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Metrics for quantifying how much different threats contribute to red lists of species and ecosystems

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Abstract
Red lists are a crucial tool for the management of threatened species and ecosystems. Among the information red lists provide, the threats affecting the listed species or ecosystem, such as pollution or hunting, are of special relevance. This information can be used to quantify the relative contribution of different threat factors to biodiversity loss by disaggregating the cumulative extinction risk across species into components that can be attributed to certain threats. We devised and compared 3 metrics that accomplish this and may be used as indicators. The first metric calculates the portion of the temporal change in red list index (RLI) values that is caused by each threat. The second metric attributes the deviation of an RLI value from its reference value to different threats. The third metric uses extinction probabilities that are inferred from red list categories to estimate the contribution of a threat to the expected loss of species or ecosystems within 50 years. We used data from Norwegian Red Lists to test and evaluate these metrics. The first metric captured only a minor portion of the biodiversity loss caused by threats because it ignores species whose red list category does not change. Management authorities will often be interested in the contribution of a given threat to the total deviation from the optimal state. This was measured by the remaining metrics. The second metric was best suited for comparisons across countries or taxonomic groups. The third metric conveyed the same information but uses numbers of species or ecosystem as its unit, which is likely more intuitive to lay people and may be preferred when communicating with stakeholders or the general public.

KEYWORDS
ecosystem collapse, expected loss of ecosystems, expected loss of species, red list index, species extinction, threat factor

Medidas para cuantificar la contribución de las diferentes amenazas a las listas rojas de especies y ecosistemas

Resumen: Las listas rojas son una herramienta crucial para la gestión de los ecosistemas y las especies bajo amenaza. Entre la información que proporcionan estas listas, son de mucha relevancia las amenazas que afectan a los ecosistemas o especies en la lista, como la contaminación o la cacería. Esta información puede usarse para cuantificar la contribución relativa que tienen los diferentes factores de amenaza para la pérdida de la biodiversidad mediante la disgregación del riesgo de extinción acumulado de varias especies en componentes que pueden atribuirse a ciertas amenazas. Diseñamos y comparamos tres medidas que logran esto y que pueden usarse como indicadores. La primera medida calcula la porción del cambio temporal en los valores del índice de listas rojas (ILR) causado por cada amenaza. La segunda medida les atribuye a las diferentes amenazas la desviación de un

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valor del ILR de su valor de referencia. La tercera medida usa probabilidades de extinción inferidas a partir de las categorías de las listas rojas para estimar la contribución de una amenaza a la pérdida esperada de especies o ecosistemas dentro de 50 años. Usamos datos de las Listas Rojas de Noruega para probar y evaluar estas medidas. La primera medida sólo capturó una porción menor de la pérdida de la biodiversidad causada por amenazas porque ignora las especies cuya categorías no cambia. Las autoridades gestoras se interesan con frecuencia en la contribución de una amenaza a la desviación total del estado óptimo. Medimos lo anterior con las medidas restantes. La segunda medida fue la mejor para comparar entre países y grupo taxonómicos. La tercera medida comunicó la misma información, pero con los números de especies o ecosistemas como su unidad, lo cual probablemente sea más intuitivo en términos sencillos y pueda preferirse para comunicarse con los actores o el público en general.

PALABRAS CLAVE
colapso del ecosistema, extinción de especies, factor de amenaza, índice de listas rojas, pérdida esperada de ecosistemas, pérdida esperada de especies

【摘要】
红色名录是濒危物种和生态系统管理的重要工具。其中, 列入名录的物种或生态系统面临的威胁 (例如污染或狩猎) 是红色名录提供的重要信息。我们可以通过将物种的累积灭绝风险分解为可归因于具体威胁的组分, 利用红色名录的信息来量化不同威胁因素对生物多样性丧失的相对贡献。为此, 我们设计并比较了 3 个指标, 第一个指标计算每种威胁因素导致红色名录指数随时间变化的比例;第二个指标将红色名录指数与其参考值的偏差归因于不同的威胁因素;第三个指标利用由红色名录类别推断出的灭绝概率, 估计威胁因素在 50 年内对物种或生态系统预期丧失情况的贡献。我们使用挪威红色名录的数据测试并评估了以上三个指标。结果发现, 第一个指标仅能捕获到威胁因素引起的生物多样性丧失的一小部分, 因为它忽略了重要性未发生变化的威胁因素。管理者通常会对给定威胁因素对总体偏离最佳状态的贡献感兴趣, 这在其余指标中有所体现。第二个指标最适合跨国家或类群的比较, 而第三个指标传达了相同信息, 但使用物种或生态系统数量作为单位, 这对非专业人士可能更加直观, 因此更适用于与利益相关者或公众的沟通。**【翻译:胡怡思;审校:聂永刚】**

关键词: 生态系统崩溃, 生态系统预期丧失, 物种预期丧失, 红色名录指数, 物种灭绝, 威胁因素

INTRODUCTION

Global (IUCN, 2021) and national (e.g., Artsdatabanken, 2018a, 2021) red lists of threatened species and ecosystems are a crucial tool for the management of natural diversity (i.e., biodiversity and geodiversity). The International Union for the Conservation of Nature (IUCN, 2012a, 2012b, 2016) Red List categories communicate the extinction risk of species to the general public and help management authorities prioritize conservation efforts. Because of their widespread use and acceptance, red lists are well suited for reporting, evaluating, and comparing the state of and trends in biodiversity at global, regional, national, and subnational levels (e.g., Kyrkjeeide et al., 2021; Mair et al., 2021).

The red list index (RLI) values are calculated from the number of species listed in the different red list categories and presented as an index value between 0 and 1 (Bubb et al., 2009; Butchart et al., 2004, 2007). One corresponds to the best possible situation, or reference state, in which all species are of least concern, whereas 0 indicates the worst possible situation, in which all (native) species are (regionally) extinct. All RLI values <1 imply that biodiversity is in a state of decline. Since its inception, the RLI has been widely used as a global and national indicator (e.g., Butchart et al., 2005, 2006, 2010; Garcia-R & Di Marco, 2020; McGeoch et al., 2010, 2015; Miranda et al., 2022; Rabitsch et al., 2016; Tittensor et al., 2014). In connection with reporting progress toward international conservation goals, such as the Aichi Targets, the Sustainable Development Goals, and the Kunming–Montreal Global Biodiversity Framework (UNEP, 2022), the RLI has been suggested as a key indicator cumulatively (i.e. including all red-list-assessed species) and to address certain prioritized groups of species, such as pollinators and reef-building corals (BIP, 2020a, 2020b).

In addition to the red list categories, red lists contain supporting information. Especially crucial for designing successful management measures is a list of threats to the assessed species (IUCN, 2022b), which allows identification and comparison of threats and prioritization of conservation actions designed to ameliorate threat factors (e.g., Chakona et al., 2022; Miranda

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et al., 2022). The RLI has also been suggested for use in summarizing the impacts of threats, such as pollution and invasive non-native species, on red-listed species (BIP, 2020c, 2020d).

The latter approach requires disaggregating the RLI into components that can be attributed to certain threats. We compared 3 different methods to carry out such disaggregation and attribution, and we evaluated them with data from Norwegian Red Lists of species and ecosystems. The first method, proposed by Butchart (2008; cf. McGeoch et al., 2010), measures only the contribution of threats to temporal changes in red list categories. We therefore devised 2 additional metrics: the contribution of threats to the deviation of the RLI from its reference value and the contribution of threats to the expected loss of species or ecosystems within 50 years.

METHODS

Norwegian Red List data

We used data from the Norwegian Red List for Species 2010, 2015, and 2021 and the Norwegian Red List for Ecosystems and Habitat Types 2018 (Artsdatabanken, 2010, 2015, 2018a, 2021; Henriksen & Hilmo, 2015; Kålås et al., 2010). These lists were assembled by expert teams who assessed native species or ecosystems following the relevant IUCN guidelines (especially Bland et al., 2017; IUCN, 2012a, 2012b, 2016, 2022a) and national guidance (Artsdatabanken, 2018b, 2020). Earlier red lists were not considered because they did not follow the current IUCN methodology, because exhaustive lists of the necessary variables were unavailable, or because the delimitation of ecosystems was too different between the versions. The data we analyzed were for species and ecosystems from mainland Norway (including coastal islands and surrounding waters) (i.e., we excluded assessments for the Norwegian territories in the high Arctic [Jan Mayen, Svalbard, and surrounding waters]). The data and code used in our analyses are openly available (Sandvik, 2023a, 2023b).

Some species on the Norwegian Red Lists have been downlisted due to rescue effects from populations of the same species in neighboring countries (IUCN, 2012a, pp. 14–16). If a species was downlisted, we included it but used its category from before its downlisting. This was motivated by the wish to assess the effects of national management measures, whereas the causes for downlisting are, by definition, not affected by such measures.

Norwegian ecosystems have been assessed at 4 different levels within the EcoSyst framework (Halvorsen et al., 2020): major ecosystem types, minor ecosystem types, subsets of minor ecosystem types defined based on environmental variables, and landforms. We analyzed these assessments first as reported in the red list. In a separate analysis, we disaggregated all major ecosystem types that had been assessed into their component minor ecosystem types. This involved the assumption that minor ecosystem types that have not been assessed for the red list share the red list category of their superordinated major ecosystem type.

Red list index

The RLI in year t is defined as follows (Bubb et al., 2009; Butchart et al., 2007):

$$\mathrm{RLI}\,(t) = 1 - \frac{\sum_{s=1}^{N(t)} W\,[C\,(s,t)]}{N\,(t) \cdot W\,(\mathrm{EX})}, \tag{1}$$

where C is the red list category of species s in year t; N is the total number of species with red list categories least concern (LC), near threatened (NT), vulnerable (VU), endangered (EN), critically endangered (CR), regionally extinct (RE), extinct in the wild (EW), or extinct (EX) in year t; and W is a predefined red list weight. According to the "equal-steps" approach (Butchart et al., 2004), the latter is defined as

$$W\,(C) = \begin{cases} 0 \text{ if} C = \mathrm{LC} \\ 1 \text{ if} C = \mathrm{NT} \\ 2 \text{ if} C = \mathrm{VU} \\ 3 \text{ if} C = \mathrm{EN} \\ 4 \text{ if} C = \mathrm{CR} \\ 5 \text{ if} C \in \{\mathrm{EX}, \mathrm{EW}, \mathrm{RE}\} \end{cases} \tag{2}$$

Because our application of the RLI is to national red lists, the relevant extinction category is RE, rather than EX or EW.

When comparing RLIs for different years, it is important that the indices be calculated with the exact same sample of species and that changes in red list categories are disregarded if they are due to improved knowledge, changes in taxonomy, and so forth, as opposed to actual population changes (Bubb et al., 2009, p. 7). Thus, we recalculated (backcast) earlier RLIs based on the knowledge in the most recent red list. Species included in the most current red list but not in an earlier red list (or listed there as data deficient [DD], not applicable [NA], or not evaluated [NE]) were added to the earlier list with the most current red list category, assuming $C(s, t_1) = C(s, t_2)$. The most current red list categories were also assigned to species whose categories had been changed for reasons other than actual population changes.

Threat scores

In accordance with IUCN's (2013) standards, Norwegian Red Lists report on threats (Artsdatabanken, 2018b, pp. 8–10; Artsdatabanken, 2020, pp. 16–19) but use a threat classification scheme that differs from IUCN (2022b) (complete list of the main threats reported in Appendix S1). For each threat factor affecting a given red list species, the red list provides information on the timing, scope, and severity of the threat. Threats with a timing other than ongoing were discarded (with the exception of RE species, for which all threats were included irrespective of timing). By doing so, we identified threats whose management would directly improve conditions for threatened species (see details in "Timing of threats"). The severity of a threat was quantified as the population decline caused by

TABLE 1 Values for the severity of threats, extinction probabilities of species, and collapse probabilities of ecosystems used to estimate threat scores and the expected loss of species and ecosystems.[a]

Variable	Range (%)	Distribution	Mean (%)
Severity (σ)			
No or negligible decline	0–2	Increasing	1.5
Slow but significant decline	2–20	Uniform	11.0
Rapid decline	20–100	Decreasing	40.0
Unknown	0–100	Beta(2, 20)	9.1
Species extinction probability within 50 years (R_{50})			
Least concern	0–2	–	0.0
Near threatened	2–5	Uniform	3.5
Vulnerable	5–43[b]	Uniform	24.0[b]
Endangered	43[b]–97[b]	Uniform	70.0[b]
Critically endangered	97[b]–100	Decreasing	97.8[b]
Regionally extinct	100	–	100.0
Ecosystem collapse probability within 50 years (R_{50})			
Least concern	0–2	–	0.0
Near threatened	2–5	Uniform	3.5
Vulnerable	5–20	Uniform	12.5
Endangered	20–50	Uniform	35.0
Critically endangered	50–100	Decreasing	62.5
Collapsed	100	–	100.0

[a]The mean values are used for the best estimate and the distributions for quantifying uncertainty.
[b]Values valid only for species with generation times of <3.3 years (details in Table 2 and the section "Expected loss of species").

the threat (measured in percent decline over 10 years or 3 generations).

For each threat factor (F) for each red-listed species (s), a threat score (θ) in year t can be calculated. Butchart (2008) and McGeoch et al. (2010) did so by letting $\theta(s, F, t) = 1$ for the dominant F affecting species s at t and $\theta(s, F, t) = 0$ for all remaining threat factors. We estimated θ as the severity (σ) scaled in such a way that all threat factors affecting a given species sum to unity:

$$\theta(s, F, t) = \frac{\sigma(s, F, t)}{\sum_{i=1}^{m_F} \sigma(s, i, t)}, \tag{3}$$

where m_F is the number of threat factors (possible values of σ are listed in Table 1). In contrast to previous studies (Garnett et al., 2018; Kyrkjeeide et al., 2021; Mair et al., 2021), we ignored the scope (i.e., proportion of the population affected by the threat) because severity quantifies the overall decline in the total population caused by a threat (Artsdatabanken, 2018b, p. 9; Artsdatabanken, 2020, p. 18; IUCN, 2013). If severity had been used to quantify the decline only in the affected proportion of the population, then in Equation (3) severity would have to be multiplied by scope. [See "Note added in proof" below.]

The red list guidelines do not specify thresholds for the negligible category of severity, so we set it arbitrarily one-tenth of the upper threshold of the following category. The values used are the arithmetic means of the respective intervals (given the distributions listed in Table 1), whereas unknown values of severity were set at a slow decline of 9.1% (mean of a beta distribution with parameters 2 and 20, which makes negligible and rapid declines equally likely during the resampling procedure [see "Quantification of Uncertainty"]).

Attributing RLI trends to threats (ΔRLI)

It has been suggested that the contribution of single threats to temporal trends in the RLI should be measured (BIP, 2020c, 2020d), an approach pioneered by Butchart (2008) and McGeoch et al. (2010). We refer to the change in RLI between times t_1 and t_2 that is solely caused by threat factor F as ΔRLI:

$$\Delta\mathrm{RLI}(F, t_1, t_2) = \frac{\sum_{s=1}^{N(t_2)} \Delta W(s, F, t_1, t_2)}{N(t_2) \cdot W(\mathrm{RE})}, \tag{4}$$

where ΔW is the proportion of the temporal change in the red list weight of species s attributable to F between the red list assessments at times t_1 and t_2.

To explicate the meaning of ΔRLI, if F is the only threat factor causing changes in categories between t_1 and t_2, RLI(t_2) would equal RLI(t_1) + ΔRLI(F, t_1, t_2). The ΔRLI is negative if the average effect of F on all species has increased, causing increase in extinction risk for the species assessed. The sum

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of all threat-wise changes equals the difference between subsequent RLI values: $\sum_{i=1}^{m_F} \Delta \mathrm{RLI}(i, t_1, t_2) = \mathrm{RLI}(t_2) - \mathrm{RLI}(t_1)$.

We estimated ΔW as follows, which seems to be in line with previous studies (Butchart, 2008; McGeoch et al., 2010):

$$\Delta W(s, F, t_1, t_2) = \begin{cases} W[C(s, t_1)] \cdot \theta(s, F, t_1) - W[C(s, t_2)] \cdot \theta(s, F, t_2) & \text{if } C(s, t_1) \neq C(s, t_2) \\ 0 & \text{if } C(s, t_1) = C(s, t_2) \end{cases}. \tag{5}$$

A positive ΔW indicates that F decreased, causing a decrease in the red list category of species s, whereas a negative ΔW indicates that F increased, causing an increase in extinction risk for species s. In cases where a species retains the same red list category, Equation (5) results in $\Delta W = 0$ for all F, irrespective of any changes in the threats' severity (Butchart, 2008; McGeoch et al., 2010).

Attributing RLI values to threats (δRLI)

An obvious alternative to the former approach, although it does not seem to have been formally described, is to attribute the total RLI to threat factors, or, more precisely, the total deviation of the RLI from unity. In other words, this approach does not ask to what degree a threat has contributed to the temporal change of the RLI; rather, it asks to what degree it contributes to the actual deviation of the RLI from the reference value (i.e., unity).

Combining Equations (1) and (3), the partial deviation of the RLI caused by F in year t can be expressed as

$$\delta \mathrm{RLI}(F, t) = \frac{\sum_{s=1}^{N} W[C(s, t)] \cdot \theta(s, F, t)}{N(t) \cdot W(\mathrm{RE})}. \tag{6}$$

This definition ensures that $\sum_{i=1}^{m_F} \delta \mathrm{RLI}(i, t) = 1 - \mathrm{RLI}(t)$ (i.e., that the sum of all threat-wise deviations equals the total deviation of the RLI from unity). To explicate the meaning of δRLI, if F is completely removed at t, RLI(t) would increase by δRLI(F, t). Or, if F is the only threat factor affecting any species at t, RLI(t) would equal 1 − δRLI(F, t).

It is not possible to directly convert ΔRLI and δRLI into each other. This is because species whose red list category has not changed are ignored when calculating ΔRLI. If one modifies ΔRLI so that all species are included (i.e., the upper part of Equation 5 is applied to all species), the modified ΔRLI* would measure the temporal change in δRLI (i.e., the relation between the 2 metrics would be $\Delta \mathrm{RLI}^*[F, t_1, t_2] = \delta \mathrm{RLI}[F, t_1] - \delta \mathrm{RLI}[F, t_2]$).

Expected loss of species (ELS_{50})

By the expected loss of species within 50 years due to F, abbreviated as $\mathrm{ELS}_{50}(F, t)$, we refer to the number of red-listed species expected to be driven to extinction by F within a time frame of 50 years in the absence of mitigation and based on the state of red-listed species at time t. This expected loss of species due to F can be estimated as

$$\mathrm{ELS}_{50}(F, t) = \sum_{s=1}^{N} R_{50}(s, t) \cdot \theta(s, F, t), \tag{7}$$

where $R_{50}(s, t)$ is the extinction probability of species s within the 50-year interval starting at time t. Red list categories are translated into extinction probabilities with red list criterion E (see Table 2). This requires the conversion of extinction probabilities to a common time frame of 50 years. For extinctions due to catastrophes, one can assume that the instantaneous extinction rate does not change over time. In this case, the conversion from time frame τ to the common time frame $T = 50$ years is

$$p'_T = 1 - \left(1 - p_\tau\right)^{T/\tau}, \tag{8}$$

where p_τ is the likelihood that a species goes extinct within time frame τ. For instance, an extinction probability of 50% within 10 years is mathematically identical to an extinction probability of 96.875% within 50 years.

For extinctions due to population declines, no such mathematical conversion is possible. Most likely, Equation (8) underestimates extinction probabilities for time frames shorter than 50 years (CR, EN) and overestimates extinction probabilities for time frames longer than 50 years (VU, NT). We therefore rounded the extinction probabilities obtained using Equation (8) upward for CR and EN and downward for VU and NT (to the nearest percent) (Table 2). We tested the sensitivity of the resulting estimate to violations of this assumption (Appendix S4).

Once the threshold values between red list categories have been converted to a common time frame of 50 years, the extinction probability of each species can be calculated as the mean of the distribution between the surrounding threshold values:

$$R_{50}(s, t) = \overline{\mathrm{dist}\left\{1 - \left[1 - p_L(s, t)\right]^{T/\tau_L(s,t)}, 1 - \left[1 - p_U(s, t)\right]^{T/\tau_U(s,t)}\right\}}, \tag{9}$$

where dist is the appropriate distribution (uniform or beta distribution, see below) within the limits provided; L and U refer to the lower and upper threshold values, respectively, of p and τ, corresponding to the red list category and generation time of species s at time t (Table 2); and the bar represents the arithmetic mean. For uniform distributions, the mean equals the midpoint between the lower and upper limit. An exception was made for LC species ($p_T < 2\%$) because it

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TABLE 2 Probabilities of extinction (p_τ) and the corresponding time frames (τ) for species that are assessed according to the International Union for the Conservation of Nature (IUCN) Red List criterion E.[a]

Threat category assignment threshold[b]				
Low	**High**	**p_τ (%)**	**τ (years)**	**p_{50} (%)**
LC	LC[c]	0	100	0
NT	–	5	100	2
VU	NT	10	100	5
EN	VU	20	max{20, min[100, 5 · $G(s)$]}	10–43
CR	EN	50	max{10, min[100, 3 · $G(s)$]}	29–97
RE	CR	100	100	100

[a]For example, the threshold between VU and NT is defined as an extinction probability of 10% within 100 years. Values follow IUCN (2012b) and for NT Artsdatabanken (2020). The $G(s)$ is the generation time of species s. For ecosystems, τ is 50 years for the low thresholds of EN and CR and for the high thresholds of VU and EN. The values for p_{50} provide (ranges of) the extinction probability within 50 years, given that the instantaneous extinction rate is constant.
[b]Threat categories: LC, least concern; NT, near threatened; VU, vulnerable; EN, endangered; CR, critically endangered; RE, regionally extinct.
[c]The high threshold for LC is set to 0 (i.e., it equals the low threshold of LC rather than of NT).

is unrealistic to assume that 1% of all LC species go extinct within 50 years. For that reason, $R_{50}(s, t)$ was fixed at 0 for LC species.

It is also possible to estimate an expected loss of species with the equal-steps approach. In this case, Equation (7) is adjusted by substituting $R_{50}(s, t)$ with $W(s, t) / W(\text{EX})$.

Quantification of uncertainty

Several sources of uncertainty in ΔRLI, δRLI, and ELS_{50} are readily quantified: extinction probability of DD species, actual threat factors if threats are reported as unknown, and precise values of the parameters σ and R_{50}. All 3 sources of uncertainty can be quantified using a resampling procedure, where different values are assigned at random. We generated 100,000 random numbers for each parameter and species.

For the extinction probability of DD species, this is accomplished by assigning to them red list categories LC–RE with probabilities P that correspond to the relative frequencies of the categories (Butchart et al., 2010). We formalized this as

$$P(C, t) = \frac{n(C, t)}{\sum_i n(i, t)}, \tag{10}$$

where $n(C,t)$ is the number of species that have red list category C in year t.

Threats listed as unknown can be treated alongside other threats, thus visualizing the magnitude of unknown threats. Alternatively, unknown threats may be converted into known threats, assuming that the distribution of unknown threats across different threat factors equals the distribution of known threats. This can be accomplished by assigning novel threats according to the frequency distribution of known threats. As an approximation, the average estimate is calculated using a correction factor $d(t)$ defined as:

$$d(t) = 1 + \frac{\delta\text{RLI}(\text{unknown}, t)}{\sum_{i \neq \text{unknown}} \delta\text{RLI}(i, t)}. \tag{11}$$

To obtain values for $\delta\text{RLI}(F, t)$ that are corrected for this source of uncertainty, they have to be multiplied by $d(t)$. Corrected values of $\text{ELS}_{50}(F, t)$ can be obtained analogously. When the same correction is intended for $\Delta\text{RLI}(F, t)$, 2 separate correction factors $d^+(t)$ and $d^-(t)$ need to be estimated (using Equation 11) for and applied to threats that have positive and negative values of $\Delta\text{RLI}(F, t)$, respectively, and to be summed thereafter.

The best estimates of ΔRLI, δRLI, and ELS_{50} are based on the values of σ, p, and τ given in Tables 1 and 2 (i.e., on the arithmetic means of the intervals of possible values for these parameters). The same intervals can be used to quantify the uncertainty concerning the best estimates by generating random numbers within the interval limits.

The distributions used were as follows:

$$\text{unif}(L, U) = L + (U - L)\,\upsilon, \tag{12}$$

$$\text{incr}(U) = U\,\text{B}(3, 1), \tag{13}$$

$$\text{decr}(L) = L + (1 - L)\,\text{B}(1, 3), \tag{14}$$

$$\text{beta}(\mu) = \text{B}\left(2, \frac{2}{\mu} - 2\right), \tag{15}$$

where L is the lower limit of the distribution (lower limits of incr [increasing] and beta = 0); U is the upper limit of the distribution (upper limit of decr [decreasing] and beta = 1); $\text{B}(\alpha, \beta)$ is a beta-distributed random number; μ is the arithmetic mean of beta; and υ is a uniformly distributed random number between 0 and 1. The means of the distributions are $(L + U)/2$ for unif, $3\,U/4$ for incr, $1/4 + 3\,L/4$ for decr, and μ for beta. Table 1 shows which distribution was used in which case. Uncertainty quantified in this way accounts for the ignorance of the exact placement of σ, p, and τ within the relevant intervals. Estimates

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TABLE 3 Number of species in 2010, 2015, and 2021 and ecosystems in 2018 on the Norwegian Red List by threat category.

Red list	Total	RE	CR	EN	VU	NT	LC	DD	NA	NE	RLI	ΣELS_{50}
Species												
2010[a]	30,555	127	284	890	1265	1310	16,762	809	2580	6528	0.9197	1146
2010[b]	21,447	127	290	908	1266	1302	16,745	809	–	–	0.9191	1160
2010(15)[c]	22,212	119	249	918	1296	1303	17,572	755	–	–	0.9232	1126
2010(21)[c]	23,744	114	299	1001	1519	1395	18,675	741	–	–	0.9200	1247
2015[a]	31,325	119	247	901	1294	1302	17,594	755	3018	6095	0.9238	1115
2015[b]	22,212	119	252	916	1294	1297	17,579	755	–	–	0.9232	1127
2015(21)[c]	23,744	114	302	999	1517	1389	18,682	741	–	–	0.9200	1247
2021[a]	33,042	112	299	977	1528	1391	18,696	741	3256	6042	0.9206	1231
2021[b]	23,744	112	305	997	1514	1392	18,683	741	–	–	0.9201	1246
Ecosystems												
2018[d]	229	0	4	22	40	34	103	7	0	19	0.8069	16.96
2018[e]	808	0	4	35	124	70	506	21	0	48	0.8812	33.62

Note: Data from Artsdatabanken (2010, 2015, 2018a, 2021).

Abbreviations: CR, critically endangered; DD, data deficient; EN, endangered; LC, least concern; NA, not applicable; NE, not evaluated; NT, near threatened; RE, regionally extinct (collapsed for ecosystems); RLI, red list index; VU, vulnerable; ΣELS_{50}, cumulative expected loss of species within 50 years.

[a]Results obtained when species downlisted due to rescue effects in neighboring countries are included with their downlisted categories.

[b]Results obtained when downlisted species received the red list categories assigned prior to downlisting.

[c]Red list assessment for year 1 corrected for knowledge in year 2.

[d]Results obtained when assessed major ecosystem types are treated as single units.

[e]Results obtained when assessed major ecosystem types are disaggregated into minor types.

are reported as the best estimate and its 95% confidence interval (CI).

RESULTS

According to the most recent Norwegian Red List for species, the RLI for 2021 was 0.92009 (95% CI 0.91965–0.92050) (Table 3). Corrected for current knowledge, the RLI has increased by 0.00010 RLI units since 2010 (Figure 1). The contribution of threat factors to this increase was measured by their ΔRLI. According to this metric, the most important threat was land-use change, which was responsible for an increase of 0.000186 RLI units (0.000145–0.000216) from 2010 to 2021 (Figure 1; Appendix S1). Several threats would have led to a decrease in RLI (i.e., had negative ΔRLI), but they were more than outweighed by the threats with positive ΔRLI.

In 2021, the deviation of the RLI from the reference value was 0.07991. The contribution of threat factors to this deviation was measured by their δRLI. According to this metric, too, the most important threat was land-use change, accounting for 0.05958 RLI units (95% CI 0.05930–0.05991) (Figure 2; Appendix S1). The importance of this and most other threats increased over time, whereas other and unknown threats decreased.

When the importance of threat factors was measured in terms of the expected loss of species (ELS_{50}), land-use change was again the most important threat, accounting for 934 species (95% CI 922–946) out of a total expected loss of 1246 species (1231–1261) (Figure 3; Appendix S1). However, the ranking of some of the other threats was slightly different (e.g., pollution was more important than climate change). The total expected loss of species, across threats, decreased by 1 species from 2010 to 2021 (Table 3).

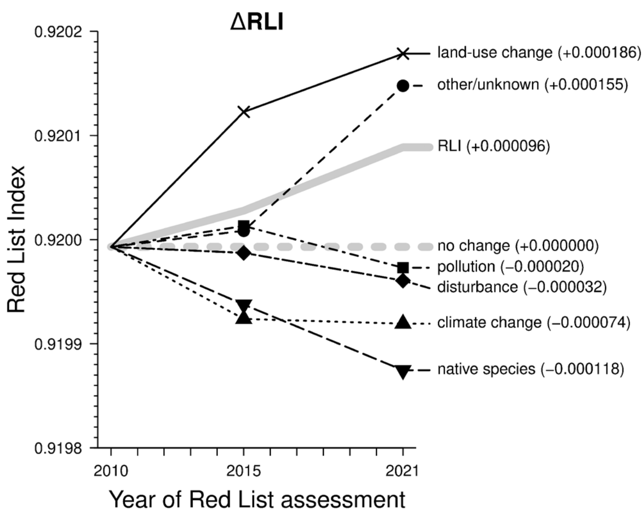

FIGURE 1 Change in the red list index (RLI) values for species in Norway over time and the contribution of the main threat factors to this change (ΔRLI) based on 142 species (out of a total of 23,744 species assessed) whose red list categories changed due to population changes (solid gray line, RLIs for 2010, 2015 [corrected for knowledge in 2021], and 2021; dotted gray line, no change; black lines, ΔRLI of the most important threat factors; values in parentheses, ΔRLI for 2021 compared with 2010; confidence intervals in Appendix S1).

The above results took the uncertainty due to DD species into account but ignored the uncertainty created by unknown threats (which were included in other threats). The same estima-

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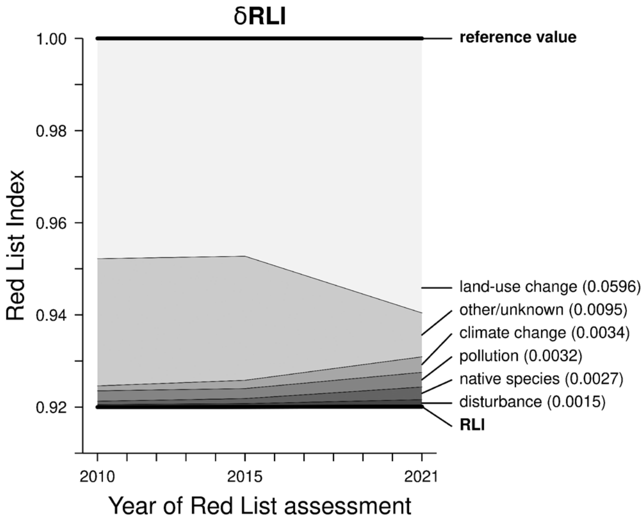

FIGURE 2 Contribution of different threat factors to deviation of red list index (RLI) values for species in Norway from the reference value (δRLI) based on 23,744 species (including 741 data deficient species) (top line, reference value of 1; bottom line, RLIs for 2010, 2015 [corrected for knowledge in 2021], and 2021; shading, δRLI of the most important threat factors; values in parentheses, δRLI for 2021; confidence intervals in Appendix S1).

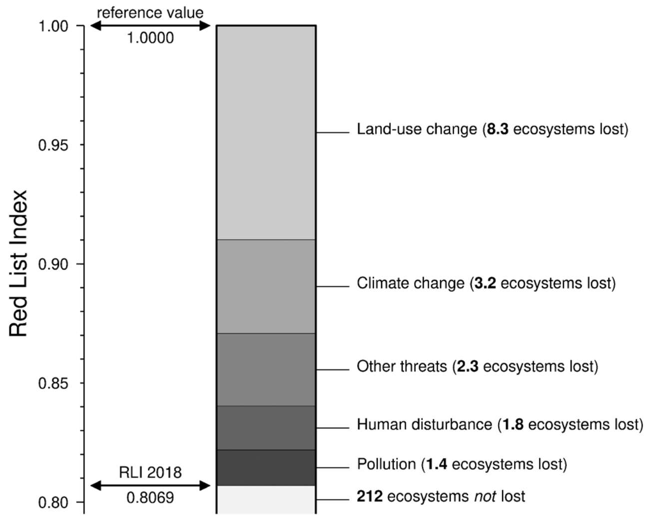

FIGURE 4 Contribution of different threat factors to deviation of red list index value for ecosystems in Norway in 2018 from the reference value (δRLI) based on 229 ecosystems (including 7 data deficient systems) (shading, δRLI of the most important threat factors; values in parentheses, expected numbers of ecosystems lost within 50 years; confidence intervals in Appendix S5).

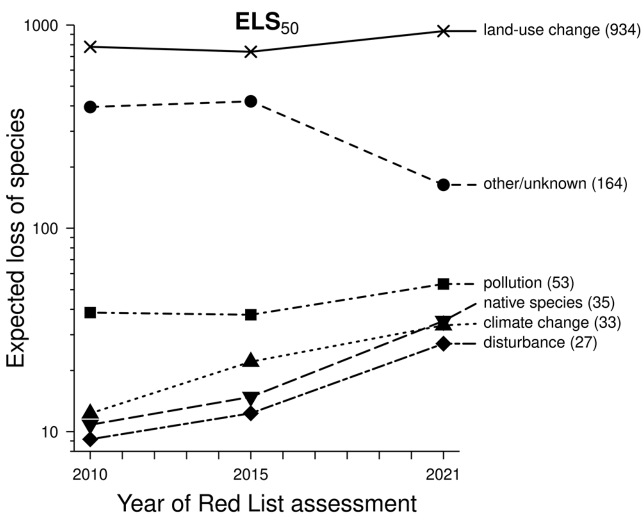

FIGURE 3 The expected loss of species within 50 years in Norway attributable to different threat factors (ELS_{50}) according to red list assessments made in 2010, 2015, and 2021 based on 23,744 species (including 741 data deficient species) (values in parentheses, ELS_{50} for 2021; confidence intervals in Appendix S1). The *y*-axis is on log scale.

tions were carried out excluding DD species (Appendix S2) and after converting unknown threats into known threats (Appendices S3 & S7–S9). The exclusion of DD species had only minor effects on ΔRLI and δRLI (compare Appendices S1 & S2), whereas all estimates for ELS_{50} were lower, as is to be expected when the sample of species included is smaller. The conversion of unknown threats did not affect the cumulative estimates of ΔRLI, δRLI, and ELS_{50}, but it increased the absolute values of all threat-wise estimates except unknown threats (compare Appendix S1 with Appendix S3 and Figures 1–3 with Appendices S7–S9). A sensitivity analysis showed that the ranking of threats according to their ELS_{50} was rather robust to the specific threshold values chosen (Appendix S4).

For ecosystems, the RLI in 2018 was 0.8069 (95% CI 0.8010–0.8124). Because the previous red list for ecosystems was not comparable, it was not possible to calculate ΔRLI values. However, δRLI and ELS_{50} could be estimated. The most important threat to ecosystems was land-use change, accounting for 0.0899 RLI units (0.0858–0.0944), for 8.3 ecosystems (7.5–9.2) out of a total expected loss of 17.0 ecosystems (15.8–18.3) (Figure 4; Appendix S5).

When all major ecosystem types were disaggregated into their subordinated minor ecosystem types, the number of ecosystems included increased from 229 to 877. As a result, the corresponding RLI was 0.8812 (95% CI 0.8787–0.8832), almost all δRLI values decreased (single exception was hunting and gathering), and all ELS_{50} values increased (Appendices S6 & S10). The 2 greatest threats were still land-use change and climate change, but the ranking of some other threats changed (compare Appendices S5 & S6). For instance, non-native species became a more prominent threat, whereas the importance of human disturbance decreased.

DISCUSSION

Comparison of the 3 metrics

The RLI for species in Norway was around 0.92 and increased (i.e., improved) marginally from 2010 to 2015 and to 2021.

The ΔRLI measures the contribution of a threat to the change in RLI relative to a previous RLI. On the other hand, δRLI measures the contribution of a threat to the deviation of

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the RLI relative to the reference value (unity). These 2 metrics, therefore, answer quite different questions. For example, 1 threat (pollution, say) may have zero ΔRLI but still explain most of the value of RLI. This is the case if most species are threatened by pollution, but this does not change between 2 red list assessments. The reverse situation is conceivable too: 1 threat (climate change, say) may have a very small δRLI but still account for the entire change of RLI between 2 red list assessments. This is the case if all the other (and dominating) threats remain unchanged, so that the entire change is due to a previously insignificant threat.

In our data set, this can be illustrated with land-use change. According to ΔRLI, land-use change led to the greatest improvement in RLI (Figure 1; Appendix S1). According to δRLI, however, land-use change was the single most important obstacle to reaching a higher RLI (Figure 2; Appendix S1). These findings are not mutually exclusive: ΔRLI may indicate that management measures have started to show first results, whereas δRLI shows that a lot remains to be done.

Management authorities will in many cases be interested in the contribution of a given threat to the total deviation from the reference value (i.e., in δRLI). Furthermore, while δRLI accounts for the entire deviation of the RLI from 1, ΔRLI only accounts for a fraction of it. In our Norwegian example, therefore, the largest δRLI (land-use change) explained 75% of RLI's deviation from unity, whereas the corresponding ΔRLI explained merely 0.2%, as can also be seen by comparing the *y*-axes of Figures 1 and 2 (cf. Appendix S1).

Expected loss of species conveys roughly the same information as δRLI, but it does so in a very different unit: species or ecosystems. This makes ELS_{50} a much more intuitive metric and pedagogically better suited to communicate with the public. One should be aware that ELS_{50} is a cumulative statistical measure, however. For example, an expected loss of 100 species does not mean that 100 specific (nameable) species will be lost within 50 years. It may mean that one can expect, for example, 70% of 143 EN species to go extinct (or 24% of 418 VU species, etc.). Another important aspect is that ELS_{50} assumes the absence of mitigation.

A drawback of ELS_{50} is that it cannot reasonably be compared across different taxa, countries, or regions because the loss of species is obviously a function of the number of species present in a given taxon, country, or region. However, ELS_{50} is well suited as a national indicator for comparing and illustrating the magnitude of different threats within a country (or taxon or region) and their change through time.

Weighting schemes

If threats are ranked according to their δRLI and ELS_{50} values, they may end up in a slightly different order (Figures 2 & 3; Appendix S1). This is not a matter of the metrics chosen but a question of the weighting schemes used, which should be addressed separately.

When introducing the RLI, Butchart et al. (2004) pointed out that it is possible to use different weightings of the red list categories when RLI is calculated. Butchart et al. (2004) advocated the equal-steps approach, which simply uses the integers from 0 (for LC) to 5 (for EX). The alternative is some kind of extinction-risk approach. This has been implemented using the threshold values of red list criterion A2 (Maes et al., 2019) or the averages of the standardized threshold values of all red list criteria (Butchart et al., 2004). However, these approaches assume a linear relationship between extinction probability and the threshold values of red list criteria A–D, an assumption that is doubtful at best. We have therefore based ELS_{50} on red list criterion E, which is defined precisely in terms of extinction probability.

One may also consider calculating RLI, ΔRLI, and δRLI with the extinction-risk approach. Whereas the extinction-risk approach more closely mirrors the actual number of surviving species, the equal-steps approach indicates the broader state of biodiversity.

When ELS_{50} and RLI are estimated using the same weighting scheme, they become convertible into each other and into other previously described measures. For example, ELS_{50} becomes identical to $N - N \cdot \text{RLI}$ (where N is the number of red-list-assessed species or ecosystems), to $T/5$ (where T is the "current threat score" [Butchart et al., 2007]), and to $N - C$ (where C is "conservation status" [Kyrkjeeide et al., 2021]).

Quantifiable sources of uncertainty

Three sources of uncertainty in ΔRLI, δRLI, and ELS_{50} can be quantified by using resampling procedures to estimate confidence intervals. This should always be done for the severity of threats. This parameter is recorded as an interval (Table 1) so that the precise value is unknown. This source of uncertainty, and for ELS_{50} the analogous ignorance of the precise value of R_{50}, has been taken into account in all our estimates.

A second source of uncertainty, which stems from DD species, has been quantified by assuming that the true but unknown red list categories of DD species have the same frequency distribution as the species that are known to be LC–RE (Butchart et al., 2010). We recommend that this source of uncertainty also be taken into account. However, ignoring it does not affect the estimates of RLI and ΔRLI and hardly affects δRLI, whereas it lowers the ELS_{50} estimates (compare Appendices S1 & S2).

The third uncertainty concerns cases in which threats are reported as unknown. In our main analyses, unknown threats were treated as a separate threat factor alongside the others. On the one hand, this had the advantage of allowing visualization of the magnitude of this specific source of uncertainty (Figures 1–3; Appendix S1). On the other hand, interpretation of some findings may be difficult. One of the most prominent temporal patterns in our data set was a decrease in the importance of other and unknown threats (Figures 1–3). This pattern was driven by unknown threats alone, indicating that it was caused by increasing knowledge of threats. This, in turn, means that at least some of the increases in the remaining threats must be due to better knowledge, too, rather than due to a

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real increase in their importance. If the unknown threats are removed mathematically, by distributing their ΔRLI, δRLI, or ELS_{50} value over the remaining threats proportional to their respective sizes, results were markedly different (Appendices S3 & S7–S9). The choice between these 2 alternatives should thus be based on the exact question one wishes to answer.

Unquantified sources of uncertainty

There are additional sources of uncertainty that we did not try to quantify because they cannot easily be addressed by resampling procedures. Using ΔRLI, δRLI, or ELS_{50} thus entails the assumption that these uncertainties would not have affected the results. The first, and most obvious, of these is the uncertainty whether, and the assumption that, red list categories have been correctly assigned, threats have been correctly identified, and their severity has been correctly classified. Second, the quantification of threat severity in terms of population decline is somewhat problematic because it does not capture other threatening processes, such as population fluctuations and habitat fragmentation. Third, while reasons for changes in red list categories are reported in Norwegian Red Lists, reasons for changes in threat factors are not. It is therefore uncertain whether a reported change in threat factors for the same species in subsequent red lists is due to improved knowledge or real changes. Fourth, Equation (3) is based on the assumption that threats have additive effects on the species affected. Possible interactions between multiple threats thus remain unaccounted for.

These 4 uncertainties are not inherent to the proposed metrics. Rather, they reflect limitations of the current IUCN methodology and the specific red list data sets analyzed. If, for instance, red lists report on the reasons for changes in threats or on interactions between threat factors, this kind of information could be included in the metrics discussed here. In addition to these 4 uncertainties, there are 2 assumptions that are specific to ELS_{50}. First, it is uncertain whether the thresholds of red list criterion E adequately describe the extinction probabilities of species that have been assessed using other criteria (A–D). In fact, IUCN (2022a, p. 16) notes that "the thresholds in criteria A–D may be more precautionary" and explicitly discourages inferring extinction probability from these criteria (IUCN, 2022a, p. 62). However, other extinction-risk approaches would have to be based on other assumptions, which may be even less plausible (e.g., that the thresholds of criteria A–D are proportional to extinction probabilities). In any case, our sensitivity analysis showed that this assumption affects the absolute value of the expected species loss, but it hardly affects the ranking of threat factors, which is the main interest for natural management (Appendix S4). Second, the conversion of extinction probabilities to a common 50-year time frame assumes that the instantaneous extinction rate does not change over time. The more common situation is that extinction probability increases as a population declines, however. Results of our sensitivity analysis suggested that the ranking of threat factors is quite robust to violations of this assumption (Appendix S4).

Timing of threats

When calculating threat metrics, we only included threats with timing recorded as ongoing (except for regionally extinct species, for which all threats were included [see "Threat scores" above]). This makes sense because only measures to alleviate ongoing threats would actually improve conditions for threatened species. This simple fact notwithstanding, however, the current red list category of a given species may still be a remnant of historical threats. For instance, a species may have become CR because of hunting in the 19th century. Although hunting may have been banned 100 years ago, the species may not have fully recovered from this historical threat, and the most relevant current threat may be land-use change. In such cases, even the removal of all ongoing threats would not guarantee that the species reaches LC. This may be an argument in favor of including historical threats as well. We recommend not doing so, however. First, detailed analyses would be necessary for any given species to establish the persisting relevance of historical threats. Second, we suggest that the metrics we devised should be understood mainly as guides to management authorities, for which ongoing threats will be the major focus.

Caveats regarding RLI for ecosystems

In red lists of species, the level of analysis is seldom problematized. They contain taxa at the species level, they may contain subspecific taxa (subspecies or varieties), but they must not contain superspecific taxa (e.g., genera) (IUCN, 2022a, p. 4). This rule is important also for the calculation of RLI or derived metrics because these are affected by the number of the entities assessed. The species level is, at least according to some species concepts (Ghiselin, 1997; Hull, 1997), the only objective, "self-defining," level in biological taxonomy. (According to the remaining species concepts, biological taxonomy does not have any objective levels.) However, for ecosystems no such level exists. This represents a problem for the calculation of RLI and derived metrics. It invalidates comparisons of ecosystem RLIs across countries. At a given geographical scale (e.g., global or national), however, ecosystem RLIs may be compared across times or threats, provided the same delimitation criteria are used.

Norwegian ecosystems have been red list assessed at different levels of the underlying EcoSyst framework (Halvorsen et al., 2020) (see "Norwegian Red List data" above). While some major ecosystem types have been assessed as such, others have been disaggregated into their subordinated minor ecosystem types. Our results showed that it matters a lot whether ecosystem RLIs are calculated for the ecosystem types reported in the red list (which contains a mixture of major and minor types) or whether RLIs are calculated at the minor ecosystem level. When all major types were disaggregated into minor types, the RLI increased from 0.807 to 0.881 (Table 3), whereas δRLI values decreased and ELS_{50} values increased (compare Appendices S5 & S6 and Figure 4 & Appendix S10). Even at a national scale, and with a clearly defined framework for outlining ecosys-

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tem types, comparisons of RLI or of RLI-derived metrics across years thus require that the same resolution (i.e., exactly the same set of ecosystem types) be used at all times.

Comments on the RLI

IUCN's official RLI guidelines state that the RLI can "show trends in extinction risk [... and] identify ecosystems and habitats where the extinction risk of species is changing most rapidly" (Bubb et al., 2009, p. 3). This focus on trends and change is echoed in the guidelines' statement that the RLI is "based on movement of species status through the IUCN Red List Categories" and that its calculation requires all species to "have been assessed for the IUCN Red List at least twice" (Bubb et al., 2009, pp. 3, 4) (see also Butchart et al.'s [2007, p. 7] statement that "the RLI is calculated from changes between [red list] categories"). However, it remains unclear why the use of the RLI should be restricted to such cases. The RLI for time t is a function only of the red list categories assigned at the very same time t (see Equation 1). Whereas the original definition of the RLI (Butchart et al., 2004) required a comparison between at least 2 assessments, the current version (Butchart et al., 2007) does not. Therefore, the RLI cannot be used only to elucidate trends of biodiversity; it can also be used to elucidate the state of biodiversity. Likewise, δRLI and ELS_{50} not only allow attributing changes of extinction risk to different threat factors, but also enable the identification and further analysis of the threat factors currently precluding all species from becoming LC. Here, the phrase *state of biodiversity* must not be taken to imply a constant biodiversity, however. This is because even a constant RLI, as long as it is <1, implies that native biodiversity is in a state of decline.

The RLI guidelines instruct one to exclude from RLI calculations all species extinct at the time of the first red list assessment (Bubb et al., 2009, p. 7). While this makes sense at the global scale, we have not followed this instruction here because RE species may return. In Norwegian Red Lists, species that have gone extinct after 1800 are listed as RE (whereas species extinct before 1800 are omitted or listed as NA). For several of these RE species, natural recolonization is possible and anthropogenic reintroductions are conceivable. In fact, from 2010 to 2021, 2 former RE species recolonized Norway from Sweden (the moth *Acronicta aceris* and the beetle *Odacantha melanura* [Artsdatabanken, 2021]). Admittedly, the year 1800 is an arbitrary date, but so is the year of the first red list assessment. We therefore recommend that every application should agree on a specific starting date and keep to it.

We posed the question how one can best quantify the overall impact of the threats affecting the species or ecosystems on a given red list. To this end, we compared 3 different metrics. The temporal change in the RLI caused by a threat (ΔRLI) can only be used if each species has been assessed at least twice, and it only quantifies the contribution of a threat to the change between 2 assessments, which may be very small. If one is interested in how much a threat contributes to the entire deviation of the RLI from its reference value, one should use δRLI. Finally, the expected loss of species or ecosystems (ELS_{50}) conveys roughly the same information as δRLI, but it does so in a unit that may be easier to communicate to stakeholders and the general public.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

NOTE ADDED IN PROOF

As a reaction to the publication of this paper, IUCN (2022b) clarified its definition of *severity*, stating that, "Severity should be scored within the scope of the particular threat." According to this definition, scope (φ) and severity (σ) need to be multiplied when calculating the threat score. Thus, Eq. 3 becomes

$$\theta(s,F,t) = \frac{\varphi(s,F,t)\cdot\sigma(s,F,t)}{\sum_{i=1}^{m_F}\varphi(s,i,t)\cdot\sigma(s,i,t)}. \tag{3}$$

Our results are unaffected by this change because the Norwegian Red Lists define *severity* as the decline in the entire population caused by a threat. The programing code has now been updated (Sandvik, 2023b) so that calculations based on both definitions can be carried out.

OPEN RESEARCH BADGES

This article has earned Open Data and Open Materials badges. Data and materials are available at https://doi.org/10.5281/zenodo.7893216 and https://doi.org/10.5281/zenodo.7930001.

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