Targeting conservation actions at species threat response thresholds

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Abstract

Given the failure of the world's governments to improve the status of biodiversity by 2020, a new strategic plan for 2030 is being developed. In order to be successful a step-change is needed to not just simply halt biodiversity loss, but to bend the curve of biodiversity loss to stable or increasing species' populations. Here, we propose a framework that quantifies species' responses across gradients of threat intensity to implement more efficient and better targeted conservation actions. Our framework acknowledges the variation in threat intensities as well as the differences among species in their capacity to respond, and is implemented at a relevant scale for national and international policy-making.

Bending the curve of biodiversity loss

Wildlife and wild places face a variety of environmental and human-induced challenges that threaten species survival [1]. Species' extinction rates now vastly exceed background rates, with earth's biodiversity perhaps entering a 'sixth mass extinction' event [2–4]. Vertebrate populations, where measured, declined by ~60% between 1970 and 2014 [5], with at least 338 terrestrial vertebrate species having become extinct since 1500 [2]. The world's governments have committed to reducing biodiversity loss by 2020. The 196 countries that are Parties of the Convention on Biological Diversity (CBD) agreed to ambitious Aichi Biodiversity Targets but despite increased efforts, the Aichi targets are unlikely to be achieved [6,7]. In the wake of these failings, Parties to the CBD are developing a post-2020 strategic plan for the actions required to improve the state of biodiversity by 2030.

If the post-2020 strategic plan is to be successful, actions to 'bend the curve' of biodiversity loss are needed in addition to robust indicators to track the status of biodiversity [5]. Recently, Mace et al. (2018) suggested three metrics that could be used to track progress, consistent with existing commitments from the world's governments [8]. Specifically, (1) Species' threat status (estimated from the Red List Index); (2) Trends in wildlife abundance (e.g. using the Living Planet Index, LPI) and; (3) Changes in local biotic integrity. The LPI, an aggregated index of population-level abundance time-series, has shown a persistent decline since 1970 [5], and global models of local biotic integrity show that across most of the terrestrial land area, both richness and abundance are greatly reduced [9] and are often below the level proposed as a planetary boundary [10]. All current trends are, at best, slow declines, yet achieving global targets requires that the trajectory is reversed, to show a recovery in population abundance across species and sites. This radical change in biodiversity outcomes cannot be achieved with only marginal improvements in species' trends; it will need a step-change from past practices that mostly aim to simply limit further decline. Instead, conservation actions that stimulate higher population growth rates and species' recovery are urgently needed.

There is ample evidence that conservation works when the right policies are in place, and there is generally adequate knowledge about species' ecology and the factors driving declines (e.g. [11]). Detailed, species specific analyses are undoubtedly necessary to plan for recovery for the most critically endangered species (e.g. vaquita *Phocoena sinus;* [12]) and population viability analysis can be used to highlight critical threats and threat intensities for groups of related species [13]. However, such approaches are not feasible across the >30,000 threatened species [14] now requiring conservation intervention. Even when threats are largely place-based and conservation is best addressed at landscape scales, a species-by-species approach is not practical. On the other hand, large-scale efforts at mapping threats and vulnerable species (e.g. [15,16]), whilst useful for prioritising conservation interventions to particular sites and taxa, lack the precision and specificity of actions needed to direct conservation in the most effective way [17]. The challenge is therefore to identify a strategy that will allow threat-response relationships to be characterised across taxa sharing threats and vulnerabilities, and at spatial scales that are relevant for conservation planning and intervention.

Here, we propose a framework that focusses on targeted conservation solutions that quantify taxon responses to threats (e.g., exploitation, land-use change, pollution) of different intensities in defined ecological units (see Text Box 1 for the threat classification scheme and definitions of terms used throughout). We suggest that such a framework will provide a level of resolution that can substantially improve the effectiveness of conservation interventions, and make bending the biodiversity curve achievable.

Gradients of threat intensity and population responses

Conservation efforts could be more efficient if directed at relevant threats and threat intensities affecting population abundance of focal species. Ninety-five percent of the Earth's land surface is now modified to some degree by humans [18], which is likely to increase given the projected growth in human populations [19] and increasing accessibility to the remaining wilderness areas [20,21]. The spatial distribution and intensity of threats is not uniform or static, and some land uses and human activities are more detrimental to species than others. Substantial efforts have gone into identifying and mapping the distribution or magnitude of threats globally and the interaction of threats with species [17,22], as well as in ranking threats in terms of their overall importance across species [7]. Different taxa are exposed to different threats in the same location, and population-level responses and thresholds to the same threat intensity vary between species for biological reasons. Hence, once threat-response relationships have been elucidated, they could be used efficiently to track threat intensities, and to design conservation interventions to reduce the intensity of the threat mechanism below a critical level, and always below the level causing a population decline.

Evidence for differences in species' responses attributable to the intensity of threat mechanism is growing. Many studies have compared abundances in control-versus-impact scenarios, e.g. hunted-unhunted or converted-intact habitats [23,24], showing that the direction and magnitude of changes in abundance differ by taxa. For some threat mechanisms and intensities, these differences have been characterised across gradients using meta-analytical frameworks. For example, evidence suggests that species' abundance and diversity measures are lower in the highest intensities within different agricultural and urban land-use categories and intensities [9,25]. In the hunting literature, much of the work on sustainable harvesting quotas is already based on harvest intensity and population size relationships, and often distance to village is used as a proxy measure for hunting pressure across a gradient. By collating and analysing studies across the tropics, the responses and thresholds of species to hunting intensity were shown to vary by body mass and feeding guild [26]. These meta-analyses use space-for-time substitution whereby comparable differences across otherwise similar sites are assumed to represent a change from one state to the other over time. However, their application and interpretation have been criticised for not adequately acknowledging that ecological processes occur over time and that ecological response times can lag behind the changing intensity of threat [27]. Furthermore, binary or ordinal categorisations of threats are also problematic as the intensity of the threat is not adequately accounted for, and thus species' responses to different threat intensities remain poorly estimated. Given these challenges and clear evidence of varied species' responses, a new framework for efficiently targeting conservation interventions is needed.

The taxa-biome-threat (TBT) framework, and what to measure

To aid large-scale policy decisions and conservation management, any framework to capture biodiversity responses across intensity gradients needs to 1) work at a scale that is relevant for policy and practical for research, 2) accurately reflect the most important local threats at that scale, and 3) allow for robust study designs that are sensitive to the habitat specificity of different taxa. Here, we outline a framework to quantify species' response thresholds across gradients of threat intensity based on a classification of threat by regionally-separated biomes by major taxa (Taxa-Biome-Threat, TBT framework) that differentiates the importance of threats for particular species, and hence helps direct conservation actions effectively (Figure 1). In the following paragraphs, we outline each aspect of the framework, and provide evidence of the validity of their inclusion.

Distribution of threats and the spatial unit of the framework

There are consistent relationships between species' declines, threat mechanisms, and closely related taxa or those sharing similar biological traits. While the drivers and sources of threats tend to be spatially clustered following patterns of human population, development, and movement [28–31], the responses of individual species to particular threat mechanisms are often a function of their biological traits (e.g. hunting [32]). Related species, often with similar life-history traits, can also be spatially clustered by region and habitat type [33–35]. The contribution of threatening mechanism and traits to changes in extinction risk show consistent patterns at least in the mammals where they have been most systematically studied [36]. Threat mechanisms interact with pressures and species' biology, so species' traits may be good predictors of species' declines [31,37–39]. While species' traits may only change very slowly over time (if at all), threats and their intensities do change, and it is becoming increasingly feasible to spatially and temporally track some threats using cartographic, remote sensing, and terrestrial sensing technologies [40]. Existing approaches to quantify habitat or species' responses to threatening processes exist in isolation or are at scales that are not always practical for policy– either too broad to show relevant trends or too localised to show general trends or to get global coverage in a reasonable amount of time. The challenge is therefore to identify a scale at which to divide the world into meaningful units that will capture both threats and habitats that are relevant to species at a scale that might be possible to inform management.

Threat mechanisms and intensities are not uniformly distributed across the world, varying by realm and by geographic region [18,41], and threats can operate at different scales [42], thus the predominant threats that species experience vary, even within the same habitat type. The ecological communities in a given area also vary across space, and are driven by biogeography and evolutionary history [43]. Ecoregions have been shown to be meaningful delineators of biodiversity patterns [44], but at the global level they are often too small and too numerous for analysis or useful policy advice (n = 867 terrestrial, 232 marine and 426 freshwater ecoregions). Biomes on the other hand, regions of the world defined by their climate, fauna and flora (n = 14, [45]), could be a more relevant unit, because they tend to provide a broad grouping of major vegetation types, as well as major phylogenetic groups of species that are found there. Biomes therefore reflect both large scale threats (e.g. deforestation in forests or overfishing in the oceans) and broadly represent key species' traits. Newbold and colleagues recently showed that biodiversity responses to climate and land-use change differ among biomes, highlighting that a regionalised approach is likely to improve the way we understand and mitigate the effects of anthropogenic pressure [46]. However, the presence of threats, and the direction and magnitude of biodiversity change differs according to both biome and region [41,47]. Existing literature on taxonomic, vegetation, and habitat classification suggests that a combination of broad-scale habitat classification combined with a classification of biogeographic realms is a plausible framework for conservation priority-setting and planning [48–51]. Moreover, the way that biomes are impacted by threats and the way in which the species within biomes respond to threats are likely to be different (e.g. [52]); for example, a recent study showed that species respond to increasing climatic extremes in a biome-specific manner [53]. Therefore, we propose the use of regional biomes defined by biogeographic realms (Figure 1, panel 1; Figure 2 for regional split of terrestrial [n = 66], freshwater [51], and marine coastal biomes [24]) as the largest spatial unit within which threat-response relationships can be usefully characterised. These regional biomes will also be more relevant to regional policy and management, e.g. the Central African Forests Commission (COMIFAC) for Afrotropical moist broadleaf forests. The TBT framework could potentially be applied at the ecoregions level, if useful for national level reporting required by the CBD but this will require significantly more effort given the number of ecoregions identified.

Monitoring taxa response thresholds

Within each regional biome, primary threats and biome-specific threat-sensitive species should be identified, and monitored across the relevant threat intensity gradient using methods appropriate to the taxa of interest (Figure 1, panels 2-5). Given that funding for conservation is limited, the selection of target taxa may need to take into account cost-effectiveness of implementing the framework and prioritise species groups that are more likely to be high-performance indicators of the threat investigated ([54]). Additionally, recent developments in remote sensing and artificial intelligence (e.g. [55–57]) have the potential to allow a substantial increase in the scale of biodiversity monitoring initiatives without a similar increase in costs. Monitoring could be targeted to certain groups of threat-sensitive surrogate or umbrella species that represent the integrity of the biome, and the diverse needs of keystone, threatened, and/or conservation priority species. Systematic trait-based species selection methods have been shown to be promising to select such surrogate species, and in identifying the number needed per habitat type [58], but must first be validated appropriately [59].

Given that species' population abundance responses across threat-intensity gradients are likely to be dynamic and non-linear, monitoring wildlife across gradients would allow conservation actions to be targeted at threat intensities where species should respond to action and lead to recovery. Importantly, the TBT framework could also be used to monitor the effectiveness of conservation interventions (e.g. [60,61]). However, this requires knowledge of the 'thresholds' that pertain in each case. Identifying species' thresholds to threat intensity could then inform management decisions (Figure 1, panels 6-7); for example, retaining a certain proportion of forest cover to maintain species abundance and diversity [62,63]. We propose that species' population abundance, or proxies of abundance (such as relative abundance, occupancy), are practical and relevant metrics for tracking species' responses, which can be used as an indicator of conservation success with stable or increasing populations as the conservation target [5,8]. We recognise the limitations of using abundance proxies (e.g. [64]), however they are reliable when derived from well-designed surveys and appropriate statistical methods, and for some taxonomic groups and field settings will be the only metrics feasible to obtain [65]. Criteria such as 1) more than one metric should be tested to assess sensitivity across a threat intensity gradient, and 2) that management priority be given to taxa with the threshold at the lowest intensity could be followed [66]. However, it is possible that there will be a range of responses to the threat gradient, which can lead to multiple thresholds being identified. In these cases, statistical methods could be used to group species' responses into homogenous classes, allowing the identification of a small number of thresholds relevant to the studied system (e.g. [67]). Alternatively, thresholds could be estimated by aggregating data across species based on *a priori* expectations about their response to threat, potentially informed by natural history traits (e.g. [68]). Although these approaches would not provide a single threshold value for the ecosystem, they would inform which groups of species are more likely to be lost as threat intensity increases and this information could be included in the decision-making process.

Evidence from field studies of species' abundance thresholds along threat intensity gradients, or intensities after which responses in abundance are most acute, are available for only a few species, threats, and biomes (examples in Table 1); more research is therefore needed to quantify species' responses. To expand on these studies, and be able to target conservation actions for the major threats to wildlife in each biome, further evidence is required for each combination of major threat and regional biome, and where possible taking into account cumulative or synergistic effects of other major threats (see Outstanding Questions). Although in many areas there is a dominant threat type (e.g. [69]), the framework could account for other threats through either: 1) directly accounting for cumulative threat gradients by evaluating additive and interactive relationships among threats [70], 2) a grid design of two threat gradients (e.g. hunting x deforestation), 3) selection of a site where the intensity of one threat type is static (e,g, [71]), or 4) if climate change is also a significant threat, then environmental dependencies can be accounted for in the analysis. Such studies should also be conducted over multiple years to account for lag effects, and to go beyond space-for-time substitution analyses. To apply this framework at the policy level, the results from these studies could be aggregated to identify the most appropriate management options to reduce threats to pre-threshold limits.

Concluding remarks

Our proposed TBT framework provides an efficient basis to plan and implement conservation actions. A systematic effort to synthesise available empirical evidence of species' response thresholds to threat intensity is likely to reveal useful generalisations to move ahead. A number of challenges to this approach remain, for example some taxa may not exhibit an obvious threshold across a gradient of threat intensity (e.g. [53,72]), and responses may be confounded by cascading effects caused by changes in abundance of other species. Species' responses could also exhibit a 'lag time' depending on the life history traits and resilience of the species, and threat mechanism [73,74]. Understanding lag times is important to manage threats or target conservation actions e.g. recovery programmes, and can be studied best by monitoring species' populations over time. Designing and conducting studies to estimate thresholds has been argued to be too challenging for practical application due to the level of resources needed, complexities of nonlinear dynamics, and difficulties in controlling for multiple factors over space and time [75–77]. Identifying and monitoring a selection of threat-sensitive indicator species to represent each regional biome could be one practical approach. We believe these challenges can be overcome, and as with most experimental designs, potential confounding variables should be measured and taken into account using appropriate modelling methods and study designs which should ideally include suitable controls, thus providing substantially more accurate estimates of biodiversity responses [78].

Quantifying taxa-biome-threat responses could be used to design more cost effective and predictive interventions. While many conservation interventions and global initiatives are focused around the fate of individual species or specific taxa, there is a growing trend to start measuring and monitoring the health of larger-scale areas such as biomes. We interpret biome health as being the viability of a suite of species that are characteristic of that biome, hence our framework could lead to well-founded methods for assessing conservation success at the regional biome scale. This framework also could be used to provide evidence for requirements to achieve national and international biodiversity targets, as well as assessment and prioritisation of conservation efforts. Whilst the funding needed might be substantial, elucidating the levels of threat intensity that species can withstand will enable cost-effective conservation across the many thousands of species requiring intervention, and hence improve the prospects of bending the curve of biodiversity loss.

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Text Box 1. Threat classification scheme

To provide clarity of meaning for specific terms used throughout, we follow Balmford et al.'s (2009) threat classification scheme [79], adapting it to include the intensity of the mechanism. The scheme starts with the underlying drivers that cause the threat, through to the unfavourable state of the target for conservation – the species population. Examples of threats include habitat destruction as a result of land-use change or pollution, and direct reduction of survival as a result of exploitation. Here, we use an example of wildlife hunting to describe the threat classification scheme.

Threat classification scheme (Balmford et al. 2009)	Example threat classification for hunting
Underlying **drivers** of a given threat.	Poverty, rapid human population growth, poor governance.
1st component of **threat**: the **source** of the threatening mechanism.	The need for food, presence of market for wildlife products.
2nd component of **threat**: threatening **mechanism** causing unfavourable state.	Hunting leading to overexploitation of the hunted population.
Unfavourable **state** of conservation target.	Negative population growth of a hunted population.

In addition, we refer to the **intensity** of the threat mechanism across a gradient from minimal to high intensity, over which species' **responses** may differ. In our hunting example, there is an intensity that is sustainable, however above a certain hunting intensity, hunting becomes unsustainable and leads to population decline. The intensity of the mechanism can be moderated by changes in **drivers** e.g. human population density, the **source**, or by changes in the **mechanisms** (more or less hunting).

Figure legends

Figure 1. Operationalising the Taxa-Biome-Threat framework, using Tropical and Subtropical Moist Broadleaf Forests in the Afrotropics as an example. 1. Identify the regional biome of interest. 2. identify the main threats to the regional biome e.g. by literature review, global threat maps based on cartographic or remotely sensing data, or local knowledge. In this example, overexploitation and deforestation were identified as the primary threats (e.g. [80,81]). 3. Identify the taxa relevant for the regional biome and sensitive to the threats being assessed e.g. based on conservation status, importance to biome (keystone), or role as surrogate species. 4. Measure threat intensity gradients directly e.g. for measuring exploitation, hunter offtakes can be monitored (e.g. [82]), or a proxy such as distance to village could be used [26]. 5. Conduct field survey along threat gradient using taxa appropriate methods over space, and ideally over time. E.g. for mammals >1kg, camera trapping is appropriate. Modelling could then directly account for cumulative threat gradients by evaluating additive and interactive relationships among them [70]. 6. Identify threshold levels at which to target conservation interventions. Letters (A, B, C) represent differential responses of species' abundances across a threat intensity gradient. We highlight the threshold response of species A (red dashed line), and the potential intensity at which a conservation intervention could be targeted to halt or reverse decline of species A (grey box). While recovery of species A would require reducing threat intensity to the threshold response, this would be inadequate for species B, and unnecessary for species C. Several methods to identify thresholds are available e.g. piece-wise regression (e.g. [83,84]), threshold occupancy models [85]. 7. If needed, further analyses could be conducted to estimate thresholds for groups of species (e.g. body size, trophic guild), or by response type [67].

Figure 2. Proposed regional biomes. Panel A: terrestrial biomes (n=14, from [45]). Panel B: freshwater biomes equivalent (Major Habitat Type, n = 12, from [86,87]. Panel C: marine biomes equivalents for coastal and shelf areas (Realms, n=12, from [48]). All panels are split by biogeographic realm (n = 8, black lines, [88,89]) to create 66 terrestrial, 51 freshwater, and 24 marine coastal regional biomes, excluding rock and ice. Colours differentiate biomes on each panel.

Tables

Table 1. Response profile across gradients of threat intensity varies by taxa and biome. Example studies show threshold responses of measured population abundance metrics.

Threat Metric	Biome	Taxon	Response Metric	Response / Threshold	Reference
Fishing	Coral reef	111 species of predatory fish, and starfish.	Density (population / reef length)	Grouped decline above ~5 people km^{-1} reef for predatory fish. Starfish increased linearly.	[90]
Fishing	Coral reef	Tetradontiformes, Angelfish, Butterflyfish, Soldierfish	Mean number per reef census	Decline in Tetradontiformes above ~1 fisher/km reef, and after 2 fishers/km reef for Angelfish and Butterflyfish	[91]
Habitat loss by oil palm	Tropical Moist Broadleaf Forest	15 species of mammal	Composition (aggregate of occurrence and relative abundance)	Decline above 45-75% of oil palm cover depending on species. Thresholds for 12/15 species. Threshold responses to increase oil palm cover were both negative (9 species) and positive (1). Five species showed no threshold in response, but 2 had a negative relationship.	[84]
Habitat loss	Tropical Moist Broadleaf Forest	1 species of mammal	Occupancy probability	Decline below 35% forest cover.	[63]
Habitat loss	Tropical Moist Broadleaf Forest	57 species of mammal, responses grouped by traits.	Relative abundance	Decline most acute between 100-50% forest cover for most species, but the relationship changed with land cover type.	[68]