Conservation attention necessary across at least 44% of Earth's terrestrial area to safeguard biodiversity

Abbreviated Title: Land area needed to conserve biodiversity

Authors

James R. Allan*[1,2,3], Hugh P. Possingham[2,4], Scott C. Atkinson[2,5], Anthony Waldron[6,], Moreno Di Marco[7,8], Vanessa M. Adams[9], Stuart H. M. Butchart[10,11], Oscar Venter[12], Martine Maron[2,8], Brooke A. Williams[2,8], Kendall R. Jones[13], Piero Visconti[14], Brendan A. Wintle[15], April E. Reside[2,8], James E.M. Watson[2,8,13]

Affiliations

[1]School of Biological Sciences, University of Queensland, St Lucia QLD 4072, Australia

[2]Centre for Biodiversity and Conservation Science, The University of Queensland, St Lucia, QLD 4072, Australia

[3]Institute for Biodiversity and Ecosystem Dynamics (IBED), University of Amsterdam, P.O. Box 94240, 1090 GE, Amsterdam, The Netherlands

[4]The Nature Conservancy, VA 22203-1606, USA

[5]United Nations Development Programme (UNDP), New York, New York, USA

[6]Cambridge Conservation Initiative, David Attenborough Building, Department of Zoology, Cambridge University, Cambridge CB2 3QZ, UK

[7]Department of Biology and Biotechnologies, Sapienza University of Rome, viale dell'Università 32, I-00185 Rome, Italy

[8]School of Earth and Environmental Sciences, The University of Queensland, St Lucia QLD 4072, Australia

[9]School of Technology, Environments & Design, University of Tasmania, Hobart, TAS 7001, Australia

[10]BirdLife International, David Attenborough Building, Pembroke Street, Cambridge CB2 3QZ, UK.

[11]Department of Zoology, University of Cambridge, Downing Street, Cambridge CB2 3EJ, UK.

[12]Natural Resource and Environmental Studies Institute, University of Northern British Columbia, Prince George, V2N4Z9, Canada

[13]Wildlife Conservation Society, Global Conservation Program, 2300 Southern Boulevard, Bronx, NY 10460-1068, USA

[14]International Institute for Applied System Analyses, Schlossplatz 1, A-2361 Laxenburg, Austria

[15]School of BioSciences, University of Melbourne, Vic., Australia

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*Correspondence to: James R. Allan. E-mail: James.allan@uqconnect.edu.au

More ambitious conservation efforts are needed to stop the global degradation of ecosystems and the extinction of the species that comprise them. Here, we estimate the minimum amount of land needed to secure known important sites for biodiversity, Earth's remaining wilderness, and the optimal locations for adequate representation of terrestrial species distributions and ecoregions. We discover that at least 64 million km^2 (43.6% of Earth's terrestrial area) requires conservation attention either through site-scale interventions (e.g. protected areas) or landscape-scale responses (e.g. land-use policies). Spatially explicit land-use scenarios show that 1.2 million km^2 of land requiring conservation attention is projected to be lost to intensive human land-use by 2030 and therefore requires immediate protection. Nations, local communities and industry are urged to implement the actions necessary to safeguard the land areas critical for conserving biodiversity.

Conserving natural areas is crucial for safeguarding biodiversity and Earth system processes[1], and is central to the Convention on Biological Diversity (CBD)'s 2050 vision of sustaining a healthy planet and delivering benefits essential for all people[2]. The current CBD Aichi Target 11 aims to protect at least 17% of land area by 2020[3], but this is widely seen as inadequate for halting biodiversity declines and averting the extinction crisis[4-6]. Post-2020 target discussions are now well underway[7], and there is a broad consensus that the amount of land and sea being set aside for conservation attention must increase[8]. Recent calls are for targets to conserve anywhere from 26 to 60% of land and ocean area by 2030 through site-scale responses such as protected areas and 'other effective area-based conservation measures' (OECMs)[9-13]. But there is increasing recognition that site-scale responses must be supplemented by broader landscape-scale actions aimed at halting vegetation destruction[14]. Global conservation targets are set by intergovernmental negotiation, but scientific input is essential to provide evidence about the location and amount of land necessary to conserve biodiversity.

Several broad scientific approaches exist that help provide evidence for global conservation, but when used in isolation, potentially provide conflicting or confusing evidence. For example, there are efficiency-based planning approaches that focus on maximising the number of species or ecosystems captured within a complementary set of conservation areas, prioritising species and ecosystems by their endemicity, extinction risk, the degree to which they are represented (or underrepresented) in existing protected areas, or other criteria[15,16]. There are also site-based approaches such as the Key Biodiversity Area (KBA) initiative[17], which aims to identify significant sites for biodiversity persistence using criteria including in relation to occurrence of threatened or geographically restricted species or ecosystems, intact ecological communities, or important biological processes (e.g. breeding aggregations)[17]. There are also proactive approaches that aim to conserve the last places that are free from human pressure, sometimes called 'wilderness areas'[18], before they are eroded. These areas are increasingly recognised as essential for Earth system functioning[19], sustaining long-term ecological and evolutionary processes[20] and long-term species persistence[21], especially under climate change[22]. Examples include boreal forests which hold one-third of the world's terrestrial carbon and many wide-ranging species[23,24], and the Amazon rainforest which needs to be maintained in its entirety, not just its most species-rich areas, for it to sustain continent-scale hydrological patterns[25].

Although all these approaches and initiatives are complementary and provide essential evidence needed to set biodiversity conservation targets, the adoption of any one of them as a unique guide for decision-making is likely to omit potentially critical elements of the CBD vision[26]. For example, a species-based focus on identifying areas in a way that most efficiently captures the most species would fail to recognise the Earth-system importance of the Boreal or Amazon forests, or the critical need to maintain large intact ecosystems globally for biodiversity[21]. Equally, a focus on proactively conserving Earth's intact ecosystems would fail to achieve representation of some of Earth's species or ecosystems[27]. Put simply, all approaches will lead to partly overlapping but often distinct science-based suggestions for area-based conservation[28]. Rather than debating the merits of any individual approach, we suggest that achieving the CBD vision requires a unified global strategy that comprehensively conserves species and ecosystems as well as Earth's remaining intact ecosystems, and we provide a methodological framework that utilises all three approaches.

Here, we identify the minimum land area requiring conservation attention globally. We start from the basis of existing protected areas (PAs), KBAs, and wilderness areas, and then efficiently add a large enough fraction of the ranges of 28,594 species of mammals, birds, amphibians, reptiles, dragonflies and crustaceans to enable their persistence[15,16,29], while also capturing representative samples of all terrestrial ecoregions[30]. We are not suggesting that all of this land should be designated as protected areas. Rather, we argue that it should be managed through a range of strategies for species and ecosystem conservation. For example, extensive areas that are remote and unlikely to be converted for human uses in the near-term could be safeguarded through effective sustainable land-use policies, while some locations may be best conserved through OECMs[31] rather than formal protected areas. We believe the appropriate governance and management regimes for any area depends in part on the likelihood of its habitat being converted to human uses[32] or degraded by human pressures[33], and as such, the response for conserving the areas we identify will be context specific.

To highlight places that need immediate attention and potentially stronger forms of environmental governance, we further calculate which parts of the land needing conservation are most likely to suffer habitat conversion in the absence of conservation. We do this by using recent harmonised projections of future land-use change by 2030 and 2050[34]. To determine best- and worst-case scenarios, we evaluated projections under two different shared socioeconomic pathways (SSPs)[35] linked to representative concentration pathways (RCPs)[36]: an optimistic scenario where the world gradually moves towards a more sustainable future, SSP1 (RCP2.6; IMAGE model), and a pessimistic scenario where regional rivalries dominate international relations and land-use change is poorly regulated, SSP3 (RCP7.0; AIM model). The areas we identify as at risk of habitat loss represent urgent priorities for conservation action through site- and landscape-scale responses.

The minimum land area requiring conservation

We estimate that, in total, the minimum land area that must be effectively conserved covers 64 million km^2 (43.6% of Earth's terrestrial area; Figure 1). This consists of 35 million km^2 of wilderness, 21 million km^2 of existing PAs ,11 million km^2 of KBAs, and 13 million km^2 (9% of Earth's terrestrial area) of additional land needed to promote species persistence based on conserving minimum proportions of their ranges (Figure 2). We find 1.9 million km^2 of overlap between PAs, KBAs and wilderness, amounting to a relatively small 5% of wilderness extent, 9% of PA extent, and 18% of KBA extent.

There is considerable variation geographically in the amount of land requiring effective conservation. We find that 60.6% of land in North America needs to be conserved, primarily due to the wilderness areas of Canada and the USA and extensive additional land areas in Central America. In contrast, only 32.3% of Europe's land area requires conservation. The proportion of land requiring conservation also varies considerably among nations (Figure 3), with notably high values in Canada (79%), Costa Rica (83%), Suriname (84%), and Ecuador (81%), where these tropical-country figures reflect high numbers of endemic species and, in Ecuador's case, a large overlap with the remaining Amazon forest (Extended Data Table 1). We also find that a larger proportion of land in developed countries (53%) requires effective conservation compared to emerging economies (47%) or developing countries (34%) (Extended Data Table 2). Many island nations have high proportions of land requiring conservation (Figure 3; Supplementary Table 1), but this is likely an artefact of the necessarily coarse resolution (30x30 km) of the analysis, where a few grid cells can encompass an entire small island.

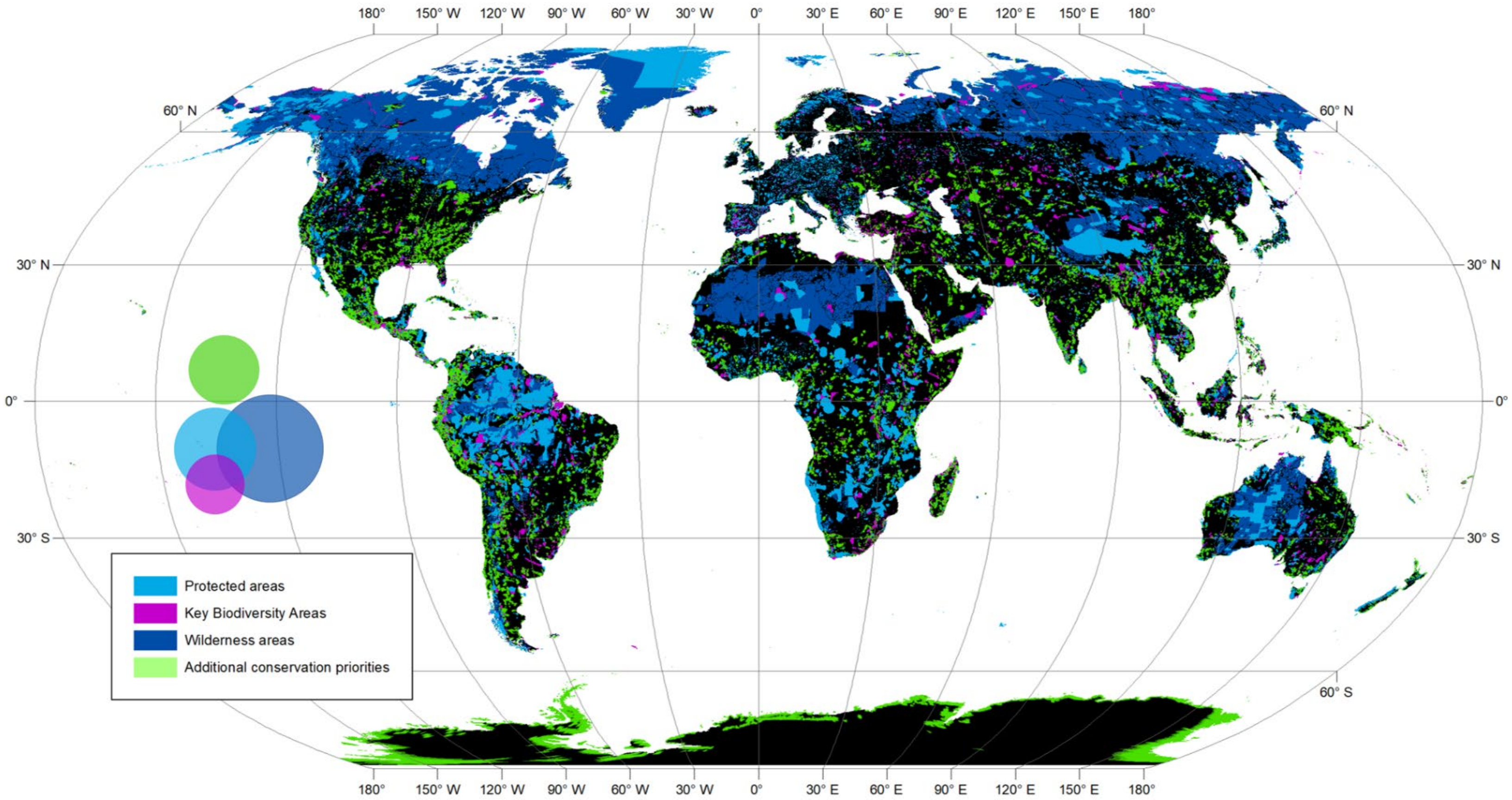

Figure 1. The minimum land area for conserving terrestrial biodiversity. The components include protected areas (light blue), Key Biodiversity Areas (purple) and wilderness areas (dark blue). Where they overlap, protected areas are shown above Key Biodiversity Areas, which are shown above wilderness areas. New conservation priorities are in green. The Venn diagram shows the proportional overlap between features.

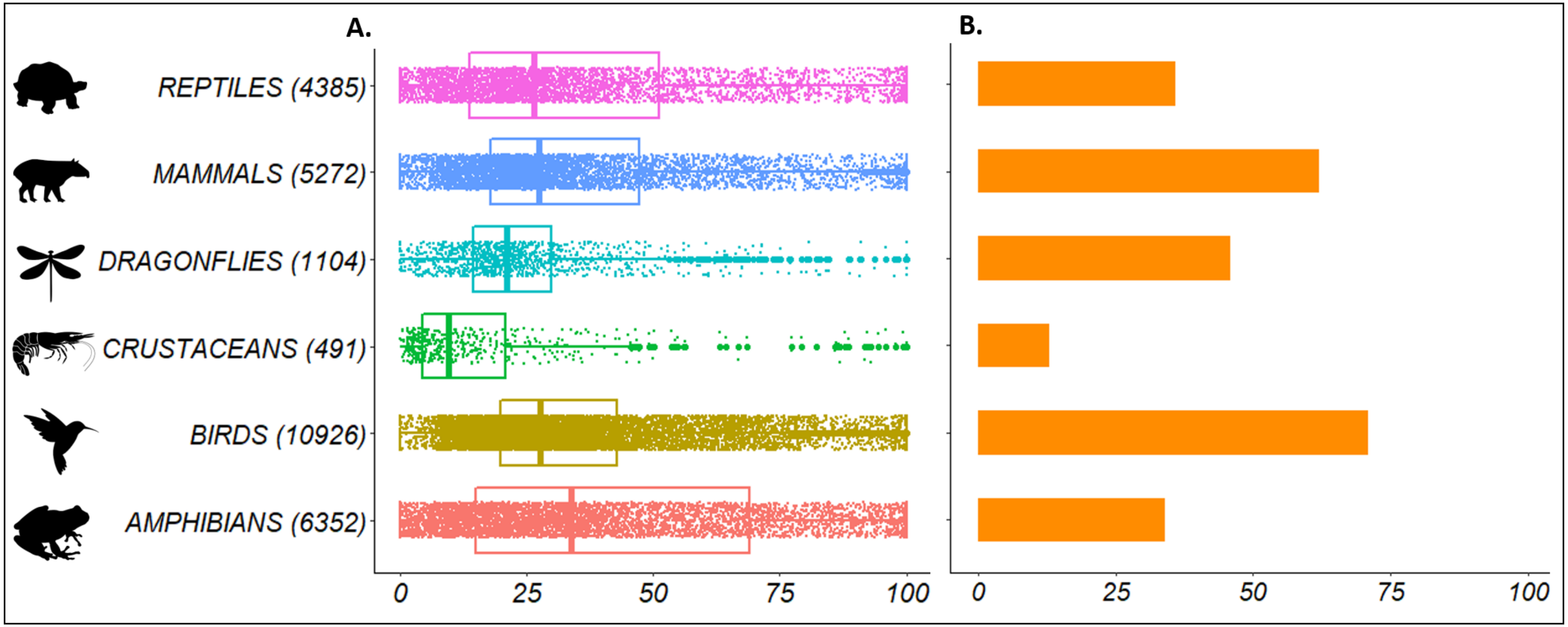

Figure 2. Gap analyses of species coverage within areas of conservation importance. A) The percentage of each species' distribution overlapping with areas of conservation importance (protected areas, Key Biodiversity Areas, and wilderness areas). Boxplots show the median and 25th and 75th percentiles for each taxonomic group. B) the percentage of species with enough of their distribution overlapping existing conservation areas to meet their species-specific coverage target (orange).

Future risk of land conversion in areas requiring conservation

Our results suggest that under the pessimistic scenario SSP3, 1.2 million km^2 (2%) of the total land area requiring effective conservation will have its habitat converted to human uses by 2030, increasing to 2.1 million km^2 (3.4%) by 2050 (Figure 4). Habitat conversion varies across continents and countries; Africa is projected to have the highest proportion of important conservation land converted by 2030 (>760,000 km^2, 6.3%), increasing to 1.4 million km^2 (11.1%) by 2050 (Extended Data Table 3). The lowest risk of conversion is in Oceania and North America. Substantially larger proportions of land requiring conservation in developing countries are projected to have their habitat converted by 2030 (4.3%), compared to emerging economies (1.3%) or developed countries (0.8%).

Based on SSP1, representing a world acting on sustainability, we estimate that 130,000 km^2 (0.1%) of the land requiring effective conservation may suffer natural habitat conversion by 2030, increasing to 3.8 million km^2 (0.5%) by 2050. This highlights that our results are sensitive to future societal development pathways, but even under the most optimistic scenario (SSP1), large extents of important conservation land are at risk of having natural habitat converted to more intensive human land-uses. We find very similar geographical patterns of risk under SSP1 as those highlighted for SSP3.

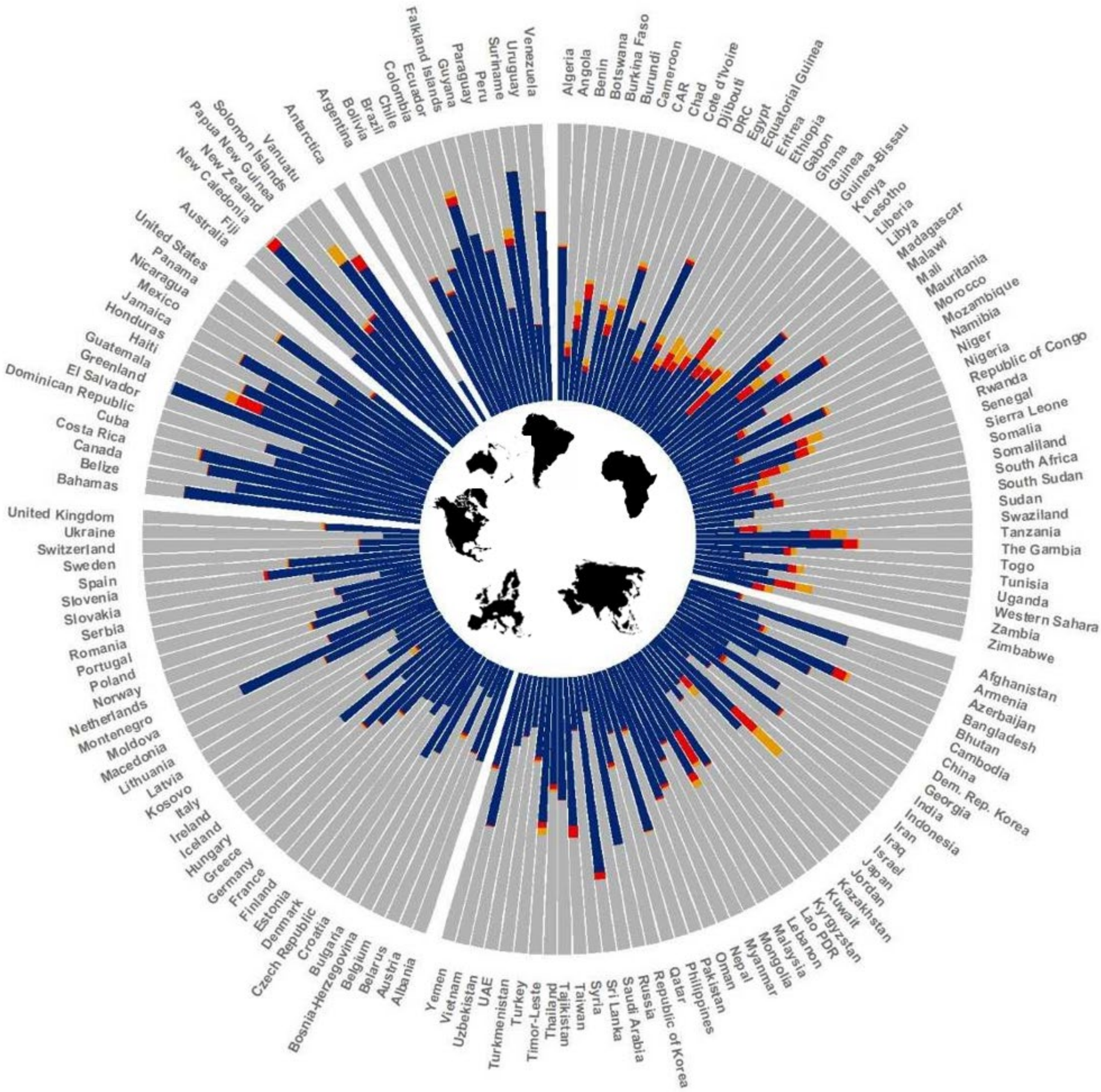

Figure 3. National level land area for conservation and projected habitat loss. Estimated proportion of each country requiring effective conservation attention that is projected to suffer habitat conversion by 2030 (red), 2050 (orange) or that are projected not to be converted (blue). Grey areas are outside the land identified for conservation. Countries with a land area < 10,000 km^2 were excluded from the figure.

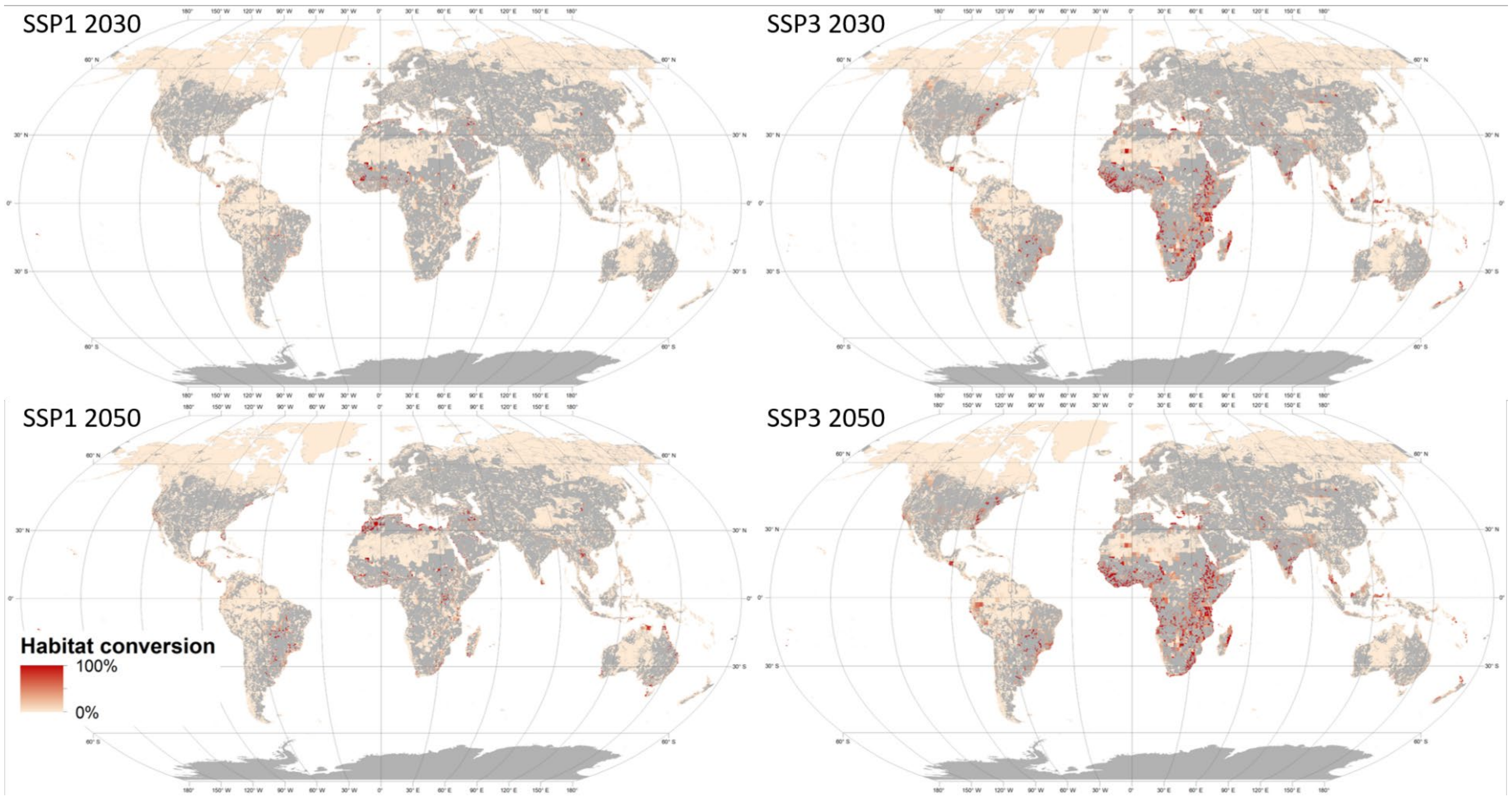

Figure 4. Future habitat conversion on important conservation land. The location of land requiring effective conservation attention and the proportion of natural habitat projected to be converted to human uses by 2030 and 2050 based on Shared Socioeconomic Pathway 1 (SSP1; an optimistic scenario) and Shared Socioeconomic Pathway 3 (SSP3; a pessimistic scenario). Grey areas are not identified as existing conservation areas or additional conservation priorities. The data on future land use does not extend to Antarctica.

Implications for global policy

Our analyses represent the most comprehensive estimate of the minimum land area requiring effective conservation attention in order to safeguard species and ecosystems while accounting for current protected areas and areas of recognised biodiversity importance (KBAs and Earth's remaining intact ecosystems). Given our inclusion of wilderness areas and also updated maps of KBAs, our estimate that 43.6% of land requires effective conservation is, unsurprisingly, larger than those from previous analyses that have focussed primarily on species and/or ecosystems, or used earlier KBA datasets (e.g. 27.9% Butchart, et al. [16], 20.2% Venter, et al. [15], and 30% Larsen, et al. [4]). Effectively conserving the land areas we identify would make a substantial contribution towards achieving a suite of targets under the Convention for Biological Diversity, including halting the extinction and decline of species (the focus of CBD Aichi Target 12), protecting areas of particular importance for biodiversity (Aichi Target 11), representing all native ecosystem types (Aichi Target 11), halting the loss of natural habitats (Aichi Target 5) and securing areas that maintain ecological and evolutionary processes[3].

Encouraging nations to adopt a more ambitious conservation agenda within the post-2020 biodiversity framework, and to scale up the proportion of land that is effectively conserved, will be challenging. However, much (70%) of the land we identify for conservation attention is still relatively intact, and therefore does not require costly conservation interventions (such as vegetation restoration activities) beyond retention policies that ensure these places remain intact[37]. But at least 1.2 million km^2 of land needing conservation - an area larger than South Africa representing 0.9% of Earth's terrestrial surface - is both important for achieving our outlined conservation objectives and likely to have its habitat converted to human uses by 2030. A tactical target aimed at immediately safeguarding these at-risk places would make a significant contribution towards addressing the biodiversity crisis, but only if combined with parallel efforts ensuring that habitat conversion is not displaced into other important conservation areas[38,39].

A diverse array of actions is required to achieve the scale of conservation necessary to deliver positive conservation outcomes. These actions include ensuring that the protected area estate is significantly expanded and managed more effectively to benefit biodiversity[12], formally recognising and expanding other effective area-based conservation measures, and implementing broad-scale responses aimed at limiting core threatening processes such as habitat conversion. Another strategy that may effectively limit the expansion of human pressures is to recognise Indigenous Peoples' rights to land, benefit sharing, and institutions, so they can effectively conserve their own lands, as there is substantial global overlap between Indigenous lands and the important conservation land we identified[40]. On all identified conservation land, regardless of its immediate risk, the expansion of roads and developments such as agriculture, forestry, and mining, need to be very carefully managed to avoid net damage to ecosystems[41]. As such, mechanisms that direct developments away from important conservation areas are also crucial, including strengthening investment and performance standards (e.g. for financial organisations such as the World Bank and other development investors[42]), and tightening existing industry certification standards.

A critical implementation challenge is that the proportion of land different countries would need to conserve is highly inequitable. In responding to this inequity, the conservation community could learn from how nations are addressing climate change. For example, under the United Nations Framework Convention on Climate Change, nations responsible for high levels of emissions of greenhouse gases are obliged to make larger emission reductions[43], following the concept of common but differentiated responsibilities that is foundational to all global environmental agendas including the CBD[44]. Since the burden of conservation is disproportionately distributed, cost-sharing and fiscal transfer mechanisms are likely necessary to ensure that all national participation is equitable and fair, and the opportunity costs of foregone developments are considered[45,46]. This is particularly important since the majority of land requiring conservation attention and at risk of immediate habitat conversion is found in developing nations.

Our estimate of the land area requiring effective biodiversity conservation must be considered the bare minimum needed, and will almost certainly expand as more data on the distributions of underrepresented species such as plants, invertebrates, and freshwater species becomes available for future analyses[47]. New KBAs will also continue to be identified for under-represented taxonomic groups, threatened or geographically-restricted ecosystems, and highly intact and irreplaceable ecosystems.

Species and ecosystems are also shifting under climate change, and as a result, are leading to changes in the location of land requiring effective conservation[48], which we could not account for. We also note that post-2020 biodiversity targets are likely to require higher levels of ecoregional representation than the 17% we used (see Methods). Finally, more land beyond the areas we identify will need to be conserved for non-biodiversity conservation purposes, such as nature-based solutions to climate change[8].

For the above reasons, our results do not imply that the land our analysis did not identify, the other 56.4% of Earth's land surface, is unimportant for conservation and global sustainable development goals. Much of this area will be important for sustaining the provision of ecosystem services to people, from climate regulation to provisioning of food, materials, drinking water, and crop pollination, in addition to supporting other elements of biodiversity not captured in our priority areas[8]. Furthermore, many human activities can impact the entire Earth system regardless of where they occur (e.g. fossil fuel use, pesticide use, and pollution), so management efforts focussed on limiting the ultimate drivers of biodiversity loss are essential[49]. Finally, we have not considered how constraining developments to locations outside of the land area needing conservation impacts solutions for meeting human needs, such as increasing energy and food demands. Leakage of more intense land use impacts into non-conservation priority areas must be carefully managed[38]. Although social objectives that lead to the betterment of all humanity are clearly important, they cannot be all achieved sustainably without limiting the degradation of the ecosystems supporting all life[1]. Integrated assessments of how we can achieve multiple social objectives while effectively conserving biodiversity at a global scale are important avenues for future research[50].

The world's nations are already discussing new post-2020 biodiversity conservation targets within the CBD and wider Sustainable Development Goals international agenda. These targets will define the global conservation agenda for at least the next decade, so it is crucial that they are adequate to achieve biodiversity outcomes[12]. Our analyses show that a minimum of 43.6% of land requires effective conservation attention, through both site- and landscape-scale approaches, which should serve as an ecological foundation for negotiations. If signatory nations are serious about safeguarding the biodiversity and ecosystem services that underpin all life on earth[1,50], then they need to recognise that conservation action must be immediately and substantially scaled-up, in extent, intensity, and effectiveness.

Methods

Mapping important conservation areas

We obtained spatial data on the location of 214,921 PAs from the January 2017 version of the World Database on Protected Areas (WDPA)[51]. This edition still contains data on PAs in China, which have largely been removed from the publicly accessible WDPA in more recent versions. We handled the WDPA data according to best-practice guidelines that are available on the protected planet website (https://www.protectedplanet.net/c/calculating-protected-areacoverage) and included regionally, nationally and internationally designated PAs. The WDPA dataset contains PAs represented as point data. In these cases, we converted the points to polygons by setting a geodesic buffer around the point based on the areal attributes of that point. We excluded points with no areal attributes. We also excluded all marine PAs, 'proposed' PAs, and UNESCO Man and Biosphere Reserves since their core conservation areas often overlap with other PAs and their buffer zones' primary goals are not biodiversity conservation. Finally, we flattened (i.e. dissolved) the PA data to remove any overlapping PAs.

We obtained data on the boundaries of 14,192 KBAs from the January 2017 version of the World Database of Key Biodiversity Areas[52]. KBAs documented with point data were treated as outlined above for PAs. We obtained global data on wilderness extent from Allan, et al. [53], utilising maps of 'pressure-free lands'. We merged PAs, KBAs and wilderness areas together, removing overlaps (i.e. again flattened the merged datasets) to create a global template of "existing important conservation areas".

Distribution and representation of biodiversity

We obtained data on the distributions of terrestrial mammals (n=5,272), amphibians (n=6,352), reptiles (including marine turtles; n=4,385), freshwater crayfish (n=491) and dragonflies and damselflies (order Odonata; n=1,104) from the IUCN Red List of Threatened Species[54]. Bird distribution data (n=10,926) were sourced from BirdLife International and Handbook of the Birds of the World[55]. These represent the most comprehensive spatial databases for these taxonomic groups, although crayfish, Odonata, and reptiles are likely still undersampled. We also included data on the distribution of terrestrial ecoregions[30], which are bio-geographically distinct spatial units at the global scale.

We set representation targets for the percentage of each species' distribution that should be effectively conserved, following previous studies (Rodrigues, et al. [29], Venter, et al. [15], and Butchart, et al. [16]). Targets were set as a function of a species' range size, and were log-linearly scaled between 10% for species with distributions >250,000km^2, to 100% for species with ranges <1,000km^2. We limited the target for species with large ranges to 1 million km^2 maximum[16]. For each ecoregion we followed[15] by setting a coverage target of 17%, in line with Aichi Target 11 of the Strategic Plan for Biodiversity[3]. We acknowledge that Aichi Target 11 expires in 2020, and that other target setting approaches are being developed, such as those based on species persistence[56], but these are currently unpublished (and the nature of post-2020 targets is still under discussion) so we chose to proceed with the widely accepted method developed by Rodrigues, et al. [29]. We carried out a "gap analysis" by calculating the proportion of each species' range that currently overlaps with the important conservation areas, and comparing this with each species' coverage target to identify under-represented species and the extent of additional range each requires.

Priority areas for the expansion of conservation efforts

We used integer linear programming to identify spatial priorities for meeting species conservation targets, whilst accounting for current protection within existing important conservation areas, and minimizing the cost (human footprint[57]) of the areas selected (the minimum set problem)[58]. We used Gurobi software (version 5.6.2) to run the spatial prioritisation, following methods developed by Beyer, et al. [59] that account for multi-species complementarity. Integer linear programming can reach optimal solutions to conservation problems if unrestricted by computing time. We applied a threshold specifying that solutions must be within 0.5% of the optimum[59], which returns a near-optimal solution and greatly reduces processing time.

To run the analysis, we first created a 30 x 30 km (900 km^2) global planning unit grid. This resolution limits the risk of commission errors when working with the available species distribution data (e.g. assuming a species is present when it is not)[16,60]. Planning units were clipped to terrestrial areas and inland lakes and waterways so that freshwater taxa could be included. We included Antarctica and

Greenland. We calculated the area of each conservation feature (e.g. species distribution and ecoregion distribution) within each planning unit, including the area within existing important conservation areas. All geospatial data processing was carried out in the Mollweide equal-area projection using a spatially enabled PostgreSQL database (using PostGIS version 2.2) or in ESRI ArcGIS version 10.5.1.

We used the sum of the human footprint[57] as a surrogate for the cost of conservation in each planning unit. The human footprint is a map of cumulative human pressure on the natural environment for the year 2009 at a 1km^2 resolution globally. We assumed that conservation will be cheaper and more feasible in areas with less human influence, and that places classified as 'built areas' are unavailable for conservation. By built areas we mean cities and major urban centres that contain no original habitat. Planning units beyond the extent of the human footprint (e.g. ice-free regions of Antarctica and remote sub-Antarctic islands) were set a cost of zero.

We repeated the entire prioritisation analysis with two additional planning unit grids. These grids were still 30 x 30 km in scale but the cells were shifted 10km East and North of the original grid, and 10km South and West of the original grid. This limits uncertainty associated with the placement of the grid, and to the best of our knowledge, our analysis is the first to use such an approach. Areal statistics reported in the methods are based on the original grid, whilst on the maps all three grids are presented simultaneously with a degree of transparency so that priority areas selected in all three analyses are highlighted. This approach also ensures a degree of fuzziness in the priority area boundaries in the maps, demonstrating to decision makers that, while scale and location of planning units will introduce subtle differences in any prioritization scenario, certain areas always stand-out as conservation priorities.

Future threats to conservation areas

To map the risk of habitat conversion occurring in the conservation areas identified, we utilised spatially explicit data on future land-use scenarios from the newly released Land Use Harmonisation Dataset v2 (http://luh.umd.edu/)[34]. To determine best- and worst-case scenarios, we evaluated projections under two different Shared Socioeconomic Pathways (SSPs)[35], which are linked to Representative Concentration Pathways (RCPs)[36]: specifically, SSP1 (RCP2.6; IMAGE), an optimistic scenario where the world gradually moves towards a more sustainable future, and SSP3 (RCP7.0; AIM), a pessimistic scenario where land use change is poorly regulated.

The harmonised land-use data contains 12 state layers (with the unit being the fraction of a grid cell in that state) for the years 2015 (current baseline), 2030 and 2050. We considered four of the state layers as natural land-cover classes, including; primary forested land, primary non-forested land, potentially forested secondary land, and potentially non-forested secondary land. Using these four classes, we calculated the proportion of natural land projected to be lost (converted to human uses) by the years 2030 and 2050 in each 30 x 30 km grid cell. From this we calculated the area of natural land projected to be lost within each grid cell. We assume that once land is converted it remains converted. Antarctica and remote islands were excluded from this part of the analyses because the land-use data does not extend to them.

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Author Contributions

J.R.A and J.E.M.W. framed the study. J.R.A., S.C.A., M.D.M. carried out the analyses. All authors discussed and interpreted the results. J.R.A and J.E.M.W. wrote the manuscript with support from all authors.

Competing interests

The authors declare no competing interests