Subnational assessment of threats to Indian biodiversity and habitat restoration opportunities

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Abstract

The active involvement of subnational authorities, cities and local governments has been identified as one of the enabling conditions to implement the Convention on Biological Diversity’s Post-2020 Global Biodiversity Framework and progress towards the United Nations’ Sustainable Development Goal 15 (Life on Land). However, there has not been any systematic application of any biodiversity metric at the subnational level to identify where the main responsibilities and opportunities lie within a country. Here, we therefore apply the recently proposed species threat abatement and restoration (STAR) metric for amphibians, birds and terrestrial mammals in 36 states and 666 districts of India, one of 17 megadiverse countries. The STAR metric takes into account the endemicity and the scope and severity of all threats affecting each species’ population hosted by the region and can quantify the potential contribution of threat mitigation and habitat restoration in a particular region towards global biodiversity goals. The larger the STAR metric score, the larger the contribution of a specified area for global species conservation. Out of 97 individual threats affecting species in India, we found that crop production is the major threat, contributing 44% of the total national STAR score followed by biological resource use such as hunting and logging (23%), and residential and commercial development (11%). Just seven out of 36 states and 66 out of 666 districts hosting high numbers of threatened and endemic species contribute 80% to the national STAR score. Importantly, the states and districts with most potential to contribute to threat abatement do not always overlap with those where habitat restoration will yield high benefits. Our analysis demonstrates the applicability and value of the STAR metric to subnational governments for biodiversity conservation elsewhere in the world.

1. Introduction

India is one of 17 megadiverse countries in the world, harbouring 7%–8% of all recorded species despite having only 2.4% of the world’s land area (Pande and Arora 2014). Its location at the tri-junction of Indo-Malayan, Afro-tropical and Paleo-Arctic realms means that it has a wide array of ecoregions with diverse habitats and climatic features enabling a vast variety of flora and fauna to thrive. Four out of 34 global biodiversity hotspots (the Western Ghats, the Nicobar Islands, the Himalayas and the north-east; Mittermeier et al 2004) and 465 important bird areas (IBAs; Rahmani et al 2016) are located in India. Around 50 000 species of flora and 100 000 species of fauna have been documented within the ten
biogeographic zones of the country, of which 23% and 28%, respectively, are endemic to India. In terms of vertebrate diversity, there have been 429 mammal, 1343 bird, 427 amphibian, 641 reptile and 3439 fish species documented in India so far (Pande and Arora 2014).

Biodiversity, including the diversity of genes, species and ecosystems, plays a key role in the proper functioning of ecosystems and supply of ecosystem services that, in turn, ensure human needs, both material and non-material, are met (Myers 1996). These services include provisioning services, such as the supply of fuel, fodder and medicine, and regulating services, such as carbon sequestration (by plants) and safeguarding against soil erosion. In addition, biodiversity has non-use, cultural, aesthetic, spiritual and existence value and supports the livelihoods and ways of life of millions of Indians (Parikh et al 2012, Bawa et al 2020).

Nature and biodiversity conservation has a long tradition in Indian culture, which is reflected in its literature, religious texts and in the national constitution and legislation (Dhee et al 2019). Forest cover in India currently stands at around 22% of the total area of the country and, unlike other economically developing countries, forest and tree cover has increased over the past 20 years despite growth in population and per capita incomes (Kumar et al 2020). The coverage of protected areas (PAs; national parks, wildlife sanctuaries, conservation reserves, community reserves) has also increased from around 3.3% to 5.1% in the past 30 years. Since the extirpation of the cheetah (*Acinonyx jubatus*) in the mid-20th century, no mammal species is known to have been lost from India (Singh and Kushwaha 2008).

Despite the above positives, Indian biodiversity faces numerous challenges in the coming decades. While forest cover has increased due to increased tree plantations, old native forest cover (which hosts relatively higher species density than plantations) has actually declined (Puyravaud et al 2010). Ghosh-Harihar et al (2019) pointed out that the small size of many PAs is not always sufficient to host a full complement of species as it hinders habitat connectivity. Moreover, a large number of species occur outside the PA system and many ecoregions are not well represented in the PAs. Forest fragmentation, resource exploitation, illegal hunting, presence of humans and invasive species are prevalent in many PAs—all of which negatively affect national conservation goals (Ghosh-Harihar et al 2019).

With around 1.4 billion people, India is the world’s second most populated country and, with rising incomes, consumption has recently been increasing across all economic classes. This is resulting in natural habitat loss, fragmentation and degradation through conversion of land use for cropland, livestock grazing, urbanisation, mining and industrial development (Pande and Arora 2014).

Agricultural intensification threatens many species through increased exposure to agrochemicals, eutrophication and loss of habitat heterogeneity. Proximity to humans and livestock is increasing parasite loads, competition for food and water, and disease transmission in wild animal populations (Hussain et al 2013). These pressures are increasingly bringing wild species into conflict with humans (Karanth et al 2012). Finally, overarching threats such as anthropogenic climate change are causing increased forest fire and ice-melting incidences, posing danger for vulnerable ecosystems such as coastal areas, dry deciduous forests and the Himalayas and species residing therein (Byers et al 2018). High population density in some parts is also a major obstacle in habitat-restoration initiatives (Luck 2007, Singh et al 2021).

Out of 1,998 Indian plant species assessed under the International Union for Conservation of Nature (IUCN) Red List 2019-3 (excluding data-deficient species), 402 (i.e. 20%) are threatened with extinction (i.e. falling under the critically endangered, endangered or vulnerable categories; IUCN 2020). For birds, mammals and amphibians, the corresponding percentages are 8%, 24% and 40%, respectively. Success in efforts to conserve biodiversity in India are thus crucial in ensuring progress towards the United Nations’ Sustainable Development Goal 15 (Life on Land). In sum, despite all of its services, biodiversity has deteriorated in past decades in India due to the push for economic development and the demands of a growing human population (Srivathsa et al 2020).

An important step towards amelioration of biodiversity loss in India is the generation of high spatial resolution quantitative information on threats affecting individual species in different regions as well as regions where habitat restoration will yield best outcomes for the species. Such information can then guide regional and national conservation policies and mitigation measures. However, almost all of the past studies highlighting anthropogenic threats to biodiversity in India have been narrow in scope as they have been limited to either specific species, a particular threat, or a small site/region (Karanth et al 2012, Hussain et al 2013).

There exist a few global studies that have calculated the biodiversity impacts due to broad land-use types (e.g. forestry, agriculture, pasture or urban) at the national level (Powell and Lenton 2013, Chaudhary et al 2017, Chaudhary and Mooers 2018) but these do not highlight the specific subnational areas, species or interventions needed, especially within large, megadiverse countries like India. Others have identified global hotspots projected to experience habitat and biodiversity loss due to human land use in the future (Güntherap and Seto 2013) or priority areas deserving protection for biodiversity purposes (Leclère et al 2020, Brodie et al 2021), but rarely identify the key threats affecting species in these

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A Chaudhary et al
hotspots. To date, there has been a lack of a scalable, consensus-based and comparable metric that can inform subnational policymakers on the relative importance of different threats and regions in their jurisdiction for biodiversity conservation, threat mitigation or habitat-restoration purposes. Moreover, private-sector companies and multinational corporations in the food, wood, textile or other sectors seeking to engage in sustainable-sourcing practices with their supply chain partners would also benefit from smart metrics able to differentiate between biodiversity footprints of products sourced from different farms or regions (Pascual et al 2017, Thorlakson et al 2018). To this end, Mair et al (2021) recently proposed a species threat abatement and restoration (STAR) metric, inspired by the structure of the 2015 Paris Agreement on climate change that allows the global climate change target to be disaggregated, such that any actor (be it a country, city or business) can determine its own carbon footprint—and have agency over the changes necessary to reduce its own greenhouse gas emissions in proportion to the reductions needed globally to meet the 2 °C target (Benveniste et al 2018). This approach is referred to as the establishment of specific 'science-based targets' (Andersen et al 2020).

The STAR metric can support a framework analogous to the Paris Agreement. The metric can be employed to monitor the progress towards a global species biodiversity goal through the establishment of science-based targets by any actors, because it is scalable across species, threats and geographies, and quantifies the contributions that abating threats and restoring habitats in specific places offer towards reducing extinction risk. The metric can measure the contributions of a given action by a certain actor towards a planetary science-based target of bending the curve of global species loss in standard units (see details in Mair et al 2021).

The specific science-based target for species extinction risk reduction for a given actor is the sum of the STAR metric values for all areas for which the actor bears responsibility. In other words, the STAR metric enables identification of specific threat-abatement and habitat-restoration opportunities in regions of interest that, if implemented, could contribute towards reduction of species extinction risk (i.e. the species could be downlisted from the threatened to the least concern category in the IUCN Red List). This metric could thus support implementation of the Convention on Biological Diversity’s (CBD) Post-2020 Global Biodiversity Framework, which is likely to include a goal of no loss of species by 2030, as a milestone towards recovery by 2050 (Hannah et al 2020, Secretariat of the CBD (SCBD) 2020) as well as action in response to the United Nations (UN) Decade on Ecosystem Restoration 2021–2030 (Young and Schwartz 2019).

However, the application of this metric has so far been limited to the national level (Mair et al 2021). There has not been any systematic application of the STAR metric at the subnational level to identify where the highest threat-abatement responsibilities and habitat-restoration opportunities lie within a country.

In India, the responsibility to conserve wildlife lies with both federal and state governments and both can pass laws relating to biodiversity conservation. India’s Biological Diversity Act, 2002 has established a three-tier implementation mechanism where the state biodiversity boards (SBB) are responsible for achieving the national biodiversity targets with support from the National Biodiversity Authority at the federal level and the district development and biodiversity management committees at the grassroots level (Bhattacharya and Bhattacharya 2019, Chavan 2020).

Moreover, the active involvement of subnational authorities, cities and local governments has been identified as one of the enabling conditions to implement the Post-2020 Global Biodiversity Framework (SCBD 2020, 2021). Hence, it is important to carry out a subnational application of the STAR metric to inform the state and district governments with which a substantial agency to take conservation action lies.

The aim of this study is to calculate the STAR metric to identify which threats are negatively affecting which species in each state/district and where habitat restoration would yield maximum returns for individual species and for reducing overall species extinction risk. The results stand to be helpful not only to local governments but also to the state and central government in forming threat-mitigation policies and reforms for saving threatened species and thus contribute towards global biodiversity conservation goals (SCBD 2020).

2. Methods

Here we calculate the STAR metric for all terrestrial amphibians, birds and mammals of India in each of the 36 states and 666 districts by intersecting the species’ area of habitat (AOH; Brooks et al 2019, IUCN 2020, Strassburg et al 2020) with the state/district boundaries. We then calculate the relative contribution of each of the 97 individual threats listed in the threats classification scheme of the IUCN Red List database (Salafsky et al 2008) to the total STAR metric threat-abatement score of each species in each state/district by considering the scope and severity of each threat (Garnett et al 2019). Finally, we also calculate STAR metric restoration scores per state/district considering the rate of recovery of a species’ population (Jones et al 2018) to calculate how much restoring the lost historical habitat of each species in each
state/district of India could contribute towards reducing their global extinction risk (Mair et al 2021).

2.1. STAR metric threat abatement score
The STAR metric threat-abatement score \( T_{t,d} \) for threat \( t \) in each district \( d \) among all species \( N \) occurring in the district was calculated using equation (1) proposed by Mair et al (2021):

\[
T_{t,d} = \sum_{s=1}^{N} P_{t,d} \cdot W_s \cdot C_{s,t}
\]

where \( P_{t,d} \) is the % of current total global AOH of each species \( s \) occurring within district \( d \) estimated by overlaying species’ AOH with polygons of district political boundaries; \( W_s \) is the IUCN Red List category weight of species \( s \) (near threatened = 1, vulnerable = 2, endangered = 3 and critically endangered = 4; based on Butchart et al 2004); \( N \) is the total number of species in the district; and \( C_{s,t} \) is the relative contribution of threat \( t \) to the extinction risk of species \( s \) which is calculated by dividing the % of a species’ population decline due to that threat with the sum of the % population declines from all threats to that species. For example, if hunting is a threat observed across the majority of a species’ global habitat range and is causing rapid declines in its population, the value of \( C_{s,t} \) will be 18 (table 1).

From equation (1), it can be seen that, for each species \( s \), the global STAR metric threat-abatement score (i.e. its maximum possible value = STAR\(_T\)) will vary from 100 if the species is near threatened, to 200 if vulnerable, 300 if endangered and 400 if the species is listed as critically endangered on the IUCN Red List.

By summing up the individual STAR\(_T\) values across all species in all regions, one can quantitatively estimate the planetary science-based target of bending the curve of global species loss (i.e. global threat-abatement effort needed for all species to become the least concern category).

The STAR\(_T\) score of each species can be disaggregated spatially based on the % of its AOH hosted by a particular region \( P_{s,d} \) in equation (1)). This will show the potential contribution of conservation actions in that region towards reducing the extinction risk for that species globally.

Further, the local STAR\(_T\) of a species can be further disaggregated by threat based on the contribution of each threat to the species’ risk of extinction \( (C_{s,t} \text{ in equation (1)}) \). This will show the contribution of abating a particular threat towards reducing the extinction risk for that species. The threat classification information in the IUCN Red List database for each species is organised into 12 broad threat classes, and several subclasses within each broad class. For example, the broad threat class ‘residential and commercial development’ has three subclasses; viz. housing and urban areas, commercial and industrial areas, and tourism and recreation areas.

2.2. STAR metric restoration score
The STAR metric restoration score \( R_{t,d} \) for the potential contribution due to restoration of species’ habitat (and threat abatement therein) in district \( d \) for threat \( t \) is calculated through equation (2) proposed by Mair et al (2021):

\[
R_{t,d} = \sum_{s=1}^{N} H_{s,d} \cdot W_s \cdot C_{s,t} \cdot M_t
\]

where \( H_{s,d} \) is the % of current total global AOH of each species \( s \) restorable within district \( d \); \( W_s \) is the IUCN Red List category weight of species \( s \); \( C_{s,t} \) is the relative contribution of threat \( t \) to the extinction risk of species \( s \); and \( M_t \) is a multiplier to discount restoration scores and is equal to 0.29 based on the median rate of recovery of a species’ population (value obtained from global meta-analysis by Jones et al 2018). The multiplier therefore reflects the lower and slower rate of success in recuperating species population through habitat restoration compared with conserving their existing habitat.

2.3. Input data compilation
For terrestrial mammals, birds and amphibian species found in India, we first obtained the data on their range maps, extinction risk category and threat classification from the IUCN Red List version 2019-3 (IUCN 2020). Species in the near threatened, vulnerable, endangered, and critically endangered categories were included in the calculation of STAR scores. The analysis included a total of 312 threatened and near-threatened species (79 amphibians, 126 birds and 107 mammals) and 97 individual threats affecting species.

Table 1. Expected % of species’ population decline \( (C_{s,t}) \) over ten years or three generations from combinations of scope and severity scores per threat. Values taken from Garnett et al (2019).

| Scope                  | Very rapid declines | Rapid declines | Slow, significant declines | Negligible declines | No decline | Causing/could cause fluctuations |
|------------------------|---------------------|----------------|---------------------------|---------------------|------------|---------------------------------|
| Whole (>90%)           | 63                  | 24             | 10                        | 1                   | 0          | 10                               |
| Majority (50%–90%)     | 52                  | 18             | 9                         | 0                   | 0          | 9                                |
| Minority (<50%)        | 24                  | 7              | 5                         | 0                   | 0          | 5                                |
The threat classification information in the IUCN Red List database for each species includes the scope (proportion of its global population impacted), severity (rate of decline driven by the threat within its scope) and timing (past, ongoing or future) of each threat. Here, we excluded threats that are ‘past and unlikely to return’ and those that are not expected to cause any or negligible decline to a species’ population. This left us with 74 threats that affect at least one species in India out of the total 97 threats listed in the IUCN Red List database. Next, the % of a species’ population decline due to a particular threat was derived from a scope-severity matrix, as shown in table 1 (Garnett et al. 2019, Mair et al. 2021). The table combines the scope of threat (proportion of species’ global population impacted) and the severity of the threat (rate of species’ population decline driven by the threat within its scope) to provide the % of species’ overall global population decline caused by the threat (approach developed by Garnett et al. 2019 and applied in Mair et al. 2021).

The current and original (pre-human) global AOH raster at 5 km grid resolution for each species was taken from Strassburg et al. (2020) who derived the AOH after applying several filters (land cover, elevation etc) to species range maps available from the IUCN Red List (Brooks et al. 2019, Mair et al. 2021). The maps of Indian state and district political boundaries were obtained from the database of global administrative areas (https://gadm.org/download_country_v3.html).

The restorable AOH for each species was calculated by simply subtracting the current AOH from the original (historical) AOH. Note that the restorable AOH for each species as calculated by us is only theoretical and does not take into account the feasibility of restoration actions on the ground which depends upon factors such as population density or other socioeconomic constraints present in the region.

3. Results and discussion

The total national STAR score (summed across all species and states) for India is 41 817 (of which 11 585 for mammals, 10 843 for birds and 19 389 for amphibians). The global STAR score for these three species groups combined is 1 223 500 as calculated by et al. (2020). Therefore, India’s national STAR score represents 3.4% of the global STAR score for these three species groups and 3.7%, 2.9% and 3.6% for mammals, birds and amphibians, respectively. Supplementary tables S1 and S2 (available online at stacks.iop.org/ERL/17/054022/mmedia) show the STAR scores for 36 states and 666 districts, respectively, for all three taxa. The names of individual states and districts can be found at the Maps of India website (https://www.mapsofindia.com/districts-india/).

The top 20% of all 36 states contribute 80% to the national STAR score of 41 817 (figures 1(a) and 2(a)). These are: the southern states of Kerala (20%), Tamil Nadu (18%), and Karnataka (13%); the north-eastern states of Arunachal Pradesh (6%) and Assam (5%); the western state of Maharashtra (5%); and the Andaman and Nicobar Islands in the Indian Ocean (12%). In contrast, the 20 states with lower STAR scores contribute only 6% to the national STAR score. This is because several of them are very small in area and host few threatened species. However, even several states with large areas (e.g. Uttar Pradesh, Bihar, Odisha and Telangana) contribute <1% to the national STAR score. The high STAR scores of the top three states (Kerala, Tamil Nadu and Karnataka) are primarily due to the presence of a number of endemic amphibian species that are critically endangered such as Fejervarya murthii, Indirana phryno Dermor, Micrixalus kottigeharensis etc. On the other hand, the high STAR scores of the north-eastern states Arunachal Pradesh and Assam are due to the presence of a high number of threatened birds and mammals such as Liocichla bugunorum, Biswamoyopterus biswasi etc (supplementary table S1).

We also calculated the STAR score at the district (county) level where a substantial agency to take local conservation actions based on people’s traditional ways of stewardship of species and ecosystems resides (figures 1(b) and 2(c); supplementary table S2). We found that the top 10% of districts (i.e. 66 out of a total of 666) contribute 83% to the national STAR score of 41 817 (figures 1(b) and 2(c)).

In contrast, the bottom 80% (533 out of 666) of districts with a low STAR score contribute just 8% to the total national STAR score. For amphibians, the STAR score for many of the districts is zero. This does not mean that these districts do not host any amphibians; rather, this is because all amphibian species in these districts are of least concern status (i.e. not threatened).

On a national level, tackling threats from annual and perennial non-timber crop production (agro-industry and smallholder farming, grazing and plantations) could contribute the greatest to reduce the extinction risk of all three species groups because it alone accounts for 44% of the total Indian STAR score (table 2; supplementary table S3).

The next important threats that need to be tackled are biological resource use (hunting and collecting birds/animals; logging and wood harvesting) and residential and commercial development (housing, urban areas, tourism, recreation areas), currently accounting for 23% and 11% of the total Indian STAR score, respectively. These three threats alone therefore contribute almost 80% of the total STAR score. Natural system modifications through construction of dams and human-driven wildfires contribute a further 6% to the total STAR score. Supplementary
Figure 1. Top Indian states (A) and districts (B) contributing the most to the total national STAR threat-abatement score for the three taxa combined (amphibians, birds and mammals). See supplementary tables S1 and S2 for scores per state and district per taxa.

Some threats affect a particular species group more than the others. For example, agriculture contributes 57% to the total STAR score of amphibians in the country compared with 33% for mammals and birds. Pollution, invasive species and natural system modifications through dams and wildfires threaten birds more than amphibians and mammals. On the other hand, hunting and logging affects mammals the most followed by birds (table 2).

The spatial distribution of different threats as shown in figure 3 and supplementary table S4 can provide guidance on the mitigation measures that need to be put in place for specific regions if these are to deliver the necessary contributions towards the delivery of global biodiversity goals. For example, threats from pollution mostly affect species in Kerala, Tamil Nadu and Maharashtra and have negligible effect in other states. Climate change and invasive species primarily pose a threat to species in the Andaman and Nicobar Islands and their effect in other states is low. Unlike other states, transportation and service corridors pose a substantial threat to species in the north-east state of Arunachal Pradesh.

Human intrusion and disturbances through recreational activities mostly affects species in Karnataka and Madhya Pradesh while disturbances through military activities are a threat to species in the northernmost state of Jammu and Kashmir. Conversely, some major threats were absent in certain states. For example, threats from residential and...
Figure 2. STAR metric threat-abatement (A)–(C) and restoration scores (B)–(D) of each Indian state and district for the three taxa combined (amphibians, birds and mammals). See supplementary tables S1 and S2 for scores per state and district per taxa. The bin thresholds were based on the Natural Jenks Breaks classification. Names of the states are mentioned in figure (A) and supplementary figure S1.

Table 2. STAR threat-abatement score per broad threat classes at the national level in India (Salafsky et al. 2008). See supplementary table S3 for the contribution of each of the 74 threat subclasses to the total STAR score.

| IUCN broad threat name                      | Amphibian STAR | Birds STAR | Mammals STAR | Total STAR | % of total |
|---------------------------------------------|----------------|------------|--------------|------------|------------|
| Agriculture and aquaculture                 | 10 960         | 3532       | 3722         | 18 213     | 44         |
| Biological resource use (hunting/logging)   | 3904           | 2208       | 3314         | 9427       | 23         |
| Residential and commercial development      | 2533           | 743        | 1130         | 4407       | 11         |
| Natural system modifications                | 714            | 1175       | 553          | 2441       | 6          |
| Pollution                                   | 320            | 919        | 146          | 1385       | 3          |
| Climate change and severe weather           | 0              | 463        | 781          | 1244       | 3          |
| Human intrusions and disturbance            | 390            | 432        | 382          | 1204       | 3          |
| Invasive species, genes and diseases        | 0              | 643        | 486          | 1129       | 3          |
| Transportation and service corridors        | 385            | 442        | 233          | 1061       | 3          |
| Energy production and mining                | 183            | 285        | 409          | 877        | 2          |
| Geological events                           | 0              | 0          | 429          | 429        | 1          |
| Other options                               | 0              | 1          | 0            | 1          | 0          |
| Total STAR threat-abatement score           | 19 389         | 10 843     | 11 585       | 41 817     | 100        |

Commercial development is absent from the northeastern states of Arunachal Pradesh and Assam (tables S4 and S5).

Table 3 shows the top 25 species with the highest STAR scores in India. These are six mammals, two birds and 17 amphibian species. All of them (except Biswamoyopterus biswasi and Viverra civettina) have their range restricted to a single state and are listed as critically endangered by the IUCN Red List.
Figure 3. Spatial distribution of threats from residential and commercial development (A) and agriculture and aquaculture (B) in India. The STAR threat-abatement score combined across all three taxa for these top two threats per state is shown. See supplementary table S4 for the STAR score of each threat per state and district.

Table 3. Top 25 species with the highest STAR score in India.*

| Taxa            | Species name                  | Common name            | STAR | Range restricted to       |
|-----------------|-------------------------------|------------------------|------|---------------------------|
| Amphibians      | Fejervarya murthii            | Ghats wart frog        | 400  | Tamil Nadu                |
| Amphibians      | Indirana gudiva               | Gundia frog            | 400  | Karnataka                 |
| Amphibians      | Indirana phrynoderma          | Kerala Indian frog     | 400  | Tamil Nadu                |
| Amphibians      | Microxalus kottigeharenseis   | Kottigehar dancing frog| 400  | Karnataka                 |
| Amphibians      | Raorchestes chalazodes        | Gunther’s bush frog    | 400  | Kerala                    |
| Amphibians      | Raorchestes griet             | Griet bush frog        | 400  | Kerala                    |
| Amphibians      | Philautus sanctisilaticus     | Sacred grove bush frog | 400  | Madhya Pradesh            |
| Amphibians      | Raorchestes shillongensis     | Shillong bush frog     | 400  | Meghalaya                 |
| Amphibians      | Pseudophilautus amboli        | Amboli bush frog       | 400  | Maharashatra              |
| Amphibians      | Nyctibatrachus dattatreyaensis| Dattatreya night frog  | 400  | Karnataka                 |
| Amphibians      | Raorchestes sushili           | Sushil’s bush frog     | 400  | Tamil Nadu                |
| Birds           | Rhinoptilus bitorquatus       | Jerdon’s courser       | 400  | Andhra Pradesh            |
| Birds           | Liocichla bugunorum           | Bugun liocichla        | 400  | Arunachal Pradesh         |
| Mammals         | Crocidura jenkinsii           | Jenkin’s shrew         | 398  | Andaman and Nicobar Islands|
| Mammals         | Crocidura andamanensis       | Andaman shrew          | 397  | Andaman and Nicobar Islands|
| Amphibians      | Rhacophorus pseudomalabaricus | Anaimalai flying frog  | 388  | Tamil Nadu                |
| Mammals         | Crocidura nicobarica          | Nicobar frog           | 378  | Andaman and Nicobar Islands|
| Amphibians      | Ingerana charlesdarwinii      | Charles Darwin frog    | 372  | Andaman and Nicobar Islands|
| Mammals         | Biswamoyopterus biswasi       | Namdapha flying squirrel| 319 | Arunachal Pradesh        |
| Mammals         | Viverra civettina             | Malabar civet          | 309  | Kerala                    |
| Amphibians      | Xanthophryne koyayensis       | Koyna toad             | 300  | Maharashtra               |
| Amphibians      | Nyctibatrachus vaasanthi      | Kalakad wrinkled frog  | 300  | Tamil Nadu                |
| Amphibians      | Raorchestes charius           | Seshachar’s bush frog  | 300  | Karnataka                 |
| Mammals         | Semnopithecus ajax            | Kashmir grey langur    | 300  | Himachal Pradesh          |
| Amphibians      | Ghatixalus variabilis         | Green tree frog        | 300  | Tamil Nadu                |

* The IUCN threat status of the first 20 species is critically endangered while that of the last five species is endangered. The mammal species *Biswamoyopterus biswasi* has 80% of its global range in the state of Arunachal Pradesh and 20% in Assam while *Viverra civettina* has 80% of its global range in Kerala and 20% in Karnataka. The habitat of three species above (*Nyctibatrachus vaasanthi, Indirana phrynoderma* and *Nyctibatrachus dattatreyaensis*) has also been highlighted by the Alliance for Zero Extinction (Ricketts et al 2005). See supplementary table S6 for a full list of Indian species and their STAR score in each state.

In fact, around ten out of these 25 species are endemic to a single district. These are the species whose conservation must be urgently prioritised in the respective state/district hosting them to prevent their global extinction. See supplementary table S6 for a full list of Indian species and their STAR score in each state.

The Indian STAR metric restoration score is 1.85% of the global STAR metric restoration score for all three taxa combined. Restoring lost habitat of different species in all states in India could contribute to an equivalent of 30% of the national STAR score (i.e. 12,554 out of the total 41,817). Habitat restoration would lead to achievement of 14%, 25% and...
63% of the national STAR score of amphibians, mammals and birds, respectively. Habitat restoration in just seven out of 35 states with the highest STAR score would lead to achievement of 61% of total STAR metric restoration score of 12 554 (figure 2(b)). These top seven states are Maharashtra, Assam, Madhya Pradesh, Karnataka, Uttar Pradesh, Tamil Nadu and Andhra Pradesh (supplementary table S1).

The top ten districts where habitat restoration will yield the highest STAR scores are widely distributed across India and are: Shahdol district in the state of Madhya Pradesh; Lakhimpur Kheri in the state of Uttar Pradesh; Chikmagalur in the state of Karnataka; Udham Singh Nagar in the state of Uttarakhand; Idukki in Kerala; Pune and Kolhapur in Maharashtra; Coimbatore and Nilgiris in Tamil Nadu; and Anantapur in the state of Andhra Pradesh (supplementary table S2).

4. Conclusions

Our results provide Indian policymakers with a spatially detailed identification of the state- and district-specific threats and the reasons for those threats which is critical information for devising effective biodiversity conservation policies. This study is the first to systematically provide such detailed information on species threats at the state and district level in India or anywhere else in the world.

We found that, while all Indian states contribute to the national STAR threat-abatement score, over 20 out of 35 Indian states contribute <1% to it (table S1). Interestingly, many of these states have high species richness but a low STAR threat-abatement score. For example, 896 species (of mammals, birds and amphibians combined) can be found in West Bengal, which is second highest in terms of species richness per state in India. However, the state ranks 19th out of 35 in terms of STAR score. This is because either most of the species in this state are not threatened (i.e. with least concern status) or the proportions of species’ global range hosted by this state are small. However, such states with low STAR scores also have important biodiversity responsibilities, and conservation investments here should aim at stemming habitat degradation to ensure that the population decline of least concern species observed globally does not happen within their boundaries.

Conversely, the southern state of Kerala ranks 15th in terms of species richness, hosting 560 species, but ranks number one in terms of STAR threat-abatement score nationally (table S1). This is because a large proportion of species in Kerala are threatened and endemic to the state. Application of the STAR metric therefore could highlight such high-scoring hotspot states and districts where urgent conservation investment is required to abate the existing threats to species. Application of simple species richness as an indicator for guiding conservation investment would not have captured such hotspots requiring urgent action.

Another important insight from simultaneous application of both the STAR metric threat-abatement and restoration score was that the subnational regions contributing heavily to them do not necessarily overlap, and thus the two metrics are complementary. For example, the northern state of Uttar Pradesh ranks fifth among the 35 states with a STAR metric restoration score of 994 but ranks 21st in the country for the STAR metric threat-abatement score. Conversely, the Andaman and Nicobar Islands rank fourth in the STAR metric threat-abatement score but 18th in the STAR metric restoration score. This highlights that, whereas in some regions threat-abatement interventions would give higher biodiversity conservation returns, in others habitat restoration would be a more effective strategy per unit investment.

We present the first systematic application of the STAR metric at a subnational level that can act as a template for similar analysis in other countries. This is important because of the increasing acceptance that implementation of the CBD’s Post-2020 Global Biodiversity Framework requires action beyond national governments. The CBD recently came up with a plan of action for biodiversity (2021–2030) indicating how subnational governments, cities and local authorities can play a much stronger role in the implementation of the Post-2020 Global Biodiversity Framework (SCBD 2021). Our analysis provides a clear demonstration of the need to target conservation actions according to each subnational jurisdiction and how these can be tailored to meet national and global outcomes for species. We also show how this can be done to identify key pressures on species that must be relieved at two subnational political levels.

The STAR metric restoration score per state/district also underscores the fact that, for positive biodiversity conservation outcomes, it is not only how much total area at the national level is restored that matters but also where precisely the restoration is being carried out (Strassburg et al 2020). Such information can be very useful for national missions on habitat restoration and species conservation as it tells exactly how many and which species could benefit from restoration of habitat in a specific place. Note that a species will only benefit from restoration if the area falls within its historical habitat range (i.e. where the climate, elevation and resources are favourable to its survival). Overall, the results show that, in order to maximise the conservation outcomes at the national level, threat abatement can be valuably complemented by habitat restoration.

We identified the species in each state/district whose conservation must be urgently prioritised because their STAR score is close to 400 (table 3, table S6). A few of them (e.g. Nyctibatrachus vasanthi, Indirana phrynoderma, Nyctibatrachus dattatreyaensis) have also been highlighted by the Alliance for...
Zero Extinction (Ricketts et al 2005) which identifies sites effectively holding the entire population of one or more critically endangered species, equating to criterion A1e of the ‘Global Standard for Identification of Key Biodiversity Areas’ (IUCN 2016). Our comprehensive analysis complements such initiatives and highlights the districts and states hosting a high number of range-restricted (endemic) and critically endangered species that may need special conservation programs (in-situ and ex-situ) to alleviate their threats, restore their habitats and preserve their genes.

The major underlying driver of the threats to species in India is a large human population of 1.4 billion people whose food, fuel, housing and infrastructure demands have been increasing with rising per capita incomes over the past three decades (Foster and Rosenzweig 2004, Ghosh-Harihar et al 2019, Singh et al 2021). This has led to encroachment of species’ habitat for smallholder/agroindustry farming, plantations, wood harvesting and infrastructure development (urban housing, roads, railways, dams) purposes. Over 50% of the Indian population is engaged in the agriculture sector and resides in rural areas where poverty is widespread (Foster and Rosenzweig 2004). The lack of economic opportunities and weak law enforcement have allowed people to exploit biological resources through, for example, hunting and forest logging. The food demand of such a huge population has led to almost 60% of the country’s land area being devoted to crop production (wheat, rice and sugarcane in particular, as well as tea) with little or no land-use plans and weak enforcement of related laws for these activities, threatening biodiversity and causing other environmental problems such as water scarcity, eutrophication and greenhouse gas (GHG) emissions (Chaudhary and Krishna 2021).

Our study reveals that agriculture is the top threat to species across India (table 2) and thus the bulk of the states’ potential contribution towards improving the threat status of species within their borders must come from application of landscape approaches to support biodiversity at the farm level (Scherr and McNeely 2008) and transitioning towards sustainable agriculture through technological, policy and behavioural interventions. Substantial alleviation of threats is also possible through investment in sustainable infrastructure development and law enforcement to tackle illegal hunting (table 2). Technological interventions can include farmers adopting sustainable intensification based on good practices that result in win–win outcomes for farmers’ income and the environment (Boillat et al 2019, Jat et al 2020). Policy interventions can range from leveraging international trade agreements for importing certain crops currently grown in biodiversity hotspots to safeguard species’ habitat at home without jeopardising the biodiversity in the exporting nation, to providing payments for ecosystem services and subsidies for biodiversity-friendly farming practices (Leclère et al 2020).

A wide range of tools, information resources and guidelines are already freely available online to support decision-makers in implementing conservation actions to ameliorate the threats to species of different taxa (e.g. see Conservation Evidence initiative, Sutherland et al 2020). For example, commonly suggested threat-abatement measures for reducing bird deaths in residential and commercial areas are the use of slant windows and underground power lines. When restoring wetlands or other in-situ threat-mitigation measures are not feasible, captive breeding and translocation are some measures suggested for amphibian conservation (Sutherland et al 2020). Further benefits are observed in forests when reduced-impact logging practices are adopted in place of clear-cutting or conventional selective logging for wood harvesting (Chaudhary et al 2016). Educational campaigns and conservation success stories from other countries (Cao et al 2017) can be used to promote consciousness amongst the local population regarding biodiversity conservation, ecosystem restoration and species habitat connectivity (St John et al 2011, Bawa et al 2020, Singh et al 2021).

As with any metric, the STAR metric has limitations. First, we only include three species groups (mammals, birds and amphibians) here, due to data-availability constraints. As more data on habitat range, extinction risk and threats become available for other taxa, the STAR metric can be expanded to other terrestrial, freshwater and marine species. Second, the species-threat data available from the IUCN Red List is not spatially explicit, meaning that it is possible that some threats affecting the majority of species population globally are absent in particular districts of India or, conversely, some threats are unique to a particular district and absent elsewhere in the world. The current application of the STAR metric does not capture such possible spatial variation in threat magnitude within species’ AOH, although this lack of information would primarily be a concern for large-range species. Third, while the application of the STAR metric enables identification of individual species that are threatened and have high endemism and thus a high STAR score, their underlying habitat range data available from the IUCN Red List (IUCN 2020) might not have been updated in some cases. For example, three of the 25 species (Namdapha flying squirrel, Malabar civet, Jerdon’s courser) with high STAR scores in India (table 3) have not been found in recent field surveys (Ashraf et al 1993, Nixon et al 2010) and thus might have been driven to extinction. For such cases, future studies should combine information from the IUCN Red List with the national/regional red list or field survey data to ground-truth the STAR results.
Finally, in theory, the STAR metric identifies which threats need to be tackled and how much habitat restoration is needed in specific places for a species to become non-threatened (i.e. to achieve least concern status). However, whether such threat abatement and restoration are practically feasible requires additional consideration of the socioeconomic realities on the ground (Estrada et al 2020). For example, our data analysis revealed the states and districts where habitat restoration will yield high STAR scores (figure 1(d)) but some of these regions such as districts in the northern state of Uttar Pradesh or the southern state of Kerala are currently very densely populated. This means that habitat restoration will be difficult or not practically feasible at all here compared to other regions in Odisha or Chhattisgarh where the population density is relatively low (Luck 2007). To fill this research gap, future studies should overlay such region-specific demographic or socioeconomic constraints to habitat restoration with the STAR metric to identify the places where conservation funds will yield the best return.

Indeed, the STAR metric is not intended to be used alone; the metric focuses specifically on reducing the extinction risk of threatened and near-threatened species, which is one aspect of overall biodiversity conservation. Rather, the STAR metric should be applied alongside other approaches that consider additional conservation and societal goals, such as preventing the population loss of current least concern species, and meeting ecosystem restoration and climate change targets.

Despite these limitations, the STAR metric offers a powerful yet simple screening tool to quantify the opportunities for both government and non-state private or business actors (Thorlakson et al 2018) at national and local levels to contribute towards a global species conservation target analogous to the Paris climate agreement’s long-term temperature goal. Specifically, its use for the 36 Indian states and 666 Indian districts demonstrates the applicability of the metric to reduce species extinction risk for other subnational governments (e.g. regions, provinces, counties) elsewhere in the world as envisaged in the Post-2020 Global Biodiversity Framework (SCBD 2020, 2021) and the United Nations’ call for ecosystem restoration. It could provide the framework for species conservation strategy by quantifying what pressures need to be tackled and exactly where they are threatening species (wherever the pressures originate). In sum, the STAR metric for species conservation in combination with other metrics for genetic (Morlon et al 2011), functional (Brodie et al 2021) and ecosystem components of global biodiversity can help track progress towards the goals and targets of the emerging Post-2020 Global Biodiversity Framework, as well as Sustainable Development Goals 14 (Life Below Water) and 15 (Life on Land).

**Data availability statement**

The underlying raw data are publicly available through the references cited in the methods section. All data that support the findings of this study are included within the article (and any supplementary files).

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**Author contributions**

A C conceived and designed the study, analysed the results and wrote the manuscript. L M overlaid state and district boundaries with species area of habitat, analysed results and edited the manuscript. BBNS generated the AOH maps for all species. T M B, V M and P J K M reviewed and edited the manuscript.

**Conflict of interests**

The authors declare no competing interests. The views expressed in this publication do not necessarily reflect those of IUCN. The designation of geographical entities in this paper, and the presentation of the material, do not imply the expression of any opinion whatsoever on the part of IUCN concerning the legal status of any country, territory, or area, or of its authorities, or concerning the delimitation of its frontiers or boundaries.

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