 30% of a species range), which are arbitrary rather than being based on individual species conservation needs. We set targets relative to the minimum amount of suitable habitat necessary to improve a species conservation status to Least Concern as inspired by IUCN criteria[15](https://www.zotero.org/google-docs/?S6j4oH). We recognise that this only takes the contemporary range (area of suitable habitat) into account, ignoring other factors of extinction risk, such as population size and trends, but the purpose is to provide ecologically credible area-based conservation targets, rather than estimating extinction risk. For all species, these targets were defined as

, (equation 1)

#### where, measured in units of km², is the species range to conserve for a given species and the total area of suitable habitat for the species. The parameters are inspired by the IUCN Red List criteria: Criterion B2 specifies that the area of occupancy should not fall below 2000 km² (plus a 10% buffer) for limiting the ‘Least Concern’ category, Criterion A sets that a species population is not to decline by more than 30% in 10 years, which parsimoniously equates to 80% of its range [15](https://www.zotero.org/google-docs/?NHwLFm), and the upper limit being defined 1 million owing to the logistic difficulties of managing extremely large areas for conservation (but see [15](https://www.zotero.org/google-docs/?PIeGm1))⁠. Whenever was smaller than 2200 km², the target was set to the whole AOH. Targets for carbon and water were set to 100% of their terrestrial coverage, but weighted in relation to biodiversity (see below).

#### Problem formulation

Areas of importance for the conservation of biodiversity, carbon and water were determined by solving a series of global optimization problems. For each feature included in the analysis we aimed to minimize the proportional shortfall noted as yj ([88](https://www.zotero.org/google-docs/?y6vomB), equation 1 & 2), that is, the relative difference between the part of the distribution of a feature which is under conservation management and the conservation target [of that feature (equation 2). This minimization was](https://www.zotero.org/google-docs/?NfCoas) subject to not exceeding a defined total area under conservation management (area budget ) set as percentages of the terrestrial land surface of the world [k = 10, 20, ..., 100%] with each PU having a cost ∈ [0,1] (equation 3). The amount of each feature in planning unit *i* is denoted as *rij* (suitable habitat in [km2], total tons of carbon [] or normalized cubic Megametres of water []). We define *xi* , as a proportional decision variable [0-1] indicating the proportion of the PU that is selected to be managed for conservation (equation 4).

Furthermore weights wj were assigned to each feature *j* that acted as multipliers of the proportional shortfall and regulated the relative emphasis given to meeting conservation targets for species, carbon and water under area constraints. We tested different weights for carbon and water, relative to biodiversity and different weights among species based on their global threat status and/or evolutionary distinctiveness (see below). The problem is formulated as follows:

*Minimize*  (equation 2)

*Subject to*

(equation 3)

(equation 4)

(equation 5)

(equation 6)

Additional constraints ensure that the overshooting of targets is not valued more than reaching the target, thereby focussing the attention of the spatial optimization towards under-represented features (equation 3), ensure that the sum of planning unit costs are smaller or equal than the global budget (equation 4) and limit the decision variable *xi* to a proportional amount (equation 5). The problem is then solved for each budget incrementally, while ensuring that current decisions build upon previous solutions (equation 6), thus effectively building nested sets of priorities with increasing budget . We repeated this process for each problem variant (defined by the set of weights in equation 7, next section) and a representative set of features (defining the species targeted for conservation in equations 1 and 2).

#### Analysis variants

To identify current gaps in conservation of species, carbon and water by protected areas, we constrained the optimization by locking in the proportion of currently protected areas (fraction of land area, Supplementary Information). To explore where conservation management would be best placed to complement the existing network of protected areas, we then jointly optimized globally for biodiversity, carbon and water by minimizing the proportional shortfall[88](https://www.zotero.org/google-docs/?FsMoci) in reaching the targets for each given budget (k = [10, 20, ..., 100%] of the terrestrial land surface). We furthermore considered a number of optimization variants in which we modified either the targets or weights assigned to each feature (biodiversity, carbon and/or water).

We tested the effect of different weights for carbon storage and water quality regulation relative to biodiversity in all analysis variants that included carbon and water. To do so we assigned sequences of weights for carbon and water from ‘none’ up to ‘equal’ preference which is obtained when their shortfall is weighted by,

(equation 7)

Where *S* is the total number of biodiversity features in the analysis (each with weight 1). The addition of 1 is needed as there are S + 2 number of features in the problem formulation, S species + carbon or water. This weighting ensures that NCPs are treated as equivalent to all species combined and that feature targets are treated ‘equally’, e.g. a decrease in value of 10% is proportional to an average 10% decrease across all species targets, in the optimization. We varied w from 1 to S + 1 with intermediate values of 1 or of max w. We visualized all variants with increasing budget and by the shortfall in carbon, water and improvement in species conservation status (Fig. 2). Because of the high computational cost of calculating prioritizations, where is the number of weights and the number of budgets, for each of the 10 representative sets, we assessed differing weights at 50 km rather than 10 km resolution. When compared to a 10 km resolution, both spatial patterns and accumulation curves were highly similar (See Supplementary Information and Extended Data Fig. 7) and so we do not expect the results to differ between these resolutions. We did not explore differential weightings of species relative to carbon and water (Figure 1-2), since all species received equal preference in the prioritization.

For biodiversity only, we also considered variants accounting for species intraspecific variation, threat status and evolutionary distinctiveness (Supplementary Information). To capture intraspecific variation, we considered each part of a species range occurring in geographically separate biomes as a separate feature with its own target [30](https://www.zotero.org/google-docs/?3J9Zfo), e.g. the Tiger (*Panthera tigris*) was split into five separate features, one for each of the five biomes overlapping the tiger range (Supplementary Information). However, we only considered this split for features in which at least 2,200 km2 of AOH (the minimum absolute target area, see target setting above) was contained within a different biome to that biome with the majority of the species range. Compared to a version without these splits and when optimizing for biodiversity, carbon and water, overall differences were relatively minor (Extended Data Fig. 9), but potentially locally important. We also collated data on species current threat status from both IUCN and BGCI and, for vertebrates, data on their evolutionary distinctiveness using phylogenetic distance to a closest relative (See supplementary Information), and then calculated weights for each species following [13](https://www.zotero.org/google-docs/?izIL0S). Using vertebrates only and identical species, we created variants where species were either unweighted, weighted by threat status or by evolutionary distinctiveness. We then optimized all variants by minimizing the target-weighted shortfalls across all biodiversity features, subject to budget constraints and compared the identified areas of conservation importance at a 10% land area budget (Extended Data Fig. 8).

#### Optimization algorithm and ranking

All problem variants were solved using a linear programming (LP) approach which has been shown to outcompete global search algorithms and heuristics in both speed and performance[89,90](https://www.zotero.org/google-docs/?VgTWYd). For each problem variant and representative set of species, we therefore obtained 10 nested optimal solutions, each resulting from solving to optimality the problem defined in equations 2 to 6 with a specific set of weights (problem variant), representative set of species, and area-budget. All solutions of the same problem variant and set of species are by design nested as area budgets increased, because we locked the solution at a budget level (e.g. 30% of land area) into the problem formulation of the next budget level (e.g. 40% of land area)*.* For all non-spatial analyses, e.g. targets accumulation curves, we report the results across all representative sets. When representing spatial patterns of priorities, to take advantage of the full plant dataset, and to analyse only one global rank for each problem variant as opposed to 10, we combined the 10 nested sets for any given problem variant, (one for each of the 10 representative sets) into one single rank. This was calculated as the arithmetic mean () of the ten representative sets and ten budgets (n = 100), each with the proportion p of the grid cells that are part of a solution, which are then ranked and binned. Constructing a grand total average across different problem formulations does not formally constitute an optimal solution, because there are 100 different objective functions (one per budget and representative set) and these cannot be jointly optimized and synthesized further than 10 optimal nested sets, as we did, without resorting to heuristic solutions. Our heuristic combination of optimal nested sets has the following characteristics: (a) it closely resembles spatial patterns and accumulation curves of individual nest sets, (b) allows us to make full use of the plant database while accounting for spatial biases in data availability, (c) allows for an estimation of the uncertainty in priority ranks due to the choice of alternative representative sets (Extended Data Fig. 1).

All maps, unless otherwise noted, were the result of aggregating the nested sets of priorities for problem formulations with both carbon and water shortfall weighted as w = S + 1, where S is the set of biodiversity features in the analysis. This equal weighting was chosen as it was the one which yielded the lowest combined shortfall across features, and the most similar shortfall across all features (Fig. 2 and Extended Data Fig. 10).

We calculated and reported on the number of targets achieved and the mean shortfall from targets first by calculating the shortfall within each representative set, feature and area budget and then as average across sets. The second step is necessary as some species are present in more than one representative set. We investigated how these performance metrics varied across taxonomic groups, threatened species and problem variants. Furthermore, ranks were extracted using country boundary shapefile data from Natural Earth and the average (arithmetic and area-weighted mean) calculated per country (Supplementary Table 2).

All data preparation and analysis was conducted in R[91](https://www.zotero.org/google-docs/?0kYgfp) mainly relying on the ‘prioritizr’ package[92](https://www.zotero.org/google-docs/?S9d3iX) with the Gurobi solver enabled (ver 8.11,[93](https://www.zotero.org/google-docs/?qTdq66)).

## Data availability All maps will be made available through <https://unbiodiversitylab.org/> and on a data repository (<https://dx.doi.org/10.5281/zenodo.5006332>). The raw input data can be requested from the respective data providers, namely IUCN, GARD, Birdlife International, Royal Botanic Gardens, Kew and predicted plant range data will be made available as part of the BIEN initiative[46](https://www.zotero.org/google-docs/?RengKu). The IUCN habitat type map used to construct the AOH is made available in the Supplementary Information. The carbon layers will be published openly in a separate data descriptor manuscript and are available upon request. Any additional raw data not listed can be made available from the authors upon reasonable request.

## Code availability Code to run comparable optimization analyses has been made available at https://github.com/Martin-Jung/NatureMapCode.

**Acknowledgements** This work was conducted by the Nature Map consortium. We thank Richard Corlett & Tom Brooks who provided feedback on an earlier version of the manuscript. We furthermore thank Tom Hengl (OpenLandMap) for his advice on the Soil Organic Carbon analysis. This study has benefited from a number of data providers and networks. We explicitly acknowledge all data providers in a separate Extended Acknowledgements owing to their length (Supplementary Information). The Nature Map project acknowledges funding from Norway's International Climate and Forest Initiative (NICFI). Collection of the plant data used in this analysis has benefited from funding in form of a GEF grant 5810-SPARC 'Spatial Planning for Area Conservation in Response to Climate Change'. CM acknowledges funding from NSF (National Science Foundation) grant DBI‐1913673. RVG was supported by Australian Research Council DECRA Fellowship (DE170100208). Furthermore, EAN and XF were funded by the Bridging Biodiversity and Conservation Science Program of the University of Arizona. NMH was supported by the European Union’s Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement no. 746334. MDM acknowledges support from the MIUR Rita Levi Montalcini programme. JCS considers this work a contribution to his VILLUM Investigator project “Biodiversity Dynamics in a Changing World” funded by VILLUM FONDEN (grant 16549) and his Independent Research Fund Denmark | Natural Sciences project TREECHANGE (grant 6108-00078B).

**Author contributions** M.J and P.V designed the study, M.J led the analysis and interpretation of the data and has drafted the manuscript; P.V conceived the study, contributed to the analysis and drafting of the manuscript; J.O.H, B.L.B, C.M contributed to creating software used in the work; A.A, C.R, S.G.-R, M.Lewis, D.S, A.vS, M.M, J.Mark, S.P, I.O, C.M, B.J.E, X.F, P.R.R, B.L.B, B.M, R.V.G contributed to acquisition, analysis and interpretation of data; B.B.N.S, J.O.H, M.D.M, J.M, W.J, D.S.R, J.McGowan, M.O, M.R, X.D.L contributed to interpretation of the data; G.O, U.R, S.M, M.Lewis, R.Gallagher, M.Lesiv, O.T contributed to acquisition and interpretation of data; X.D.L, V.K, L.M, N.B, G.W, S.F, J.D.S, G.S.-T and M.O contributed to conception of the study; V.M.A, S.P.A, S.C.A, J.R.B, R.T.C, L.H, R.Govaerts, P.A.M, J.K.M, D.M.N, N.M.-H, E.A.N, D.S.P, P.R.R, J.-C.S, C.V, J.J.W provided data and contributed to interpretation of the data. All authors contributed to revising the manuscript.

**Supplementary Information** is available for this paper.

Correspondence and requests for materials should be addressed to MJ and PV.

**Competing interests**: The authors declare no competing interests

Reprints and permissions information is available at [www.nature.com/reprints](http://www.nature.com/reprints)

## References

[1. Díaz, S. *et al.* Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* **366**, eaax3100 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[2. Leclère, D. *et al.* Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature* **585**, 551–556 (2020).](https://www.zotero.org/google-docs/?d9esU1)

[3. Butchart, S. H. M., Miloslavich, P., Reyers, B. & Subramanian, S. M. Chapter 3. Assessing progress towards meeting major international objectives related to nature and nature’s contributions to people. in *IPBES Global Assessment on Biodiversity and Ecosystem Services* 1–355 (IPBES, 2019).](https://www.zotero.org/google-docs/?d9esU1)

[4. Griscom, B. W. *et al.* Natural climate solutions. *Proc. Natl. Acad. Sci.* **114**, 11645–11650 (2017).](https://www.zotero.org/google-docs/?d9esU1)

[5. CBD. Zero draft of the Post-2020 Global Biodiversity Framework. (2020).](https://www.zotero.org/google-docs/?d9esU1)

[6. Anderson, C. M. *et al.* Natural climate solutions are not enough. *Science* **363**, 933–934 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[7. Dinerstein, E. *et al.* A Global Deal For Nature: Guiding principles, milestones, and targets. *Sci. Adv.* **5**, eaaw2869 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[8. Visconti, P. *et al.* Protected area targets post-2020. *Science* **364**, eaav6886 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[9. Soto-Navarro, C. *et al.* Mapping co-benefits for carbon storage and biodiversity to inform conservation policy and action. *Philos. Trans. R. Soc. B Biol. Sci.* **375**, 20190128 (2020).](https://www.zotero.org/google-docs/?d9esU1)

[10. Greve, M., Reyers, B., Mette Lykke, A. & Svenning, J.-C. Spatial optimization of carbon-stocking projects across Africa integrating stocking potential with co-benefits and feasibility. *Nat. Commun.* **4**, 2975 (2013).](https://www.zotero.org/google-docs/?d9esU1)

[11. Strassburg, B. B. N. *et al.* Global priority areas for ecosystem restoration. *Nature* **586**, 724–729 (2020).](https://www.zotero.org/google-docs/?d9esU1)

[12. Brooks, T. M. *et al.* Global Biodiversity Conservation Priorities. *Science* **313**, 58–61 (2006).](https://www.zotero.org/google-docs/?d9esU1)

[13. Pouzols, F. M. *et al.* Global protected area expansion is compromised by projected land-use and parochialism. *Nature* **516**, 383–386 (2014).](https://www.zotero.org/google-docs/?d9esU1)

[14. Allan, J. R. *et al.* Conservation attention necessary across at least 44% of Earth’s terrestrial area to safeguard biodiversity. *bioRxiv* (2019) doi:10.1101/839977.](https://www.zotero.org/google-docs/?d9esU1)

[15. Fastre, S., Mogg, C., Jung, M. & Visconti, P. Targeted expansion of Protected Areas to maximise the persistence of terrestrial mammals. *bioRxiv* **3124**, 1–19 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[16. Rinnan, D. S. & Jetz, W. Terrestrial conservation opportunities and inequities revealed by global multi-scale prioritization. *bioRxiv* (2020) doi:10.1101/2020.02.05.936047.](https://www.zotero.org/google-docs/?d9esU1)

[17. Hannah, L. *et al.* 30% land conservation and climate action reduces tropical extinction risk by more than 50%. *Ecography* (2020) doi:10.1111/ecog.05166.](https://www.zotero.org/google-docs/?d9esU1)

[18. Kier, G. *et al.* A global assessment of endemism and species richness across island and mainland regions. *Proc. Natl. Acad. Sci.* **106**, 9322–9327 (2009).](https://www.zotero.org/google-docs/?d9esU1)

[19. McInnes, L. *et al.* Do Global Diversity Patterns of Vertebrates Reflect Those of Monocots? *PLoS ONE* **8**, e56979 (2013).](https://www.zotero.org/google-docs/?d9esU1)

[20. Pollock, L. J., Thuiller, W. & Jetz, W. Large conservation gains possible for global biodiversity facets. *Nature* **546**, 141–144 (2017).](https://www.zotero.org/google-docs/?d9esU1)

[21. Daru, B. H. *et al.* Spatial overlaps between the global protected areas network and terrestrial hotspots of evolutionary diversity. *Glob. Ecol. Biogeogr.* **28**, 757–766 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[22. Chaplin-Kramer, R. *et al.* Global modeling of nature’s contributions to people. *Science* **366**, 255–258 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[23. Newbold, T. *et al.* Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science* **353**, 288–291 (2016).](https://www.zotero.org/google-docs/?d9esU1)

[24. Locke, H. *et al.* Three Global Conditions for Biodiversity Conservation and Sustainable Use: an implementation framework. *Natl. Sci. Rev.* (2019) doi:10.1093/nsr/nwz136.](https://www.zotero.org/google-docs/?d9esU1)

[25. Wilson, E. O. *Half-earth: our planet’s fight for life*. (WW Norton & Company, 2016).](https://www.zotero.org/google-docs/?d9esU1)

[26. Laffoley, D. *et al.* An introduction to ‘other effective area-based conservation measures’ under Aichi Target 11 of the Convention on Biological Diversity: Origin, interpretation and emerging ocean issues. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **27**, 130–137 (2017).](https://www.zotero.org/google-docs/?d9esU1)

[27. Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B. & Kent, J. Biodiversity hotspots for conservation priorities. *Nature* **403**, 853–858 (2000).](https://www.zotero.org/google-docs/?d9esU1)

[28. Venter, O. *et al.* Harnessing Carbon Payments to Protect Biodiversity. *Science* **326**, 1368–1368 (2009).](https://www.zotero.org/google-docs/?d9esU1)

[29. Strassburg, B. B. N. *et al.* Global congruence of carbon storage and biodiversity in terrestrial ecosystems. *Conserv. Lett.* **3**, 98–105 (2010).](https://www.zotero.org/google-docs/?d9esU1)

[30. Dinerstein, E. *et al.* An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. *BioScience* **67**, 534–545 (2017).](https://www.zotero.org/google-docs/?d9esU1)

[31. Woodley, S. *et al.* A Review of Evidence for Area-based Conservation Targets for the Post-2020 Global Biodiversity Framework. *Parks* **25**, 31–46 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[32. Enquist, B. J. *et al.* The commonness of rarity: Global and future distribution of rarity across land plants. *Sci. Adv.* **5**, eaaz0414 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[33. Rapacciuolo, G. *et al.* Species diversity as a surrogate for conservation of phylogenetic and functional diversity in terrestrial vertebrates across the Americas. *Nat. Ecol. Evol.* **3**, 53–61 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[34. Venter, O. *et al.* Targeting Global Protected Area Expansion for Imperiled Biodiversity. *PLoS Biol.* **12**, e1001891 (2014).](https://www.zotero.org/google-docs/?d9esU1)

[35. Chauvenet, A. L. M., Kuempel, C. D., McGowan, J., Beger, M. & Possingham, H. P. Methods for calculating Protection Equality for conservation planning. *PLoS ONE* (2017) doi:10.1371/journal.pone.0171591.](https://www.zotero.org/google-docs/?d9esU1)

[36. Waldron, A. *et al.* Reductions in global biodiversity loss predicted from conservation spending. *Nature* **551**, 364–367 (2017).](https://www.zotero.org/google-docs/?d9esU1)

[37. Possingham, H. P., Bode, M. & Klein, C. J. Optimal Conservation Outcomes Require Both Restoration and Protection. *PLOS Biol.* **13**, e1002052 (2015).](https://www.zotero.org/google-docs/?d9esU1)

[38. Cameron, E. K. *et al.* Global gaps in soil biodiversity data. *Nat. Ecol. Evol.*, 6–7 (2018).](https://www.zotero.org/google-docs/?d9esU1)

[39. Jetz, W. *et al.* Essential biodiversity variables for mapping and monitoring species populations. *Nat. Ecol. Evol.* **3**, 539–551 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[40. Violle, C. *et al.* Functional Rarity: The Ecology of Outliers. *Trends Ecol. Evol.* **32**, 356–367 (2017).](https://www.zotero.org/google-docs/?d9esU1)

[41. Di Marco, M., Ferrier, S., Harwood, T. D., Hoskins, A. J. & Watson, J. E. M. Wilderness areas halve the extinction risk of terrestrial biodiversity. *Nature* **573**, 582–585 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[42. WCVP. World Checklist of Vascular Plants. *World Checklist of Vascular Plants* http://wcvp.science.kew.org/ (2020).](https://www.zotero.org/google-docs/?d9esU1)

[43. IUCN. IUCN 2019. The IUCN Red List of Threatened Species. Version 2019.2. *IUCN Redlist* www.iucnredlist.org (2019).](https://www.zotero.org/google-docs/?d9esU1)

[44. Birdlife International. *Digital boundaries of Key Biodiversity Areas from the World Database of Key Biodiversity Areas*. (2019).](https://www.zotero.org/google-docs/?d9esU1)

[45. Roll, U. *et al.* The global distribution of tetrapods reveals a need for targeted reptile conservation. *Nat. Ecol. Evol.* **1**, 1677–1682 (2017).](https://www.zotero.org/google-docs/?d9esU1)

[46. Enquist, B., Condit, R., Peet, R., Schildhauer, M. & Thiers, B. Cyberinfrastructure for an integrated botanical information network to investigate the ecological impacts of global climate change on plant biodiversity. *PeerJ Prepr.* (2016) doi:10.7287/peerj.preprints.2615.](https://www.zotero.org/google-docs/?d9esU1)

[47. Maitner, B. S. *et al.* The bien r package: A tool to access the Botanical Information and Ecology Network (BIEN) database. *Methods Ecol. Evol.* **9**, 373–379 (2018).](https://www.zotero.org/google-docs/?d9esU1)

[48. Anderson-Teixeira, K. J. *et al.* CTFS-ForestGEO: a worldwide network monitoring forests in an era of global change. *Glob. Change Biol.* **21**, 528–549 (2015).](https://www.zotero.org/google-docs/?d9esU1)

[49. Forest Inventory and Analysis National Program. www.fia.fs.fed.us/ (2013).](https://www.zotero.org/google-docs/?d9esU1)

[50. Peet, R., Lee, M., Jennings, M. & Faber-Langendoen, D. VegBank – a permanent, open-access archive for vegetation-plot data. *Biodivers. Ecol.* **4**, 233–241 (2012).](https://www.zotero.org/google-docs/?d9esU1)

[51. Boyle, B. & Enquist, B. SALVIAS – the SALVIAS vegetation inventory database. *Biodivers. Ecol.* (2012) doi:10.7809/b-e.00086.](https://www.zotero.org/google-docs/?d9esU1)

[52. Wiser, S. K., Bellingham, P. J. & Burrows, L. E. Managing biodiversity information: Development of New Zealand’s National Vegetation Survey databank. *N. Z. J. Ecol.* (2001).](https://www.zotero.org/google-docs/?d9esU1)

[53. DeWalt, S. J., Bourdy, G., ChÁvez de Michel, L. R. & Quenevo, C. Ethnobotany of the Tacana: Quantitative inventories of two permanent plots of Northwestern Bolivia. *Econ. Bot.* **53**, 237–260 (1999).](https://www.zotero.org/google-docs/?d9esU1)

[54. Dauby, G. *et al.* RAINBIO: A mega-database of tropical African vascular plants distributions. *PhytoKeys* (2016) doi:10.3897/phytokeys.74.9723.](https://www.zotero.org/google-docs/?d9esU1)

[55. Fegraus, E. Tropical Ecology Assessment and Monitoring Network (TEAM Network). *Biodivers. Ecol.* **4**, 287–287 (2012).](https://www.zotero.org/google-docs/?d9esU1)

[56. Oliveira-Filho, A. T. Um sistema de classificação fisionômico-ecológico da vegetação neotropical: segunda aproximação. in *Fitossociologia no Brasil - Métodos e estudos de caso - Volume II* (2015). doi:10.1016/j.jns.2007.02.032.](https://www.zotero.org/google-docs/?d9esU1)

[57. Butchart, S. H. M. *et al.* Shortfalls and Solutions for Meeting National and Global Conservation Area Targets. *Conserv. Lett.* **8**, 329–337 (2015).](https://www.zotero.org/google-docs/?d9esU1)

[58. Rondinini, C., Stuart, S. & Boitani, L. Habitat suitability models and the shortfall in conservation planning for African vertebrates. *Conserv. Biol.* **19**, 1488–1497 (2005).](https://www.zotero.org/google-docs/?d9esU1)

[59. Brooks, T. M. *et al.* Measuring Terrestrial Area of Habitat (AOH) and Its Utility for the IUCN Red List. *Trends Ecol. Evol.* **34**, 977–986 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[60. IUCN. Habitats Classification Scheme, Version 3.1. 1–14 (2012).](https://www.zotero.org/google-docs/?d9esU1)

[61. Lesiv, M. *et al. Global planted trees extent 2015*. (Zenodo, 2020).](https://www.zotero.org/google-docs/?d9esU1)

[62. Gorelick, N. *et al.* Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sens. Environ.* **202**, 18–27 (2017).](https://www.zotero.org/google-docs/?d9esU1)

[63. Meyer, C., Weigelt, P. & Kreft, H. Multidimensional biases, gaps and uncertainties in global plant occurrence information. *Ecol. Lett.* **19**, 992–1006 (2016).](https://www.zotero.org/google-docs/?d9esU1)

[64. Meyer, C., Kreft, H., Guralnick, R. & Jetz, W. Global priorities for an effective information basis of biodiversity distributions. *Nat. Commun.* **6**, 8221 (2015).](https://www.zotero.org/google-docs/?d9esU1)

[65. Brummitt, R. K. *World geographical scheme for recording plant distributions*. (International Working Group on Taxonomic Databases for Plant Sciences (TDWG), 2001).](https://www.zotero.org/google-docs/?d9esU1)

[66. Santoro, M. *GlobBiomass - global datasets of forest biomass*. (PANGAEA, 2018). doi:10.1594/PANGAEA.894711.](https://www.zotero.org/google-docs/?d9esU1)

[67. Santoro, M. & Cartus, O. ESA Biomass Climate Change Initiative (Biomass\_cci): Global datasets of forest above-ground biomass for the year 2017. (2019) doi:10.5285/bedc59f37c9545c981a839eb552e4084.](https://www.zotero.org/google-docs/?d9esU1)

[68. Buchhorn, M. *et al.* Copernicus Global Land Cover Layers—Collection 2. *Remote Sens.* **12**, 1044 (2020).](https://www.zotero.org/google-docs/?d9esU1)

[69. Bouvet, A. *et al.* An above-ground biomass map of African savannahs and woodlands at 25 m resolution derived from ALOS PALSAR. *Remote Sens. Environ.* **206**, 156–173 (2018).](https://www.zotero.org/google-docs/?d9esU1)

[70. Xia, J. *et al.* Spatio-Temporal Patterns and Climate Variables Controlling of Biomass Carbon Stock of Global Grassland Ecosystems from 1982 to 2006. *Remote Sens.* **6**, 1783–1802 (2014).](https://www.zotero.org/google-docs/?d9esU1)

[71. Spawn, S. A., Lark, T. J. & Gibbs, H. K. A New Global Biomass Map for the Year 2010. in *A New Global Biomass Map for the Year 2010* (2017).](https://www.zotero.org/google-docs/?d9esU1)

[72. Schepaschenko, D. *et al.* Improved estimates of biomass expansion factors for Russian forests. *Forests* (2018) doi:10.3390/f9060312.](https://www.zotero.org/google-docs/?d9esU1)

[73. Eggleston, S., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K. *2006 IPCC guidelines for national greenhouse gas inventories*. vol. 5 (2006).](https://www.zotero.org/google-docs/?d9esU1)

[74. Hengl, T. & Wheeler, I. Soil Organic Carbon Stock in kg/m2 for 5 Standard Depth Intervals (0–10, 10–30, 30–60, 60–100 and 100–200 Cm) at 250 M Resolution. (2018) doi:10.5281/ZENODO.2536040.](https://www.zotero.org/google-docs/?d9esU1)

[75. Hengl, T. & Nauman, T. Predicted USDA soil orders at 250 m (probabilities) (Version v0.1). http://doi.org/10.5281/zenodo.2658183 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[76. Mulligan, M. WaterWorld: a self-parameterising, physically based model for application in data-poor but problem-rich environments globally. *Hydrol. Res.* **44**, 748–769 (2013).](https://www.zotero.org/google-docs/?d9esU1)

[77. Mulligan, M. Trading off agriculture with nature’s other benefits, spatially. in *The Impacts of Climate Change on Water Resources in Agriculture* 184–204 (CRC Press, 2014).](https://www.zotero.org/google-docs/?d9esU1)

[78. van Soesbergen, A. & Mulligan, M. Potential outcomes of multi-variable climate change on water resources in the Santa Basin, Peru. *Int. J. Water Resour. Dev.* (2018) doi:10.1080/07900627.2016.1259101.](https://www.zotero.org/google-docs/?d9esU1)

[79. van Soesbergen, A. & Mulligan, M. Uncertainty in data for hydrological ecosystem services modelling: Potential implications for estimating services and beneficiaries for the CAZ Madagascar. *Ecosyst. Serv.* (2018) doi:10.1016/j.ecoser.2018.08.005.](https://www.zotero.org/google-docs/?d9esU1)

[80. Linke, S. *et al.* Global hydro-environmental sub-basin and river reach characteristics at high spatial resolution. *Sci. Data* **6**, 283 (2019).](https://www.zotero.org/google-docs/?d9esU1)

[81. Kukkala, A. S. & Moilanen, A. Core concepts of spatial prioritisation in systematic conservation planning. *Biol. Rev.* **88**, 443–464 (2013).](https://www.zotero.org/google-docs/?d9esU1)

[82. Adams, V. M., Pressey, R. L. & Naidoo, R. Opportunity costs: Who really pays for conservation? *Biol. Conserv.* **143**, 439–448 (2010).](https://www.zotero.org/google-docs/?d9esU1)

[83. Armsworth, P. R. Inclusion of costs in conservation planning depends on limited datasets and hopeful assumptions. *Ann. N. Y. Acad. Sci.* **1322**, 61–76 (2014).](https://www.zotero.org/google-docs/?d9esU1)

[84. Eklund, J., Arponen, A., Visconti, P. & Cabeza, M. Governance factors in the identification of global conservation priorities for mammals. *Philos. Trans. R. Soc. B Biol. Sci.* **366**, 2661–2669 (2011).](https://www.zotero.org/google-docs/?d9esU1)

[85. McCreless, E., Visconti, P., Carwardine, J., Wilcox, C. & Smith, R. J. Cheap and Nasty? The Potential Perils of Using Management Costs to Identify Global Conservation Priorities. *PLoS ONE* **8**, e80893 (2013).](https://www.zotero.org/google-docs/?d9esU1)

[86. Carwardine, J. *et al.* Cost-effective priorities for global mammal conservation. *Proc. Natl. Acad. Sci.* **105**, 11446–11450 (2008).](https://www.zotero.org/google-docs/?d9esU1)

[87. Rodrigues, A. S. L. *et al.* Effectiveness of the global protected area network in representing species diversity. *Nature* **428**, 640–643 (2004).](https://www.zotero.org/google-docs/?d9esU1)

[88. Arponen, A., Heikkinen, R., Thomas, C. D. & Moilanen, A. The Value of Biodiversity in Reserve Selection: Representation, Species Weighting, and Benefit Functions. *Conserv. Biol.* **19**, 2009–2014 (2005).](https://www.zotero.org/google-docs/?d9esU1)

[89. Beyer, H. L., Dujardin, Y., Watts, M. E. & Possingham, H. P. Solving conservation planning problems with integer linear programming. *Ecol. Model.* **328**, 14–22 (2016).](https://www.zotero.org/google-docs/?d9esU1)

[90. Hanson, J. O., Schuster, R., Strimas‐Mackey, M. & Bennett, J. R. Optimality in prioritizing conservation projects. *Methods Ecol. Evol.* 2041–210X.13264 (2019) doi:10.1111/2041-210X.13264.](https://www.zotero.org/google-docs/?d9esU1)

[91. R Core Team. *R: A Language and Environment for Statistical Computing*. (R Foundation for Statistical Computing, 2019).](https://www.zotero.org/google-docs/?d9esU1)

[92. Hanson, J. *et al. prioritizr: Systematic Conservation Prioritization in R*. (2019).](https://www.zotero.org/google-docs/?d9esU1)

[93. Gurobi Optimization, L. *Gurobi Optimizer Reference Manual*. (2019).](https://www.zotero.org/google-docs/?d9esU1)

## Figure legends

**Map

Description automatically generated**

**Fig. 1: Global areas of conservation importance for terrestrial biodiversity, carbon and water**. All features were jointly optimized with equal weighting given to each feature (central point in the series of segments in Fig. 2) and ranked by the most (1-10) to least (90-100) valuable areas to conserve globally. The triangle plot shows the extent to which protecting the top-ranked 10% and 30% of global land areas (dark brown and yellow areas on the map) contributes to improving species conservation status, storing carbon and ensuring clean water. Percentages in the triangle plot refer to the proportion of all species targets reached (Fig. 3) or the average shortfall of carbon and water. The map is at 10 km resolution in Mollweide projection. A map highlighting the uncertainty in priority ranks can be found in Extended Data Fig. 1.

A picture containing map

Description automatically generated

**Fig. 2: Implications of different relative weights given to carbon or water over achieving species conservation targets**. (a) Each ‘boomerang-shaped’ segment of dots represents a series of conservation prioritisation variants with a common area budget (from 10% of land areas bottom left to 100% at top-right, visually indicated are 10%, 30% and 50% solution in form of filled circles). Axes indicate the proportion of all carbon and water quality regulation features conserved, colours represent the proportion of species for which a species conservation status could be improved to ‘Least Concern’ as inspired by IUCN Red List criteria (but see methods), and the point size indicates the difference in weighting given to carbon or water relative to biodiversity, ranking from none to equal weighting (see methods). A detailed view on curves of relative shortfall for 10%, 30% and 50% can be found in Extended Data Fig. 10. (b-c) Global areas of conservation importance if 10% (dark-brown), or 30% (yellow), of land area is managed for conservation while preferring (b) carbon protection over water or (c) water protection over carbon.

Graphical user interface, logo, company name

Description automatically generated

**Fig. 3: Accumulation curves showing how the number of species targets met increases with amount of land area optimally allocated with and without current protection.** Proportion of species targets reached for an (a,c,e) optimal prioritization and (b,d,f) building on current terrestrial protected areas (15% of land area indicated by red dot). (a,b) Target accumulation curves for analysis variants including other features such as NCP; (c,d) for different taxonomic groups when optimizing biodiversity only to conservation; (e,f) for species classified as threatened or not (see Methods) when optimizing for biodiversity only. Accumulation curves of features without biome splits can be found in Extended Data Fig. 9.

**Fig. 4: Change in global areas of biodiversity-only importance after adding plant species**. (a) Calculated as the difference in areas of biodiversity importance with either plant species included or excluded. Positive changes (yellow to dark green) in rank imply an increase in priority if plant species are considered, while negative changes (light to dark blue) show a decrease in priority ranks. The map is at 10 km resolution in a Mollweide projection. (b) Average change in ranks per biome after plants have been added. (c) Vertebrate species representation curves of areas necessary to be managed for conservation with (solid) and without plants (dashed) included.