A metric for spatially-explicit contributions to science-based species targets

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The Convention on Biological Diversity's post-2020 Global Biodiversity Framework will likely include a goal to stabilise and restore the status of species. Its delivery would be facilitated by making the actions required to halt and reverse species loss spatially explicit. We develop a "Species Threat Abatement and Restoration" (STAR) metric, which is scalable across species, threats and geographies. STAR quantifies the contributions that abating threats and restoring habitats in specific places offer towards reducing extinction risk. While every nation can contribute towards halting biodiversity loss, Indonesia, Colombia, Mexico, Madagascar and Brazil combined have stewardship over 31% of total STAR values for terrestrial amphibians, birds and mammals. Among actions, sustainable crop production and forestry dominate, contributing 41% of total STAR values for these taxonomic groups. Key Biodiversity Areas cover 9% of the terrestrial surface but capture 47% of STAR values. STAR could support governmental and non-state actors to quantify their contributions to meeting science-based species targets within the framework.

The Convention on Biological Diversity (CBD) sets the policy framework for biodiversity conservation and sustainable use through the commitments of 195 countries and the European Union. The Strategic Plan for Biodiversity 2011-2020 included Aichi Biodiversity Target 12, which set the goal for 2020 of preventing the extinction of known threatened species and improving and sustaining their conservation status. Despite government commitments and successful efforts for certain species[1], overall extinction risk continues to increase, and widespread implementation shortfalls will prevent Target 12 from being met[2]. A new global framework with revised goals and targets is currently being negotiated, which places the stabilisation and restoration of species' populations as an outcome goal for 2030, as a stepping-stone towards the CBD's 2050 Vision[3,4].

The Aichi Biodiversity Targets were largely approached as a list of twenty discrete targets, not making explicit how progress towards pressure-reduction targets would support progress towards biodiversity-outcome targets[5]. In contrast, the proposed post-2020 Global Biodiversity Framework explicitly states the need to reduce threats to halt the loss of biodiversity, and proposes specific subtargets for threat reduction[3]. While the major direct threats to species are well-documented[2], establishing specific targets for threat reduction is complex, because there are large numbers of threatened species (>30,000 species assessed as threatened on the IUCN Red List[6]), rapid deteriorations (revealed by the Red List Index[7,8]), and large spatial variation in species' distributions, extinction risk trends and the threats impacting them[9]. Tools that support actions to address these threats include the documentation of species recovery[10], identification of important sites[11], and systematic conservation planning[12]. However, no mechanisms yet exist to quantify the contributions that particular actions in particular places could make towards abating threats to and restoring habitat for threatened species worldwide, to support achievement of the goals of the post-2020 biodiversity framework.

Results and Discussion

The Species Threat Abatement and Restoration metric

We develop and analyse a "Species Threat Abatement and Restoration" (STAR) metric, which evaluates the potential benefit for threatened species of actions to reduce threats and restore habitat. Like the Red List Index[7,8], STAR is derived from existing data in the IUCN Red List and is intended to help address an urgent need. STAR is spatially explicit, enabling identification of specific threat abatement and habitat restoration opportunities in particular places, which if implemented, could reduce species extinction risk to levels that would exist without ongoing human impact. Abatement of threats to species encompasses reduction in threat intensity and/or action to mitigate the impacts of threats. Positive population and/or distribution changes, and resulting reduction of species extinction risk, have been documented in response to threat abatement[13]. STAR assumes that for the great majority of species (see Supplementary Discussion) *complete* alleviation of threats would reduce extinction risk through halting decline and/or permitting sufficient recovery in population and distribution, such that the species could be downlisted to the IUCN Red List category of Least Concern. We recognize that complete threat reduction is difficult, incremental conservation gains will need to be tracked at the species level[23] and species recovery will vary across a species' range[23].

For each species, a global STAR threat-abatement (STAR$_T$) score is defined. This varies from zero for Least Concern species to 100 for Near Threatened, 200 for Vulnerable, 300 for Endangered and 400 for Critically Endangered (using established weighting ratios[7,8]). The sum of STAR$_T$ values across all species represents the global threat abatement effort needed for all species to become Least Concern. STAR$_T$ scores can be disaggregated spatially, based on the area of habitat currently available for each species in a particular location (as a proxy for population proportion). This shows the potential contribution of conservation actions in that location to reducing the extinction risk for all species globally. The local STAR$_T$ score can be further disaggregated by threat, based on the known contribution of each threat to the species' risk of extinction (see Methods). This quantifies how actions that abate a specific threat at a particular location contribute to the global abatement of extinction risk for all species.

The STAR metric also includes a complementary habitat restoration component to reflect the potential benefits to species of restoring lost habitat. During the UN Decade on Ecosystem Restoration (2021-2030), restoration efforts are likely to expand. The STAR restoration component applies a similar logic to the STAR threat-abatement component, but for habitat that has been lost and is potentially restorable ('restorable area of habitat'). The STAR restoration component does not make assumptions about the extent of habitat restoration required for individual species, but instead quantifies the potential contribution that habitat restoration activities could make to reducing species' extinction risk. For a particular species at a particular location, the STAR restoration (STAR$_R$) score reflects the proportion that restorable habitat at the location represents of the global area of remaining habitat for that species. Importantly, a multiplier is applied to STAR$_R$ scores to reflect the slower and lower success rate in delivering benefits to species from restored habitat compared with conserved existing habitat[14]. Again, $STAR_R$ scores can be disaggregated by threat, and summed across species within the location.

STAR is intended to provide a metric to underpin the establishment of science-based targets as explicit contributions from individual actors towards the post-2020 biodiversity framework, by allowing assessment of actions and locations according to their potential ability to deliver towards international conservation targets. Individual spatially-based $STAR_T$ and $STAR_R$ scores, for all species present in a particular location or country, represent a proportion of the global opportunity to reduce species' extinction risk through threat abatement and restoration respectively. For each species, the total $STAR_T$ score could be achieved by the complete abatement of all threats in remaining habitat, or an equivalent value of the STAR metric can be achieved by a combination of threat abatement in remaining habitat and restoration of lost habitat (with concomitant threat abatement therein). The metric can support establishment of science-based targets by a range of actors across spatial scales. By enabling governments and non-state actors to quantify their potential contributions, STAR, along with other tools, could facilitate achievement of global policy goals, notably the species component of the Sustainable Development Goals and the expected post-2020 Global Biodiversity Framework.

STAR uses existing publicly available datasets: species' extinction risk categories and threats available from the IUCN Red List[6] (or, for country endemics not yet assessed globally, from national red lists), and species' area of habitat estimated using species' ranges, habitat associations, and elevation limits, along with digital elevation models and current and historical land cover maps (here, we used back-cast land cover maps of the distribution of habitat pre-human impact, as in[15]). To demonstrate the utility of STAR, we calculated global STAR scores for those groups of terrestrial vertebrate species that are comprehensively assessed on the IUCN Red List, i.e. threatened and Near Threatened species of amphibians, birds and mammals globally (n=5,359).

Potential to reduce species extinction risk

Globally, the greatest contribution that could be made to reduce the extinction risk of these groups is tackling threats from annual and perennial non-timber crop production, which account for 24.5% of the global $STAR_T$ score (Figure 1). A further 16.4% is contributed by logging and wood harvesting. There are likely to be specific targets for reducing agriculture and forestry threats in the post-2020 framework[3] and applying STAR quantifies the large potential contribution that mitigating these threats could make to the goal for species conservation. Appropriate activities to deliver on such targets range along a continuum from land sharing through to land sparing[16].

STAR can be used in combination with existing policy and planning tools to quantify the potential contribution of action targets towards species conservation outcomes. The proposed post-2020 framework includes an action target for the protection of sites of particular importance to biodiversity[3]. Key Biodiversity Areas[11], which include Important Bird & Biodiversity Areas[17] and Alliance for Zero Extinction sites[18], correspond to such sites. Key Biodiversity Areas so far cover 8.8% of the terrestrial surface (www.keybiodiversityareas.org; identification is ongoing), but already capture 47% of the global $STAR_T$ score for the vertebrate groups analysed. They represent large proportions of some national $STAR_T$ scores: >70% in Mexico and Venezuela, and >50% in Madagascar, Ecuador, the Philippines and Tanzania.

$STAR_T$ scores can also support target-setting at national and sub-national scales to help meet international policy goals. The control and eradication of invasive species forms one of the CBD's proposed post-2020 action targets[3]. New Zealand has already set a "Predator Free 2050" goal that aims to eradicate three invasive mammal species by 2050. New Zealand contributes 0.8% to the global $STAR_T$ score for the three vertebrate groups included in this study. Achieving the Predator Free 2050 goal would contribute 30% of the total $STAR_T$ score for New Zealand, amounting to 0.2% of the global $STAR_T$ score.

All countries contribute towards the global STAR$_T$ score, but scores are highly skewed, with a few countries having high STAR$_T$ scores and most having low scores for the vertebrate groups analysed (Figure 2a; Extended Data 1). The highest scoring countries are located in biodiverse regions with many threatened endemic species[19]: Indonesia contributes 7.1% of the global STAR$_T$ score, Colombia 7.0%, Mexico 6.1% Madagascar 6.0% and Brazil 5.2%. These top five countries contribute 31.3% of the global STAR$_T$ score. In contrast, the lowest scoring 88 countries together contribute only 1% of the global STAR$_T$ score. This does not imply that these low-scoring countries have negligible species conservation responsibilities: the global decline in even common species indicates that all countries must act to reverse the degradation of nature and restore the diversity and abundance of species and integrity of ecosystems[20] as well as preventing extinctions at a national scale. Moreover, most countries have a Red List Index[21], or an equivalent, quantifying their progress or failure in reducing global extinction risk of assessed species relative to their national responsibility for global species conservation; STAR provides a means to guide the reduction of extinction risk and so assist all countries in meeting national species conservation targets.

At the global level, we estimated that an equivalent to 55.9% of the global STAR$_T$ score for vertebrates could, theoretically, be achieved by restoring lost habitat within current range (Figure 1). Ecosystem restoration objectives have been identified in many national biodiversity strategies for the CBD, as well as in many countries' commitments under the Bonn Challenge, and as part of Nationally Determined Contributions under the United Nations Framework Convention on Climate Change (UNFCCC). The STAR metric has the potential to support restoration initiatives alongside species conservation targets by quantifying the potential benefit to particular species of restoring habitat in specific places[22] (Figure 2b). Restoration may be particularly important for some species, including those assessed under Red List sub-criteria D/D1 (with a very small population), or Bac (with a small range with severe fragmentation, plus extreme fluctuations). For species uniquely assessed under these criteria (2.8% of those included in this study), threat abatement alone is unlikely to eliminate extinction risk, and so might need to be complemented by restoration in order to achieve

Least Concern status (see Supplementary Discussion). Moreover, depending on habitat loss and threat type, restoration of habitat may be beneficial for a larger proportion of threatened species.

Application of STAR at the landscape scale

We tested the landscape-scale application of the STAR metric in the southern part of Bukit Tigapuluh landscape, in central Sumatra, Indonesia (Figure 3a). The Bukit Tigapuluh Sustainable Landscape and Livelihoods Project is a sustainable commercial rubber initiative. The study area (approximately 88,000 ha) includes a 5 km buffer, which is set aside to support local livelihoods, wildlife conservation areas and forest protection and restoration, and two ecosystem restoration areas, which form a conservation management zone that protects the Bukit Tigapuluh National Park from encroachment.

The total $STAR_T$ score for the study area represents 0.2% of the $STAR_T$ score for Sumatra, 0.04% of that for Indonesia and 0.003% of the global $STAR_T$. The major threats are from annual and perennial non-timber crops, logging and wood harvesting, and collecting terrestrial animals (Figure 3b). The proximate causes of these pressures in the project area are rubber cultivation, oil palm cultivation, industrial logging, subsistence wood cutting, and hunting. STAR analysis shows that areas with the greatest potential to contribute to species conservation through threat mitigation are in remaining natural habitat close to the National Park, with a small area of high potential also to the west, where the relatively small distribution of the Orbiculus leaf-nosed bat (*Hipposideros orbiculus*) overlaps the site (Figure 3A). Additionally, due to recent forest loss, 47% of the $STAR_T$ score for the study area could be achieved through habitat restoration (i.e. $STAR_R$). Investment in these management actions has the potential to deliver these quantified contributions to national and global biodiversity targets.

Operationalisation and future development

The STAR metric makes use of the best available data, producing results that are relevant to policy and practice. However, there is scope for future refinement as the underlying data improves. Here, the STAR metric covers amphibians, birds and mammals globally, constituting a well-studied but small proportion of taxonomic diversity (see Extended Data 2 and 3 for variation among taxa). STAR can be expanded to other taxonomic groups, including freshwater and marine species, as data become available (reptiles, cacti, cycads, conifers, freshwater fish and reef-building corals are among the groups imminently available for incorporation). Global application of STAR will require comprehensive assessment of taxonomic groups, testing of the transferability of the STAR metric assumptions among taxa as Red List coverage expands, and further development of methods to calculate area of habitat. Area of habitat calculation does not currently capture spatial variation in species' population density, which will be important for many species[23]; such data have not been gathered on a global scale yet and could be incorporated as available.

The completeness of threat data in the IUCN Red List is uneven but is continually improving. The STAR metric does not currently reflect spatial variation in threat magnitude within species' ranges; more broadly there is a lack of information on the spatial distribution of threats[24]. Most species included in this study have relatively small ranges; total current area of habitat is <5,000 km^2 for 55%, <1,000 km^2 for 33%, and within a single country for 66% (Extended Data 4). This prevalence of small ranges may reduce the significance of spatial variation in threats. Nevertheless, threats may vary spatially for any species not confined to a single location, and there is scope to use threat mapping to inform the likely spatial distribution of threats[24]. Application of STAR at the landscape or site level, for instance to set targets or identify management actions (e.g. Figure 3), will therefore require verification of the presence and distribution of threatened species (including restorable habitat), and assessment of the distribution and severity of threats. Such assessments should examine synergies among threats[25] and potential leakage in response to threat mitigation[26]; context-specific processes that cannot be accounted for in the global metric. At the global level, periodic recalibration of STAR scores based on updated Red List assessments will be necessary to account for the emergence of new threats[27] and the changing extinction risk of species[7,8] as well as the inclusion of additional groups not previously assessed. Where uncertainty cannot be reduced in a given application of STAR, sensitivity analyses (for example see Methods section below) can be used to explore and quantify uncertainty. For a summary of sources of uncertainty and approaches to quantify and reduce uncertainty in STAR calculations, see Supplementary Table 1 and Extended Data 5.

STAR alone does not identify conservation priorities, but could be harnessed alongside other data, for example on costs and benefits of conservation actions, to support conservation planning and prioritisation[12]. The STAR metric identifies what, in principle, needs to be done for species to achieve Least Concern status; however, the feasibility of abating threats will depend on the specific threat and context. Threats such as climate change or infectious disease cannot be reduced significantly through local action only. However, they may be mitigated through measures such as (for climate change) conservation translocations or increasing habitat connectivity to support distribution shifts[28]. Habitat restoration is a particularly important strategy to mitigate climate change impacts, and STAR quantifies the contribution of habitat restoration in combination with threat abatement to reducing species' extinction risk. Appropriate prioritisation[22] and local planning are needed to identify the spatial urgency, feasibility and expected benefit from restoration. Furthermore, while in principle complete delivery of $STAR_T$ would achieve downlisting to Least Concern for the great majority of species, the varying reasons for raised extinction risk reflected in different Red List criteria are – necessarily – not conveyed when creating a standardised index (see Supplementary Discussion). Moreover, delivery of $STAR_T$ does not equate to long-term species recovery. Other tools exist to support more ambitious goals, notably the IUCN Green Status of Species, which is complementary to STAR in its data inputs and requirements, scope and audience, and in that it assesses progress towards species' full recovery and ecological functionality[10]. Over time, the Green Status approach may also provide additional data that could enhance STAR, but the urgent need is to quantify how actions can contribute to achieving species goals using already available data.

Finally, countries with high $STAR_T$ scores face intense pressures on biodiversity, but these pressures often originate from beyond their borders. This is owing both to global-scale threats, such as climate change and infectious disease, and to market forces operating beyond national boundaries. Global-scale and transboundary threats cannot necessarily be addressed within habitats, but require concerted actions within and among countries, for example through national commitments to reduce greenhouse gas emissions, implementation of biosecurity measures to prevent the spread of invasive alien species, and enforcement of restrictions imposed by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). STAR scores can indicate the need for such actions, which then require implementation in a non-local context. International trade in commodities and services is an important and growing driver of biodiversity loss. Some countries with high consumption per capita (e.g. in Northern Europe) have relatively low in-country STAR$_T$ scores, suggesting that it is important to consider embodied (i.e. full lifecycle) as well as direct impacts for products and processes. For example, Germany contributes only 0.01% of the global STAR$_T$ score, but is the third biggest importer of biodiversity impacts through commodity supply chains[29]. There is therefore urgent need to advance supply chain analyses[29] in order to quantify and account for the biodiversity impacts driven by end-consumers.

Policy implications

STAR can be disaggregated to identify and quantify the opportunities for both countries and non-state actors to contribute their shares of action towards a global species conservation goal. In doing so, STAR can support a framework analogous to the UNFCCC’s 2015 Paris Agreement, which provided a new model for global environmental governance. Uptake of this model among non-state actors has been promising, with 476 companies[30] and 98 cities[31] (as of 5 October 2020) establishing science-based targets for greenhouse gas emissions reduction at the level necessary to deliver the Paris Agreement. Moreover, the approach will doubtless be applied to analyse whether the sum of Nationally Determined Commitments, set by individual countries, is indeed sufficient to hold climate change to 1.5–2°C[32]. STAR provides an equivalent metric to guide establishment of science-based targets for conserving species-level biodiversity. STAR will need to sit alongside equivalent metrics for ecosystems (e.g.[33]) and potentially also genetic diversity[34], consistent with the CBD's definition of biological diversity, in supporting the establishment of science-based targets in the post-2020 framework.

The application of STAR would have important implications for conservation and sustainable development. In terms of the post-2020 biodiversity framework, it could facilitate the establishment of targets to mitigate threats to the level necessary to halt and reverse biodiversity loss. Such an approach could be extended across the other biodiversity-related conventions, with, for example, the Ramsar Convention on Wetlands calibrating its global target as the $STAR_T$ score for wetland biodiversity. It could similarly be extended to inform delivery of the biodiversity-related targets of Sustainable Development Goals 14 (Life below water) and 15 (Life on land); aligned with the role of the Red List Index[7-9] as an official indicator. Finally, and perhaps most fundamentally, the approach provides a common metric for the conservation of threatened species that stands to incentivise voluntary contributions from actors beyond national governments: cities, states and provinces, the private sector, and indigenous and local communities. The increasing recognition of the importance of polycentric governance in addressing global environmental challenges[35] suggests that such broadening of contributions is not only desirable, but essential and urgent.

Methods

Data inputs

Calculation of the STAR metric requires information on species' extinction risk, threats, and current and restorable Area of Habitat[36] (AOH). Species' extinction risk categories and threat classification data were obtained for amphibians, birds and mammals from the IUCN Red List version 2019-3[6]. These taxonomic groups are comprehensively assessed on the IUCN Red List (meaning >80% of the taxonomic group assessed; recent taxonomic splits mean that 16% of amphibian species have been recently recognised and not yet assessed for the IUCN Red List) and range maps are available for nearly all species. Species assessed as Near Threatened and threatened (Vulnerable, Endangered and Critically Endangered) were included in the analysis. Least Concern species were not included, as threats are not coded for the majority of Least Concern species on the IUCN Red List. Data Deficient species were also excluded, as these are too poorly known to classify their extinction risk, and they often lack data on threats, habitats, elevation and/or distribution[6].

The IUCN/Conservation Measures Partnership Threat Classification Scheme is hierarchical[37,38], and threats to species are classified at the most detailed level possible. For each threat to each species, the scope (proportion of the global population impacted), severity (rate of decline driven by the threat within its scope) and timing (past, ongoing, or future) of the threat are coded as part of the Red List assessments. Threats that were recorded as "past and unlikely to return" were excluded from the analysis. Threats that were not expected to cause a population decline were also excluded; these were threats with a severity scored as "no decline", and threats with a combination of severity scored as "negligible decline" and scope scored as either the minority or majority of the species' distribution (see explanation in *STAR calculation* below and Supplementary Table 2). Consequently, any species recorded as suffering only from threats that were not expected to cause a population decline were excluded from the analysis.

The extent of current and restorable Area of Habitat[36] (AOH) for species was determined using 5 km resolution species' AOH rasters. We calculated species current AOH following[15]. We used the European Space Agency "Climate Change Initiative" (ESA CCI) land use and cover maps[39] from 2015, with 300 x 300 m pixel size. The ESA CCI original 37 land cover classes were reclassified into ten major classes (forests, wetlands, arid ecosystems, natural grasslands, shrublands, croplands, cultivated grasslands, rock and ice, and urban areas), and then matched to the habitat classes from IUCN Red List assessments. Species' range maps[6,40] were then overlaid with land cover and digital elevation maps to map the area of habitat within each species' range, constrained by the species' elevation range (from the IUCN Red List). Species' range map polygons are coded for presence and origin[41]; we excluded from current AOH parts of species' ranges where the species' presence was recorded as Extinct, Possibly Extant or Presence Uncertain, leaving only parts recorded as Extant, Probably Extant (a category that is being phased out) and Possibly Extinct. We also excluded parts of each species' range where the species' origin was recorded as Introduced, Vagrant or Origin Uncertain, thus leaving only parts recorded as Native, Reintroduced or present through Assisted Colonisation.

Original area of habitat represented the extent of original ecosystem types before human impact (i.e. the land cover before conversion to croplands, pasturelands or urban areas; following[15]). ESA CCI land use and cover maps from 1992 were used to inform back-casting of the extent of original ecosystem types. Species range maps were then overlaid with this back-cast land cover and with digital elevation maps to map the original area of habitat within each species range. For the purposes of this analysis, the extent of species original AOH was constrained to within individual species' range maps according to the IUCN Red List; these range maps largely reflect current range limits due to a lack of consistent information across all species on their historical, recently extirpated range. As with current AOH, we included in original AOH only parts of each species' range where the species' origin was recorded as Native, Reintroduced or present through Assisted Colonisation according to the origin coding of the IUCN Red List assessments[41]. We also excluded parts of each species' range where the species' presence was recorded as Possibly Extant or Presence Uncertain. However, for original AOH, we additionally included parts of species' ranges where the species was recorded as Extinct, for all species for which this information was available. Species restorable AOH was then calculated as the difference between original and current AOH. A total of 5,359 species (2,055 amphibians, 1,957 birds and 1,347 mammals) were included in the analysis based on the availability of the necessary data.

STAR calculation

To calculate STAR values, we used data on the extent of species' current AOH and restorable AOH, extinction risk (IUCN Red List category) and the relative contribution of each threat to the species' extinction risk. The STAR metric is calculated for all Near Threatened and threatened species present at a location. 'Location' in this context represents any spatially defined area; the maximum size is the entire area of the globe, while the minimum practical size is determined by the spatial resolution of habitat maps available for species. The STAR threat-abatement score (T) for a location (i) and threat (t) is calculated among all species as:

$$T_{t,i} = \sum_{s}^{N_s} P_{s,i} W_s C_{s,t}$$

where $P_{s,i}$ is the current Area of Habitat[36] (AOH) of each species (s) within location (i), expressed as a percentage of the global species' current AOH; W_s is the IUCN Red List category weight of species s (Near Threatened = 1, Vulnerable = 2, Endangered = 3 and Critically Endangered = 4[7,8]); C is the relative contribution of threat[38] t to the extinction risk of species s; and N_s is the total number of species at location (i). The relative contribution of each threat to the species' extinction risk was calculated as the percentage population decline from that threat (derived from the product of severity and scope for that threat in each species' IUCN Red List assessment as in[42]; see Supplementary Table 2) divided by the sum of percentage population declines from all threats to that species. Scores were calculated using the most detailed threat classification available and then aggregated to higher levels in the threat classification scheme by summing scores.

The STAR restoration score (R) for the potential contribution of habitat restoration (and threat abatement therein) at location i for threat t is calculated as:

$$R_{t,i} = \sum_{s}^{N_s} H_{s,i} W_s C_{s,t} M_{s,i}$$

where $H_{s,i}$ is the extent of restorable AOH for species s at location i, expressed as a percentage of the global species' current AOH, and M_i is a multiplier appropriate to the habitat at location i to discount restoration scores. Here, we use a global multiplier of 0.29 based on the median rate of recovery from a global meta-analysis[14] assuming that restoration has been underway for ten years (the period of the post-2020 outcome goals).

The STAR metric assumes that abating all current and plausible future threats in species' current AOH would stabilise species populations and distributions, such that they would be downlisted to Least Concern (with few exceptions: see Supplementary Discussion).

$STAR_T$ and $STAR_R$ scores were mapped at the 5 km grid cell resolution. For each species, the $STAR_T$ score per grid cell was calculated by multiplying each species' total $STAR_T$ score by the proportion of the species' current AOH in the grid cell. The $STAR_R$ score per grid cell was calculated by multiplying the species' total $STAR_R$ score by the proportion of species' restorable AOH present in the grid cell. Global maps of total $STAR_T$ and $STAR_R$ scores were produced by summing the respective score maps across all species. For presentation, maps were aggregated to the 50 km resolution by summing scores across cells.

We calculated $STAR_T$ scores for 196 regions (195 recognised countries, including their dependencies, plus Antarctica). The proportion of species' current AOH within each country was estimated by overlaying species' current AOH with polygons of national boundaries. The STAR calculation was then applied at the country level.

STAR$_T$ scores were calculated for Key Biodiversity Areas. The boundaries of Key Biodiversity Areas already formally identified were obtained from the World Database of Key Biodiversity Areas[43] on 13 January 2020. Polygon data were available for 15,782 sites. STAR$_T$ scores for terrestrial sites were calculated by overlaying the Key Biodiversity Area polygons onto the global 5 km grid cell resolution rasters of STAR$_T$ scores, which were generated as described above.

In order to relate STAR$_T$ scores to conservation policy in the example of New Zealand, we calculated STAR$_T$ scores per invasive species. Where species have been assessed as threatened by invasive non-native/alien species or diseases, the invasive threat has been documented at genus or species level in 85% of cases. In the case of New Zealand, the invasive threat was documented in 97% of cases, allowing the STAR$_T$ score for invasive species to be calculated at the level of the individual species.

Calculation of STAR$_T$ and STAR$_R$ scores for Bukit Tigapuluh landscape in Indonesia was carried out at a higher spatial resolution than for the global STAR analysis, in order to provide more detailed maps at the landscape scale. The Bukit Tigapuluh landscape is dominated by forest, and so only species associated with forest according to the IUCN Red List habitat classification scheme[44] were included. We used species distribution polygons[6,40] combined with Global Land Analysis and Discovery maps of forest cover change[45] at the 30 m resolution to calculate species' current AOH and restorable AOH at the location. Based on available forest change data, current AOH was calculated from forest cover in the year 2018, while restorable AOH was forest lost since 2000. Species AOH was clipped to species' elevation limitations using species' elevation data from the IUCN Red List combined with a digital elevation map[46]. Thus, species' current and restorable AOH were calculated at 30 m resolution for the extent of the Bukit Tigapuluh landscape. Species' global AOH (at 5 km resolution, as described above) was then used to calculate the proportion that species' current and restorable AOH at the location represented of the species global current AOH.

All data processing and analyses were carried out using the software R[47].

Sensitivity analyses to inform STAR development

The sensitivity of $STAR_T$ scores to variation in the metric's various components was explored in order to inform the development of the metric. All sensitivity analyses were carried out using data on birds, due to the completeness of their Red List assessment data (see Supplementary Methods for detailed methods).

Threat scope and severity data are largely complete for birds but missing for the majority of amphibian and mammal species; this information is recommended but not required documentation for Red List assessments, so is not consistently documented. Approaches to dealing with missing scope and severity data were explored (see Supplementary Methods and Extended Data 6) and it was concluded that using the median of possible values of scope and severity to replace missing data was a suitable approach (see also Supplementary Discussion).

The effect of applying equal steps weighting, log steps weighting and no weighting to species Red List categories was investigated (Extended Data 7a-b). Equal steps weighting was selected, rather than relative extinction risk weights, for the same reasons as articulated for the Red List Index[7,48], as relative extinction risk (log step) weights would make $STAR_T$ values overwhelmingly dominated by threats to Critically Endangered species, whereas the 'equal steps' weights lead to $STAR_T$ scores representing opportunities to improve the extinction risk of a much wider set of threatened and Near Threatened species. Importantly, equal steps align the weighting of species in STAR metric to the weighting of species in the well-established RLI.

The effect of giving greater weight to larger proportions of species' current AOH per location and lower weight to smaller proportions of species current AOH per location[49] was explored (Extended Data 7c), with a view to reflecting the role of habitat configuration in species' persistence. However, this was not adopted, in order to maintain the scalability and additivity of the metric.

The percentage population decline expected to be caused by a particular threat was the median value from within the range of expected percentage population declines for the particular combination of scope and severity scores (which represent bands of possible values). The effect of varying the expected percentage population decline within this range for each combination of scope and severity scores was explored, and the metric was found to be robust to this variation (Extended Data 8).

Data availability statement

Species' extinction risk category, threat data, elevation limitations, habitat associations and distribution polygons are publicly available under specified Terms and Conditions of Use from the IUCN Red List website[6]. KBA boundaries are available from the World Database of Key Biodiversity Areas[43], again under specified Terms and Conditions of Use. The European Space Agency "Climate Change Initiative" (ESA CCI) land use and cover maps are available at www.esa-landcover-cci.org[39]. Forest cover change maps are available from https://glad.umd.edu[45]. Digital elevation maps are available from https://earthexplorer.usgs.gov[46]. Global STAR threat-abatement and restoration scores for amphibians, birds and mammals at 50 km grid cell resolution are available in TIFF file format as Supplementary Data 1 and 2.

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Author contributions

LM led on analysis, development and manuscript drafting. LAB, TMB, SHMB, FH and PJKM led on design and development, and made substantial contributions to manuscript preparation. FCB, NDB, JMME, EJM-G, MH, KM, NBWM, DCR, ASLR, XS and BBNS contributed substantially to conceptual development and manuscript preparation. CRB, CG-C, AI, MI, EL, BCM, KP and MFT contributed to conceptual development and data acquisition and analysis. ELB, CB, GC, AC, ME, GABdF, RGalt, AG, LG, RGoedicke, JMHG, RDG, SLLH, DGH, JHughes, JHutton, MPWK, LMN, ENL, AJP, PP, HPP, AR, ECR, CR, JDS, JSiikamäki, CS, GS, SS, ALS, CAS-N, SNS, HJT, AV, FV, LRV and JW contributed to the conceptual development of the work. SB, MB, IJB, VC, CC, NAC, JF, LRG, CH-T, RJ, AJ, LNJ, LPK, TELJ, PFL, BL, DM, MP, BAP, CMP, MCR, NSR, JPR, JSmart and BEY contributed to the acquisition of data. FH & PJKM contributed equally to conception and coordination.

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Competing Interests Statement

The authors declare the following competing interests: E.C. Regan works for Springer Nature, the publishers of Nature Ecology & Evolution.

Supplementary Information

Supplementary Information is available for this paper.

Figures

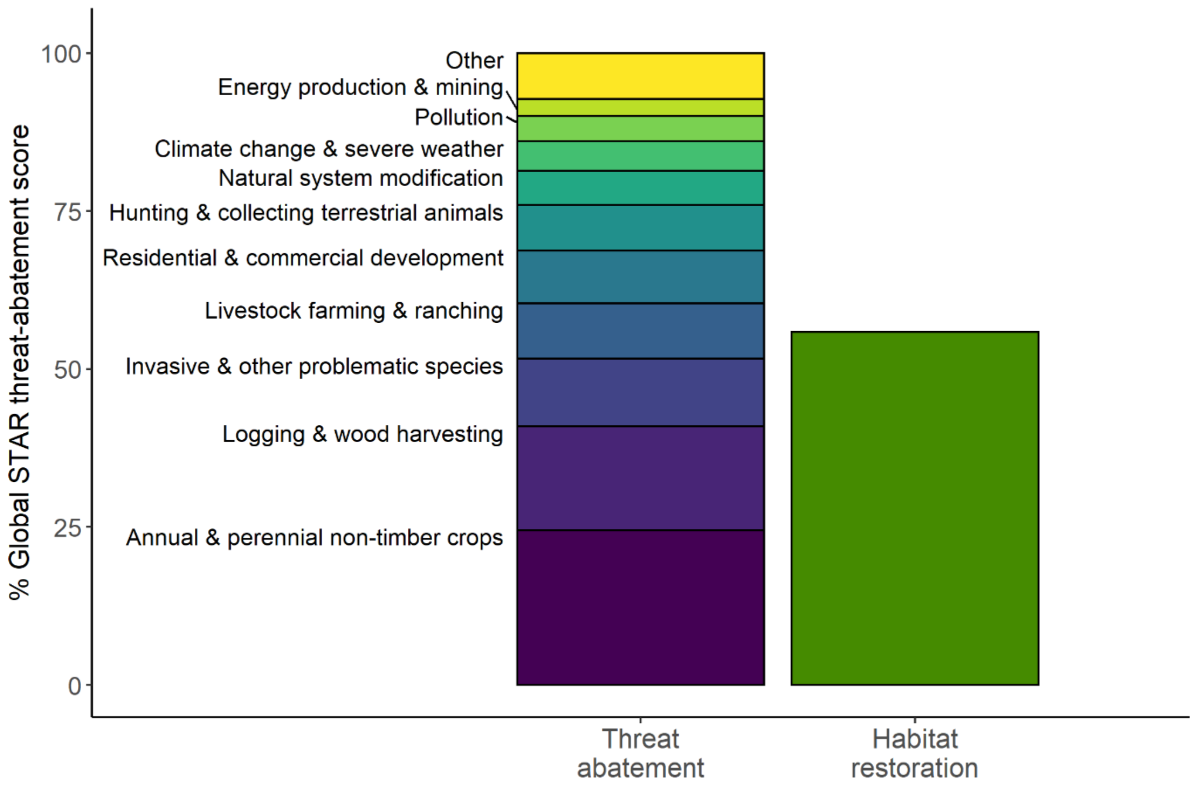

Figure 1. The contribution to the global STAR threat-abatement score of different threats and the potential contribution of habitat restoration. The total global STAR threat-abatement score represents the global threat abatement effort needed for all Near Threatened and threatened (Vulnerable, Endangered and Critically Endangered according to the IUCN Red List) amphibian, bird and mammal species to be reclassified as Least Concern. This score can be disaggregated by threat type, based on the known contribution of each threat to species' risk of extinction. The STAR restoration score quantifies the potential contribution that habitat restoration activities could make to reducing overall species' extinction risk. The total STAR threat-abatement score thus could be achieved by the complete abatement of all threats in existing natural habitat, or through a combination of threat abatement in existing habitat and restoration of lost habitat (with concomitant threat abatement therein).

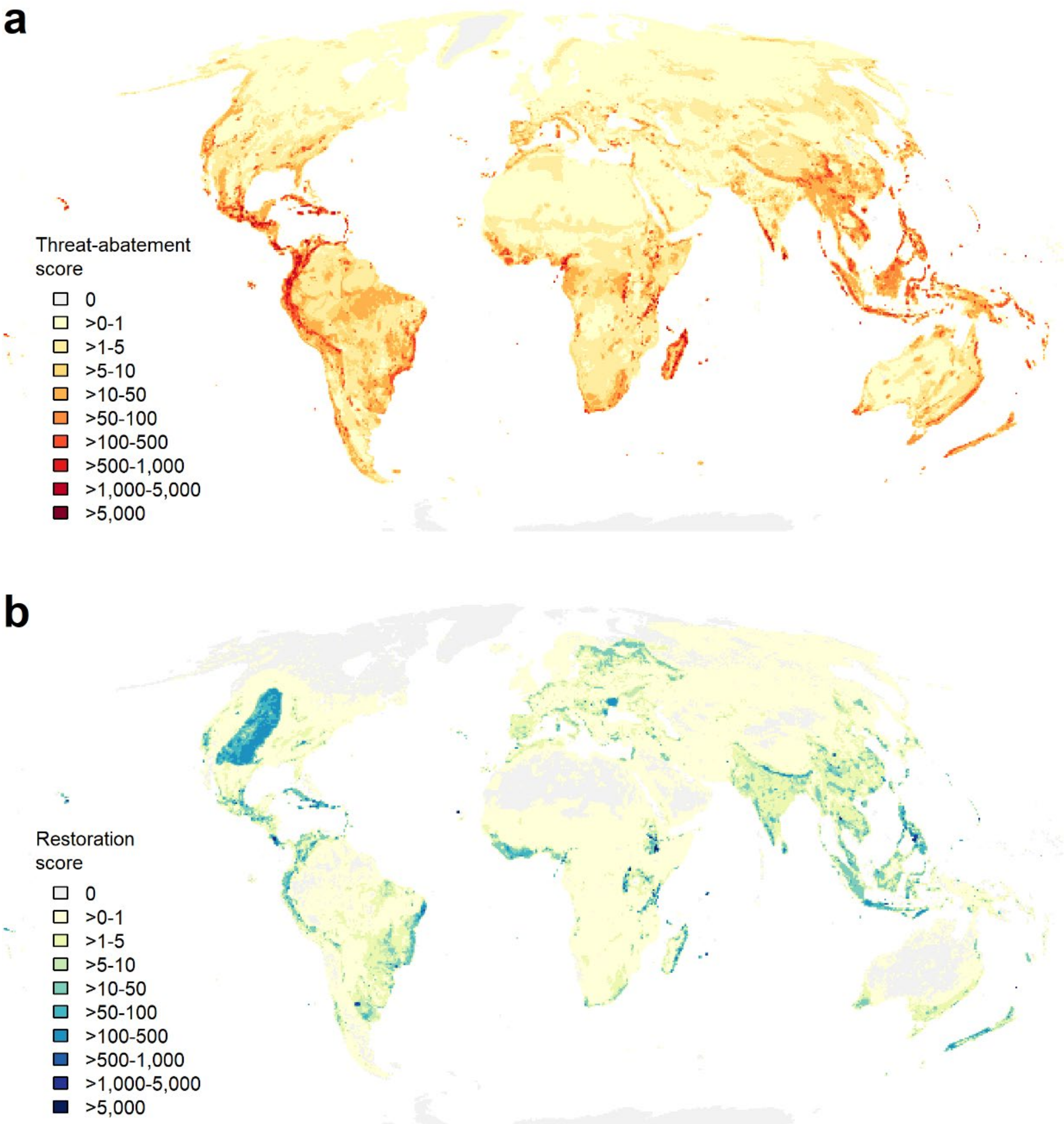

Figure 2. Global STAR scores for amphibians, birds and mammals at a 50-km grid cell resolution for (a) STAR threat-abatement scores and (b) STAR restoration scores. Each species has a global STAR threat-abatement score weighted relative to their extinction risk. This global STAR threat-abatement score can be disaggregated spatially, based on the area of habitat currently available for each species in a particular location. The total STAR threat-abatement score per grid cell (a) is thus the sum of the individual species' STAR threat-abatement scores per grid cell across all Near Threatened and threatened species of amphibians, birds and mammals included in this study. The global STAR restoration score per species reflects the potential contribution that habitat restoration activities could make to reducing species' extinction risk, and is spatially disaggregated based on the

availability of restorable habitat. Thus, the total STAR restoration score per grid cell (b) is the sum of the individual species’ STAR restoration scores per grid cell across all species included in this study.

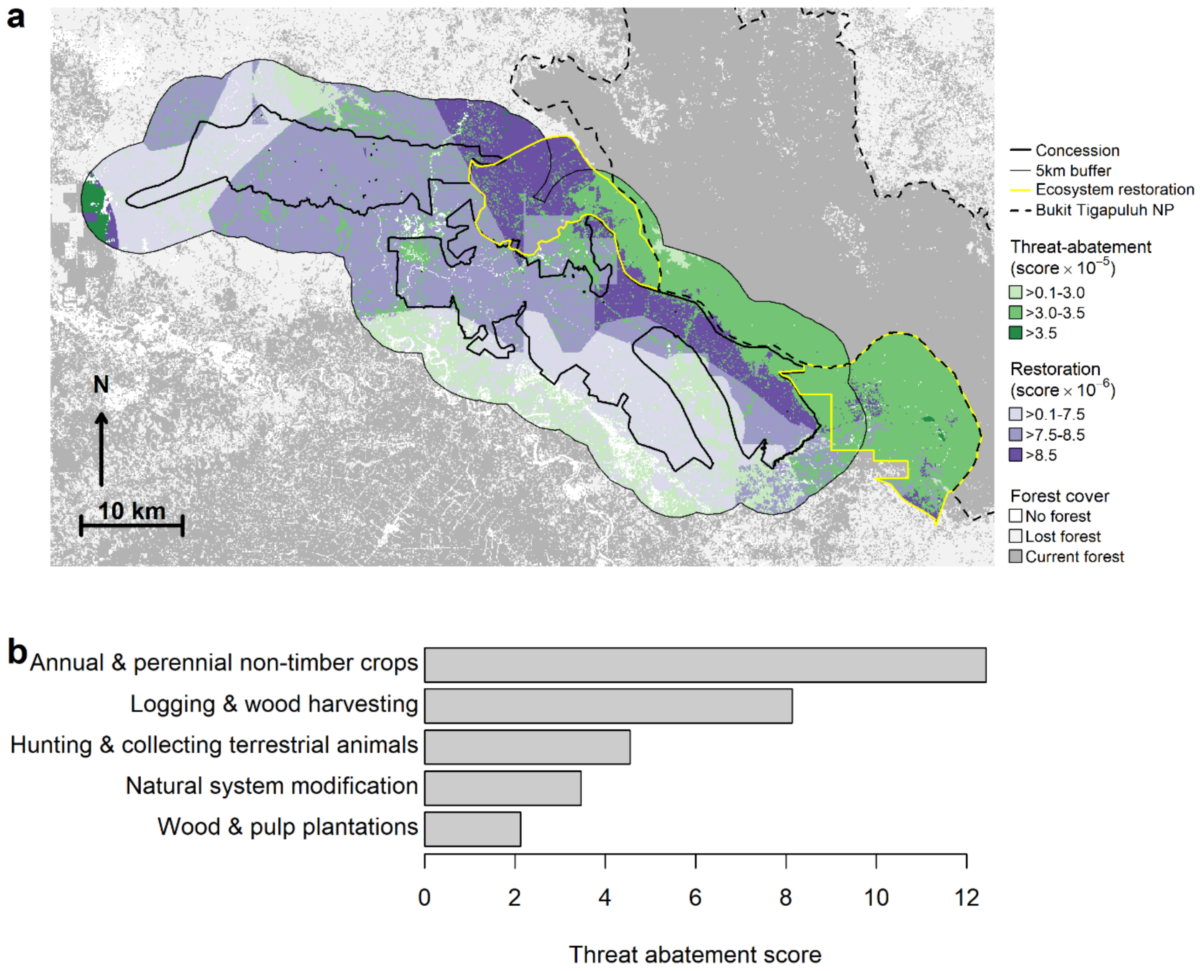

Figure 3. STAR results for the Bukit Tigapuluh Sustainable Landscape and Livelihoods Project. The Bukit Tigapuluh Sustainable Landscape and Livelihoods Project is a sustainable commercial rubber initiative. The study area (approximately 88,000 ha) includes a 5 km buffer, which is set aside to support local livelihoods, wildlife conservation areas and forest protection and restoration, and two ecosystem restoration areas, which form a conservation management zone that protects the Bukit Tigapuluh National Park from encroachment. STAR results are shown for: **(a)** mapped STAR threat-abatement scores in areas with remaining forest (green) and restoration scores in areas where forest has been lost (purple) at the 30 m grid cell resolution; and **(b)** total STAR threat-abatement scores per threat for the top five highest scoring threats across the study area (the concession, 5 km buffer, and ecosystem restoration areas combined).