

## Accelerated Article Preview

# Nearly half of reef-building corals face elevated relative risk of extinction

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**Title : Nearly half of reef-building corals face elevated relative risk of extinction**

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## Summary

Coral reefs are diverse marine ecosystems that provide ecological functions and economic and social benefits across over 100 tropical countries. Warming driven by climate change is a primary threat to coral reefs and is increasing the frequency of global coral bleaching events. Here we reassessed the IUCN Red List status of 892 reef-building coral species, first assessed in 2008<sup>1</sup>. Because species-level population trends are unavailable for most reef-building corals, population reductions were inferred using proxies based on global coral cover trends and projected annual severe bleaching under SSP2-4.5, both over three decades, adjusted using trait-based estimates of species vulnerability. Of the 774 species with sufficient data to be assessed, 340 (44%) were classified as threatened under IUCN Red List criteria. Thirty-three species were assessed as

Critically Endangered, 251 as Endangered, and 56 as Vulnerable, most due to risk of population reduction associated with projected thermal stress. These findings predate the three hottest years on record and the fourth global coral bleaching event (2023-2025), and the first exceedance for an annual mean of the 1.5°C global warming threshold. The findings reinforce the importance of limiting further warming to maintain coral biodiversity and reef ecosystem function. The Red List assesses the relative extinction risk of species, whereby species are placed in categories of increasing risk by comparing their population size, decline and geographic range against standardised thresholds. The Red List does not predict whether or when a species may go extinct. As the ranges of coral species remain under-surveyed, future assessments would be strengthened by species-level population data and thermal-stress and recovery metrics that better capture range-representative dynamics.

## Main

Coral reefs are highly diverse marine ecosystems that provide essential ecological functions, and valuable economic and social benefits, across >100 tropical countries<sup>2</sup>. Warming due to global climate change is emerging as a primary threat to coral reefs and is triggering global bleaching events with increasing frequency<sup>3,4</sup>, with steady ocean warming evident since at least the 1960s and acceleration since 2015<sup>5</sup>. The first global coral bleaching event in 1998 resulted in mass mortality of corals, and a decline of 16% of hard coral cover on reefs globally<sup>6</sup>. In 2008 one-third of reef-building corals were classified as threatened with extinction using coral cover change as a proxy of decline<sup>1</sup>, subsequent global bleaching events (2010 and 2014–2017) each severely impacted 10-15% of coral cover<sup>7</sup>, and by 2020 global coral cover had declined by half<sup>8,9</sup>. The years 2023-25 have been the three hottest on record, with annual mean global temperature exceeding 1.5°C above pre-industrial levels in 2024<sup>10</sup>. Projections of seawater temperature to 2100, together with interactions with multiple threats such as pollution, fishing pressure, disease outbreaks, deoxygenation and acidification, primarily determine when and where, rather than if, conditions will become unviable for corals<sup>11-13</sup>.

In light of this escalating decline we reassessed the extinction risk of reef-building corals, that was first assessed in 2008<sup>1</sup> using the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species (RL). The RL is the global standard for estimating relative risk of extinction for species, prioritized by international conventions such as the Convention on Biological Diversity, the Convention on Trade in Endangered Species and others, and is thus a primary indicator used in allocating resources at national and other scales to conservation and biodiversity protection<sup>14</sup>. This reassessment of reef-building corals (Order Scleractinia plus reef-building octocorals and hydrocorals in the families Helioporidae, Tubiporidae, and Milleporidae) incorporates five main improvements in methods and data (see Suppl. Mat. and <sup>1,15,16</sup>), including: i) quantitative analysis of updated global data on coral cover change, ii) inclusion of a new dataset on temperature projections and future thermal stress, iii) updates to supporting datasets, particularly on coral taxonomy and species traits, iv) an increase in the number of species assessed from 845 to 892, and v) reduction in the number of Data Deficient (DD) species from 141 to 118, thereby increasing the number of species classified from 704 to 774. Limitations, including reliance on coral cover as a habitat proxy and a single thermal-stress metric (degree heating weeks, DHW; see Methods), warrant future refinement as data becomes available.<sup>14,16,17</sup>

Of the 774 species assessed, 340 (44%) were classified as threatened (Critically Endangered (CR) - 33 species; Endangered (EN) - 251; Vulnerable (VU) - 56), 16 (2%) were Near Threatened (NT), and 418 (54%) were Least Concern (LC) (Table 1). Of the species classified as threatened or NT, the majority (93%) were based on estimated population reduction (Table SI3) due to projected heat stress using a mid-range climate scenario SSP2-4.5 (Criterion A3, n=310), a minority on historical

decline in coral cover (A2, n=23), and one species based on both (A2, A3). Twenty four species qualified due to their small geographic range and continuing decline (B), three of these also qualifying under population reduction (A2). All range-restricted species were either threatened or NT.

**Table 1. IUCN Red List status of reef-building corals in 1998, 2008 and 2024.** Results for 2024 and the re-analysis of 1998 and 2008 were calculated using the updated methods applied in this study (see Suppl. Mat.). See Table SI4 for examples of species risk calculations. Percentage values are rounded to the nearest integer.

|                              | 2024       |                | 2008       |             | Pre-1998  |            |
|------------------------------|------------|----------------|------------|-------------|-----------|------------|
|                              | n          | %              | n          | %           | n         | %          |
| <b>Threatened (CR+EN+VU)</b> | <b>340</b> | <b>43.9</b>    | <b>145</b> | <b>18.7</b> | <b>52</b> | <b>6.7</b> |
| Critically Endangered (CR)   | 33         | 4.4            | 29         | 3.7         | 7         | 0.9        |
| Endangered (EN)              | 251        | 32.4           | 81         | 10.5        | 24        | 3.1        |
| Vulnerable (VU)              | 56         | 7.2            | 35         | 4.5         | 21        | 2.7        |
| Near Threatened (NT)         | 16         | 2.1            | 33         | 4.3         | 24        | 3.1        |
| Least Concern (LC)           | 418        | 54.0           | 596        | 77.0        | 698       | 90.2       |
| <b>Total classified</b>      | <b>774</b> | <b>(86.8%)</b> |            |             |           |            |
| <i>Data Deficient (DD)</i>   | 118        | (13.2%)        |            |             |           |            |
| <b>Total assessed</b>        | <b>892</b> |                |            |             |           |            |

### Corals face increasing relative extinction risk

Updates in methods and data used in this study were applied to revise earlier estimates of relative extinction risk for 1998 and 2008, enabling assessment of ‘genuine’ changes in extinction risk as defined by IUCN <sup>1,17</sup>. Extinction risk increased for 100 species from 1998 to 2008, and for 210 species from 2008 to 2024 (Table 1, Fig. 1a). Across both periods, the largest transition was species shifting status from LC to EN, and the largest increase in CR species occurred from 1998 to 2008. Only four species increased in extinction risk across both periods, all classified as LC in 1998, with three species classified as CR in 2024 (*Ctenella chagius*, *Dendrogyra cylindrus* and *Porites syverdrupi*) and one as VU (*Echinophyllia tarae*). No assessment has confirmed extinction of any warm water reef-building coral species <sup>18</sup>. Recalculation of extinction risk in earlier years enables evaluation of genuine changes in extinction risk using the Red List Index (RLI) <sup>17</sup>, which declined from 0.96 prior to 1998 to 0.74 in 2024 (Fig. 1b). This decline (-0.07 to -0.094 per decade) is faster than that of any other comprehensively assessed taxonomic group (-0.002 to -0.039 per decade). Some species improved in risk status (Table SI6): five species from NT in 1998 to LC in 2008, and 24 species from NT and VU in 2008 to LC and NT in 2024. Non-genuine revisions to the status for some species <sup>16,17</sup> resulted in a higher number of species now recognized as threatened in 1998 (52, compared to 13 estimated previously <sup>1</sup>), but a lower number threatened in 2008 (145, compared to 231) (Table SI6).

## Patterns of relative extinction risk

Our analysis covered the full global distribution of coral reefs, assessing 807 species from the Indo-Pacific and 85 from the Atlantic. The proportion of threatened species was consistent across the vast majority of coral reef regions (between 38-51% in the Indo-Pacific, Caribbean and Mediterranean, Fig. 2a) and highest in peripheral regions where species richness is low, ranges are small, and endemism is high, often under marginal reef conditions (e.g., Brazil, southeast Pacific, Japan; Fig. 2b). Data gaps, indicated by the proportion of Data Deficient species, were highest along the West African coast where species richness is very low and corals grow on rocky substrates (Fig. 2c). Elsewhere, data deficiency was relatively uniform with only scattered islands showing high data deficiency.

In the Indo-Pacific, 43% (301) of coral species were threatened (Table SI7), with the majority (246 species) classified as EN. Of these, 191 belong to the Acroporidae, followed by Pocilloporidae (20), Poritidae (9) and Merulinidae (8) (Fig. 3A, Table SI8). Three families (Milleporidae, Acroporidae, Pocilloporidae) had more than half of their species listed as threatened. Acroporidae, the most speciose scleractinian coral family and key reef builder, showed particularly severe risk: 191 species (68% of 279 species) were EN in 2024, predominantly in the genera *Acropora* (99 of 147 species) and *Montipora* (64 of 88), compared to only 53 species in 2008. Pocilloporidae also contribute substantially to reef complexity and rapid colonization of disturbed substrates with 28 species threatened (61% of 46 species). By contrast, families with slower-growing colonies with massive boulder morphology such as Merulinidae, Poritidae, and Lobophylliidae exhibited lower extinction risk, with only three species classified as CR, all in Poritidae (Fig. 3a). Species in other families remain largely LC, though VU and EN species were present across multiple families.

The Indo-Australian Archipelago/Coral Triangle (IAA/CT) is the global center of scleractinian coral diversity<sup>19</sup>. Although this region shows no overall decline in coral cover to date<sup>7,20</sup> it hosts the highest number of threatened species. This apparent paradox is due to the extraordinary diversity and endemism of Acroporidae in the region combined with their high susceptibility to thermal stress, driving the high extinction risk of 217 of the 279 acroporids (Table SI8), corroborating findings from many field studies. This highlights a primary weakness of total coral cover as an indicator of coral reef state, as compositional change may be occurring but not detected as space formerly occupied by vulnerable species is claimed by resistant or fast-growing species<sup>21</sup> accompanied by losses in genetic and functional diversity supporting reef ecosystem processes<sup>21,22</sup>. In this context, using coral cover as a metric of reef status may mask proximity to a possible threshold of sudden coral cover loss once the limits of the remaining resistant species are exceeded. Peripheral reef regions (e.g., central Pacific, eastern tropical Pacific) generally harbor lower species richness, particularly in the Acroporidae, thus may have less vulnerable assemblages. But their geographic isolation and reduced functional redundancy (i.e., few species performing similar ecological roles) may render them more vulnerable to mass bleaching events and coral cover loss<sup>7,23</sup>.

In the Atlantic, 50% of species were classified as threatened and 33% were CR (Table SI7), and seven families (Acroporidae, Dendrophylliidae, Meandrinidae, Milleporidae, Merulinidae, Faviidae, Agariciidae) have more than half of their species listed as threatened (Fig. 3b, Table SI9)<sup>15</sup>. The iconic Caribbean acroporids (*Acropora cervicornis* and *A. palmata*), along with the pillar coral *Dendrogyra cylindrus*, have suffered severe population declines exceeding 80%, resulting in their classification as CR. These losses are largely attributed to recurrent disease outbreaks and thermal stress, and to ensuing chronic fertilization constraints and recruitment failure, undermining recovery. The decline of once-dominant reef-building *Acropora* populations has caused structural flattening of reef surfaces, resulting in major losses of ecological functions and services<sup>24</sup>. Within

the southwestern Atlantic (northeastern Brazil), where endemism is highest, extinction risk is especially acute. Here and across the Caribbean additional losses have been documented in major bleaching and mortality events since 2020, raising the possibility of local extinctions<sup>25,26</sup>. In both the Indo-Pacific and the Atlantic, extreme decline in monotypic genera, the only representatives of their lineages (e.g. *Ctenella chagius* and *D. cylindrus*), are of particular concern, as their loss would disproportionately affect scleractinian diversity.

### Uncertainty vs. urgency

A wide variety of factors contribute to uncertainty in assessing species extinction risk, with repeated assessments applying improved data and methods. Systemic solutions to challenges are incorporated into overall guidance<sup>14,16</sup>. Importantly, uncertainty alone does not justify not assessing a species or classifying it as DD when the available evidence supports an indirect assessment, noting that the purpose is not to forecast extinction, but to provide increasingly reliable estimates of relative extinction risk that can support decisions<sup>14,16</sup>. For taxonomic rigour we applied standard practice and used currently accepted nomenclature as documented in the World Register of Marine Species (WoRMS), as coral taxonomy remains in flux and species-level taxonomic relationships continue to be debated<sup>27,28</sup>. Emerging molecular techniques have helped establish a more stable evolutionary framework<sup>27,29</sup>, enabling long-standing hypotheses regarding cryptic species diversity<sup>30</sup> to be tested with samples distributed across geographic and environmental gradients<sup>31</sup>. These reveal that some species currently thought to be widespread may comprise multiple restricted-range species<sup>30,32</sup>, thus under-estimating extinction risk. As robust phylogeographic reconstructions grounded in morphological and reproductive data and type material are completed and incorporated into WoRMS, future assessments may incorporate these updates.

The most robust basis for assessing extinction risk under the IUCN RL Criteria is species-specific population trend estimates, but these were only available for 15 species (five Atlantic and ten Indo-Pacific, e.g. *Mussismilia harttii*, Table SI4), up from five in 2008<sup>1</sup>. Abundance data for most other species still only cover portions of their global ranges, and available estimates at regional scales predate the second global coral bleaching events in 2010, making them unsuitable for current use<sup>33,34</sup>. In the absence of such data, we applied the guidance of Criterion A to use the most comprehensive global spatial dataset on changes in total coral cover as a habitat proxy<sup>7</sup>, as used in the first assessment in 2008<sup>1</sup>, but strengthened by quantitative analysis of trends. This is the appropriate choice because abundance and extinction risk are distinct: (i) large population size alone does not confer low risk as fragmentation, recruitment failure, loss of genetic diversity, and range contractions can still drive species toward extinction<sup>34</sup> and (ii) high number of individuals do not buffer risk against density-independent, range-wide and directional threats such as thermal stress<sup>35</sup>. Criterion A accounts for this, considering population reduction such that a species may have a high number of individuals across the global population yet qualify as threatened.

New measures of thermal exposure to predict coral bleaching are under development as limitations of existing metrics are increasingly recognized<sup>36,37</sup>. DHW was used here as it suitably integrates the time and degree of heat stress using variables provided in global climate models<sup>38,39</sup>, but more precise predictive metrics should be integrated in future analyses as they become validated<sup>40–42</sup>. Data on coral traits are increasingly available for many species but are not yet available across all species, or across global ranges of many species. We thus updated traits used in 2008, using 12 traits (Table SI2) scored on a three-point scale for heat-stress tolerance (high, moderate and low susceptibility) and used as a proxy for capacity adaptation to limited warming of 1°C<sup>43</sup>. Notably, trait data currently available does not enable any consideration of intra-specific variation, such as

across subregions. Modeling and empirical studies do suggest that some assemblages or regions may adapt more rapidly to change, and multiple avenues of environmental buffering and of species and/or population responses have indeed been documented<sup>44</sup>. Yet, most evidence indicates that even the most diverse and resilient corals and reefs are unlikely to keep pace with unabated climate change and other compounding threats<sup>45</sup>.

The RL approach carries potential for both over- and under-estimation of risk. Coral cover is a habitat proxy, and where its relationship to population size is non-linear, habitat-based trends may over- or understate the true change in mature individuals. Where evidence is limited, the precautionary principle selects the higher-risk category<sup>14,16</sup>. While this risks overestimation of extinction risk, improved data enables downlisting in future updates. By contrast, under-estimation of extinction risk may undermine action that mitigates threats, and may result in unnoticed, irreversible extinction. Reducing uncertainty in future coral extinction risk assessments will require taxonomically resolved, range-representative and temporally relevant data that enable estimation of species-specific abundance trends interpreted against relevant trait data as discussed above.

### Are coral reefs at a threshold?

Our results show that by 2020, nearly half of coral species were at elevated relative risk of extinction under the RL framework, for most species inferred from aggregate coral cover trends and projected thermal stress, rather than species-specific population estimates. This risk was escalating more rapidly than for any other comprehensively assessed taxonomic groups (Fig. 1b). By 2020 global coral cover had declined by half of historical baselines<sup>7-9</sup>, all coral reefs assessed on the IUCN Red List of Ecosystems (Western Indian Ocean and Caribbean) were Vulnerable to Critically Endangered<sup>46</sup>, and reef diversity, productivity and resilience were in decline<sup>21,47</sup>. In 2023, global surface ocean temperatures rose an unprecedented 0.25°C<sup>48</sup> such that annual global mean temperatures exceeded 1.5°C pre-industrial levels for the first time in 2024<sup>10</sup>, and 2023-25 became the three hottest years on record during which the fourth global coral bleaching event affected 84% of the world's coral reefs<sup>49</sup>.

The 1.5°C warming threshold established by the Intergovernmental Panel on Climate Change (IPCC), based on a 20-year average, is projected to be crossed as early as 2028<sup>50</sup>. This threshold marks the start of the range from 1.5 to 2°C warming identified by the IPCC across which, among other impacts, coral reefs are “projected to decline by a further 70–90% at 1.5°C (*high confidence*) with larger losses (>99%) at 2°C (*very high confidence*)” (Key Message B4.2<sup>51</sup>). The recent Global Tipping Points Report (GTPR) lowered this critical range for coral reefs to 1–1.5°C on the basis of impacts already experienced, prompting the proposal that coral reefs may be close to a critical tipping threshold globally<sup>52</sup>. As with other such global aggregates, these mask high levels of heterogeneity down to local scales, of both thermal stress exposure and of responses from individual coral to ecosystem levels (e.g.<sup>53,54</sup>). With multiple lags in the response of the ocean-climate system to emissions, and of corals and reefs to changes in the ocean, it is also unclear what future committed loss for corals may be.

Ninety-three per cent of threatened and Near Threatened species in our assessment qualified through population decline projected from thermal stress, so the IPCC projection that 10–30% of coral reefs could remain at 1.5°C warming and less than 1% at 2°C<sup>51</sup> provides useful reference points for conservation planning. Approximately 32% of coral reef area is currently within designated protected areas, though only a small proportion of this covers the most thermally resilient reefs, and just 2.5% of total reef area is under effective and strict protection<sup>55</sup>. Conventional coral reef restoration is highly localized due to the labour- and technology-intensive

nature of reef regeneration actions (median of 100 m<sup>2</sup>, maximum of 1 ha in 2020<sup>56</sup>). Research is increasingly focused on scaling these efforts and diversifying the coral and other reef species life histories and ecological interactions targeted by interventions<sup>57</sup>. However, major thermal stress events may erase years of restoration effort<sup>26</sup>, driving increasing attention to enhancing tolerance and adaptive capacity of corals and their associates<sup>58</sup>. A major question is therefore whether the full gamut of (effective) restoration interventions<sup>57</sup> can be scaled to cover 1% of coral reef extent globally, or approximately 800 km<sup>2</sup> of coral reef (global area of primary coral habitat = 80,213 km<sup>2</sup><sup>59</sup>). These areas of reef, of “10-30%” and “1%” of reef under protection and restoration, may no longer be connected in regional systems as they were historically. Surviving coral reefs may persist in increasingly isolated refuges, with reduced taxonomic and functional diversity. Nevertheless, these sites may represent hundreds to thousands of local to regional efforts aimed at maintaining corals and coral reef systems at some level of viability under future climate regimes<sup>2,23,53</sup>, and benefiting local communities and economies<sup>9</sup>.

Importantly, it should be recognized that the threshold values of 1.5 and 2°C warming arose from earth and climate system interactions and the need for policy guardrails culminating in the Paris Agreement in 2015<sup>60</sup>. They hold no inherent basis as critical thresholds in the life histories and ecologies of corals, or coral reef ecosystems. From 1998 to 2024, warming spanned a range of approximately 1°C and triggered four global bleaching events, demonstrating the wide diversity of impacts to and responses of corals and reefs over space and time. We can expect diverse (though narrowing) responses to further increments to and above 2°C warming. Recognizing this highlights the risks and high costs of delayed action associated with further increments in warming<sup>61</sup>, and the importance of each tenth of a degree increase. Further, investing in effective management across the full extent of coral reefs will be important to facilitate transitions to novel reef assemblages to retain maximum possible function, since decline of corals in many locations is inevitable. This is a foundational element of climate justice and equity, to promote the best possible transitions for emerging ecosystems and addressing the needs and rights of coastal communities and economies<sup>62,63</sup>.

Coral reefs exemplify the broader failure to halt decline in biodiversity from the full range of direct drivers impacting it<sup>8,64</sup>. Using total coral cover data aggregated across species, which as it stands is the best available proxy for assessing the relative extinction risk of reef-building corals, this study estimated increasing extinction risk across the three time points studied, ending with 44% of species at elevated relative risk by 2020. This was prior to climatic conditions affecting corals deteriorating markedly in 2023–25 during the 4th global bleaching event<sup>35,47</sup>, so this proportion is likely higher now, just five years later. As the threats facing corals rise, greater efforts will be required to safeguard remaining coral populations, and to invest in measures that allow corals to persist where possible in the Anthropocene<sup>2,23,53</sup>. To achieve this goal, governments and economic actors will need to transform the primary drivers of continuing climate change and other growing threats<sup>61,64</sup>.

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## Figure captions

**Fig. 1. Changes in extinction risk of non-Data Deficient reef-building coral species in 1998, 2008, and 2024.** A) Coral species in each IUCN Red List category, including transitions in threat status across periods (n=774). B) Red List Index (RLI)<sup>17</sup> for reef-building coral species in 1998, 2008, and 2024 (n=773), with sampled RLI for other comprehensively sampled taxonomic groups - amphibians, birds, cycads, mammals and sharks and rays (Source, <https://www.iucnredlist.org/assessment/red-list-index> and <sup>91</sup>). An RLI value of 1 indicates that all species qualify as Least Concern (LC), and 0 that all species are Extinct.

**Fig. 2. Global patterns of reef-building coral diversity and extinction risk.** A) Total species richness. B) Percentage of threatened species relative to total species richness. C) Percentage of Data Deficient species relative to total species richness.

**Fig. 3. IUCN Red List status of reef-building coral species by family in the Indo-Pacific (left) and Atlantic (right) realms.** Box sizes are proportional to the number of species in each IUCN Red List category for the most speciose families (8 families in the Indo-Pacific and 7 plus Acroporidae in the Atlantic). Species richness is indicated in brackets for each realm and family. See Tables SI7 and SI8 for full details across all families.

## Methods

Reassessments for 892 reef-building coral species were conducted by the IUCN Species Survival Commissions' Coral Specialist Group and more than 67 coral experts from across the globe, all of whom contributed extensive amounts of input and data. The taxonomy followed the most recent classifications from the World Register of Marine Species and the full species list can be found in the Supporting Information. The number of species assessed increased from the first assessment by 47, from 845, representing changes in taxonomy and species described and reduction in the number of Data Deficient species (from 141 to 118). All methods are based on the standard Guidelines for applying the IUCN Red List of Threatened Species<sup>16</sup> with adjustments detailed in the Supplementary Material and referring to the earlier assessment in 2008<sup>1</sup>, and previously reported for Atlantic corals<sup>15</sup>.

For each species, information on their distribution, population, habitat and ecology, threats, and conservation efforts were revised and updated by a group of experts and added to the species' Red List account in the IUCN Species Information System (SIS). Following the IUCN Red List guidelines v14<sup>16</sup>, species extinction risk was assessed based on one or more of the following criteria, selecting the one with the highest risk (Table SI1): Population size reduction (A), Geographic range (B), Small population size and decline (C), Very small or restricted population (D), and Quantitative analysis (E). These Criteria provide a standardized methodology for measuring relative extinction risk for a wide range of species, discretized into eight categories, ranging from Least Concern (LC) to Extinct (EX), and Data Deficient (DD) for cases when the information available for a species is insufficient to estimate their extinction risk. Species assessed as either Vulnerable (VU), Endangered (EN), or Critically Endangered (CR) are considered threatened (elevated risk) and may represent conservation priorities.

All species distributions were mapped on ArcGIS 10.7.1 based on Corals of the World, published literature, and expert knowledge<sup>65,66</sup>. Polygons were created and clipped to a shoreline buffer corresponding to the first 100 km or to 200 m depth (whichever is further), rather than known reef

habitat, to consistently map corals across the entire ocean basin. These included regions lacking coral reefs (e.g., Eastern Atlantic) and potential off-reef habitats. The assessments were released on the IUCN Red List website ([www.iucnredlist.org](http://www.iucnredlist.org)) in December 2022 (Atlantic species) as part of update 2022-2<sup>15</sup> and October 2024 (Indo-Pacific species) as part of update 2024-2.

Almost all coral species were assessed under Criterion A, which measures population reduction over a time of 10 years or 3 generation lengths, whichever is greater. Generation length is defined as the average age of reproductive parents of the current cohort, applied in this assessment as the average age of a reproductive adult colony. Criterion A is best applied to widespread species where the rate of decline exceeds the species' rate of recovery<sup>67</sup> and can be applied to a period of three generations in the past (A2), in the future (A3), or a combination of past and future (A4) time frames where the causes of reduction are ongoing or may not be reversible. To qualify for a threatened category in A2, A3 and A4 the quantitative threshold of estimated population reduction begins at 30% for Vulnerable, followed by 50% for Endangered, and 80% or higher for Critically Endangered. The previous assessment used an estimated average age for reproducing "adult" coral colonies of 10 years for most corals. In the absence of better estimates, we retained this estimate, and thus applied a three-generation length time period of 30 years (see Suppl. Material).

All but 15 of the coral species assessed lack species-specific quantitative data to estimate population size and/or trends over a 30-year time frame across the majority or entirety of their global range. Where direct observational data are lacking, Criterion A allows data on habitat decline or other proxy variables that reflect habitat changes to be used as a surrogate<sup>16,68</sup>. The percent cover of hard corals is the most widely used indicator of coral reef ecosystem health and an Essential Ocean Variable<sup>7,69-71</sup>. Coral cover is a direct measure of total coral abundance and is available with global coverage updated to 2020 and was used as the primary indicator for coral reef habitat decline. However, species are not evenly distributed across ecosystems<sup>72</sup> and can have varying species-specific responses to ecosystem changes. To estimate population reduction in the past (A2) we calculated the amount of coral cover decline within each species' range over a 3-generation length or 30-year period then adjusted this based on species vulnerability traits, to estimate population reduction for each coral species.

To estimate population reduction in the future (A3) we utilized the projected onset of annual severe bleaching (ASB) over a 3-generation length time period, corresponding to 2020 – 2050. ASB describes the timeframe during which reefs are expected to experience severe bleaching events annually that result in large reductions in live coral and are not predicted to recover<sup>39,73</sup>. Heat stress for corals is quantified when sea surface temperature (SST) exceeds 1°C above the maximum monthly mean, and the indicator is cumulative during a 12-week period<sup>39,74</sup>. ASB is expected to occur above 8 Degree Heating Weeks (DHW), which may reflect a 1°C exceedance over 8 weeks, 2°C for 4 weeks, etc, during the 12-week window. While there is emerging support for other measures of thermal exposure to predict coral bleaching<sup>36,37,39,75-77</sup>, DHW was used here as it suitably integrates the time and degree of heat stress via variables provided in global climate models<sup>38</sup>. More precise predictive metrics with region-specific resolution and temporal adjustments should be integrated in future analyses as they become validated<sup>40-42</sup>.

The onset of ASB was calculated from sea surface temperature projections made available by UNEP<sup>38</sup>, which combined the 2019 IPCC CMIP6 global climate models and WCMC-UNEP global coral reef distribution map. Annual maximum DHW values were calculated for 0.25° (27 x 27 km) grid cells that contain reef habitat (to 30 m depth) across the globe to estimate the average year for the onset of annual severe bleaching (ASB) across species ranges<sup>38</sup>. We applied two climate change scenarios (Shared Socioeconomic Pathways, SSP): SSP2-4.5, a more moderate climate change scenario that better tracks current policy projections, and SSP5-8.5, a worst-case scenario<sup>46,78</sup>. We applied the results for SSP2-4.5, as SSP5-8.5 is now considered overly

pessimistic based on current emissions reduction commitments and trajectories<sup>79–81</sup>, and results for SSP5-8.5 drive very high and uniform risk of extinction across most species. To account for coral adaptation to thermal stress, we calculated two estimates of ASB onset, one for species with no adaptation (0°C) and a second assuming a capacity for 1°C of adaptation (see further text below, and Supplementary Material).

Criterion B is applied to species with small ranges. A species is considered threatened if its global distribution range is small, a plausible major threat is identified, and there is evidence of fragmentation and/or a continued decline in habitat, population, or range size. Specifically, a species must have an extent of occurrence (EOO) of less than 20,000 km<sup>2</sup> or an area of occupancy (AOO) of less than 2,000 km<sup>2</sup> as defined by the IUCN Red List guidelines v14 (2022).

Data were compiled for all species for 12 traits were compiled from the first coral extinction risk assessment<sup>1</sup> updated from varied sources<sup>65,66,82–87</sup> and selected for coverage across all species assessed (Table SI2). Traits included depth range (as a proxy of exposure and considered two different ways), general abundance, range size, reef habitat dependence, recovery potential, and susceptibility to bleaching, Crown-Of-Thorns Starfish (COTS) predation, susceptibility to stony coral tissue loss disease (SCTLD), susceptibility to general disease, exploitation for the aquarium trade, and ocean acidification (OA). The traits are used as indicators of species vulnerability to varied threats, addressing susceptibility, exposure or a combination of both. Each trait was classified into three levels of vulnerability: low (1), medium (2) or high (3) (Table SI2). Where species-specific trait data were lacking, traits were assigned a moderate score of 2. Overall vulnerability of a species was based on the higher of the average or mode of all trait scores (10 for Atlantic species and 11 for Indo-Pacific species). Species which scored high across a majority of the traits are inferred to be more vulnerable to population reductions from anthropogenic and other threats.

The potential for adaptation to future heat stress was based on species' overall vulnerability to bleaching as well as preferred depth range (Supplementary Material). Species that are estimated or known to be resistant or moderately susceptible to bleaching were inferred to have the ability to adapt to some warming<sup>58,88,89</sup>. The estimate of ASB for these species was based on the likelihood that the species may adapt to at least 1°C above the 1°C exceedance over the monthly maximum. Species with a high susceptibility to bleaching and restriction to <30 m depth were inferred to have a low potential for adaptation to heat stress, and tested for ASB against a 1°C exceedance over the monthly maximum.

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**Data Availability**

The species-level Red List assessments generated in this study, including extinction risk category, criteria, and supporting rationale for all 892 reef-building coral species, are freely available on the IUCN Red List website ([www.iucnredlist.org](http://www.iucnredlist.org)) and in the IUCN Species Information System (SIS), as part of the 2022-2 (Atlantic) and 2024-2 (Indo-Pacific) updates. Underlying input data are from third-party public sources: coral cover trends from the Global Coral Reef Monitoring Network's 2020 Status of Coral Reefs of the World report <sup>7</sup>; species distributions and taxonomy from Corals of the World <sup>66</sup> and the World Register of Marine Species <sup>90</sup>. The compiled species trait scores, generation length assumptions, and per-species criteria calculations used to derive each assessment are provided in the accompanying Supplementary Information (Tables SI1–SI10).

**Acknowledgements**

We dedicate this work to our colleague and friend, Dr. Kent E. Carpenter, who died on 12 July 2026. Dr. Carpenter initiated and led the first Red List assessment of reef-building corals, catalyzing the formation of the IUCN SSC Coral Specialist Group and global attention to coral reef conservation.

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**Author contributions**

Conceived and led study, drafted manuscript: DOO, BP, FCB

Data management and analyses: CL, EP, KK, KS, LG, NC, RvH

Assessed and reviewed species: AB, AC, ADM, AE, ARS, BC, BW, BWH, CINL, CJL, CSLN, DB, DH, DKK, DOO, EC, EG, EK, ET, EV, FCB, FN, GA, GR, HMG, JC, JF, JJ, JJA, JKB, JM, JPQ, KA, KR, KSL, KSN, LAF, LDV, MJCC, MS, MV, MVK, MWM, NS, PCL, PK, PPK, PR, RDRM, RR, SG, SNP, SSK, TS, WD, WYL, ZR, ZW

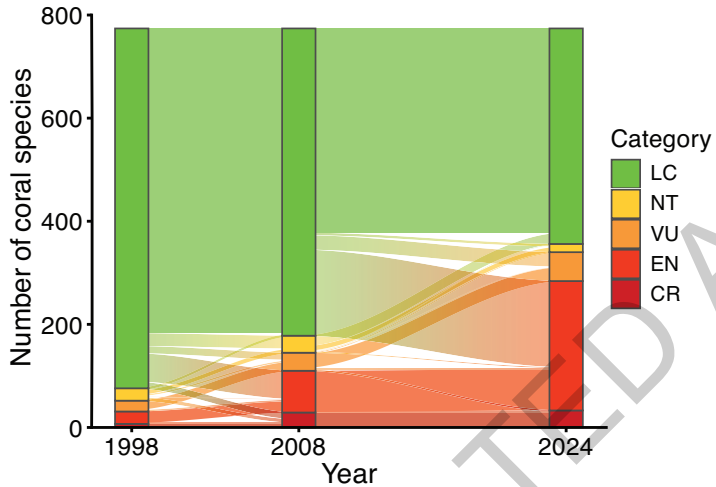
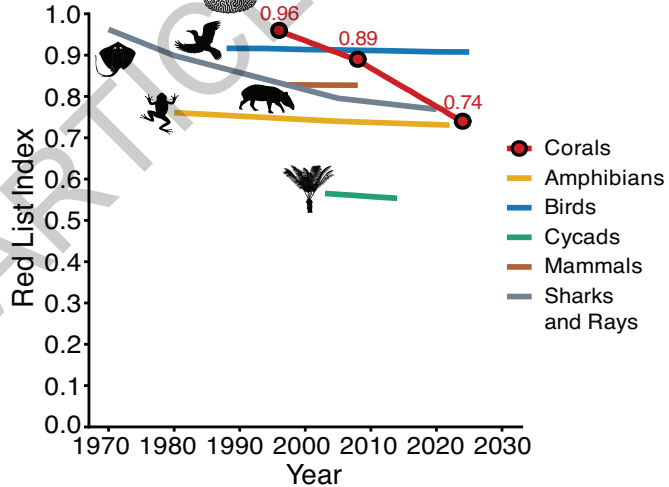
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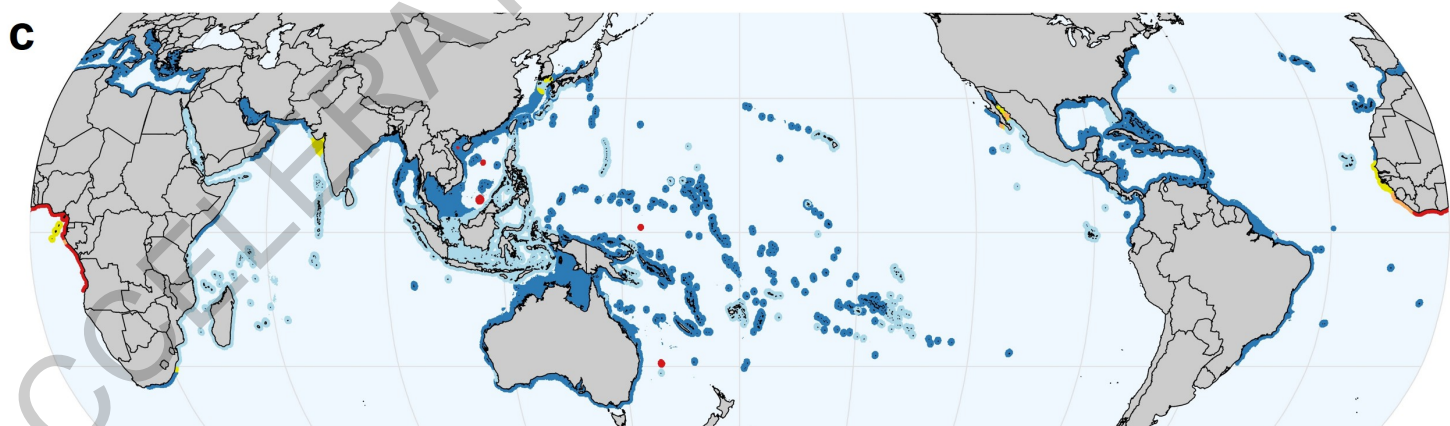
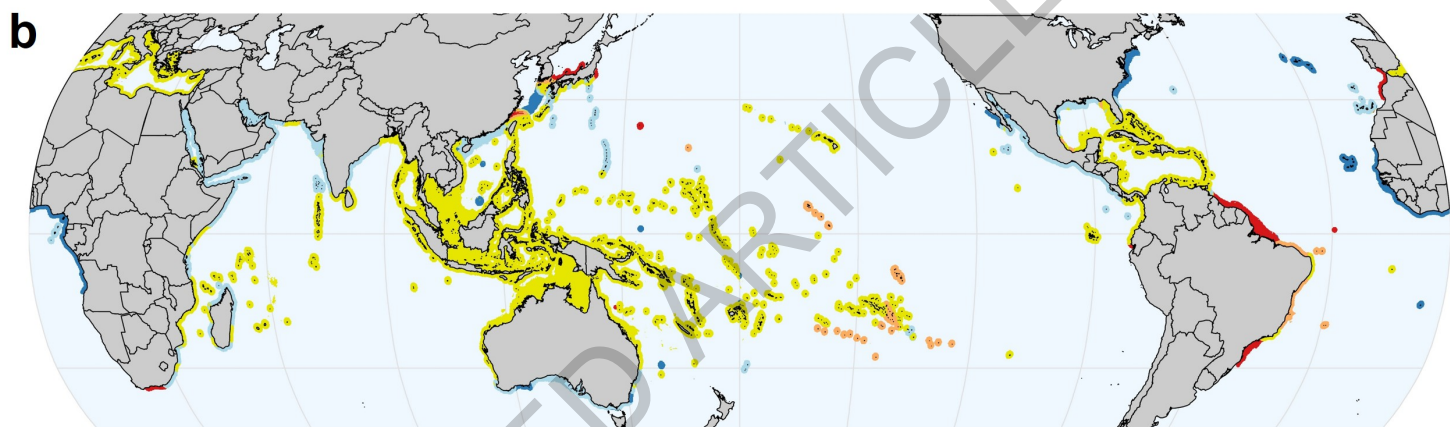
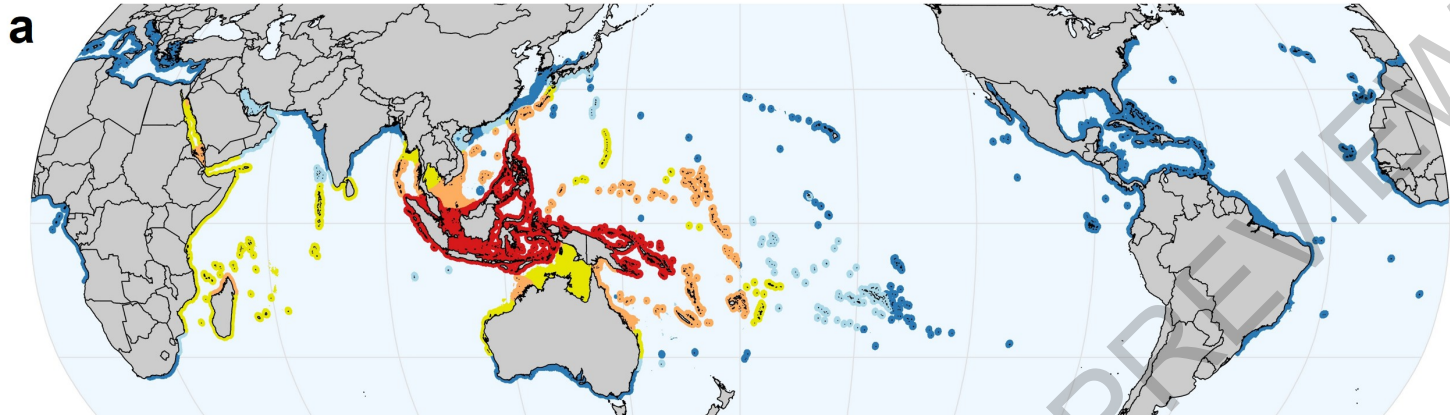
**Competing interests**

The authors declare no competing interests.

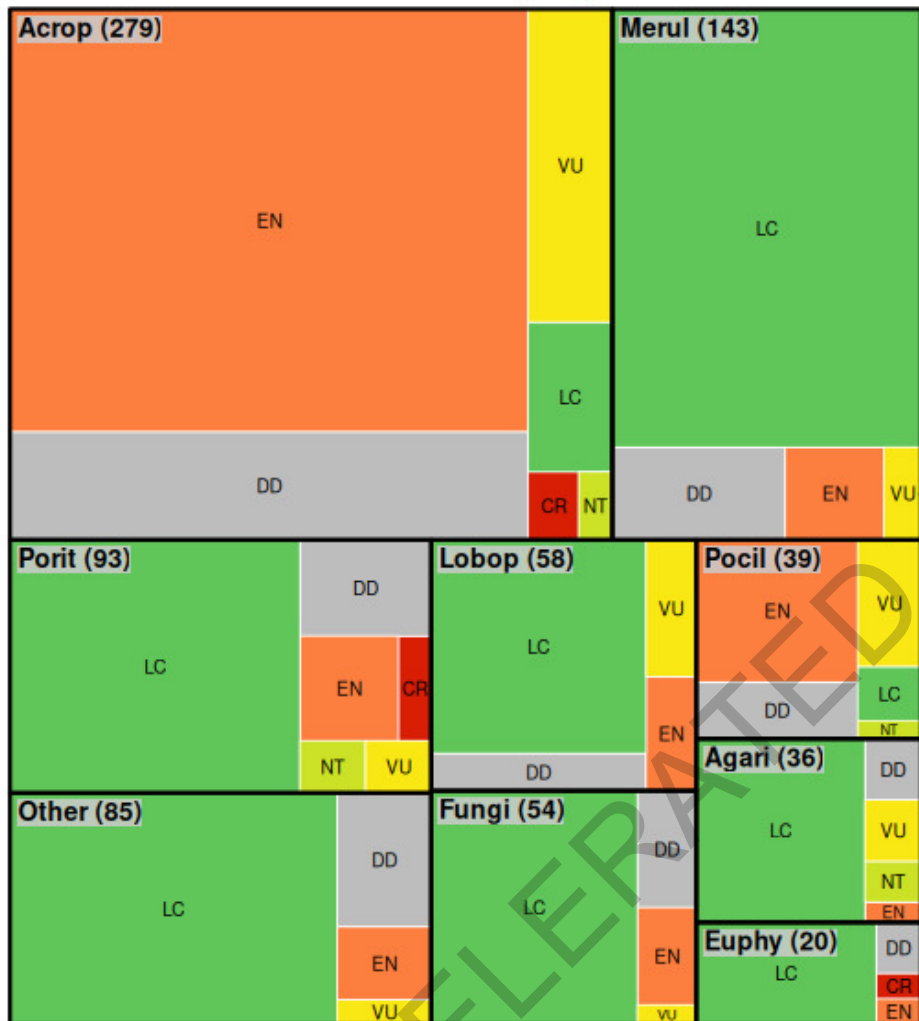
**Additional Information**

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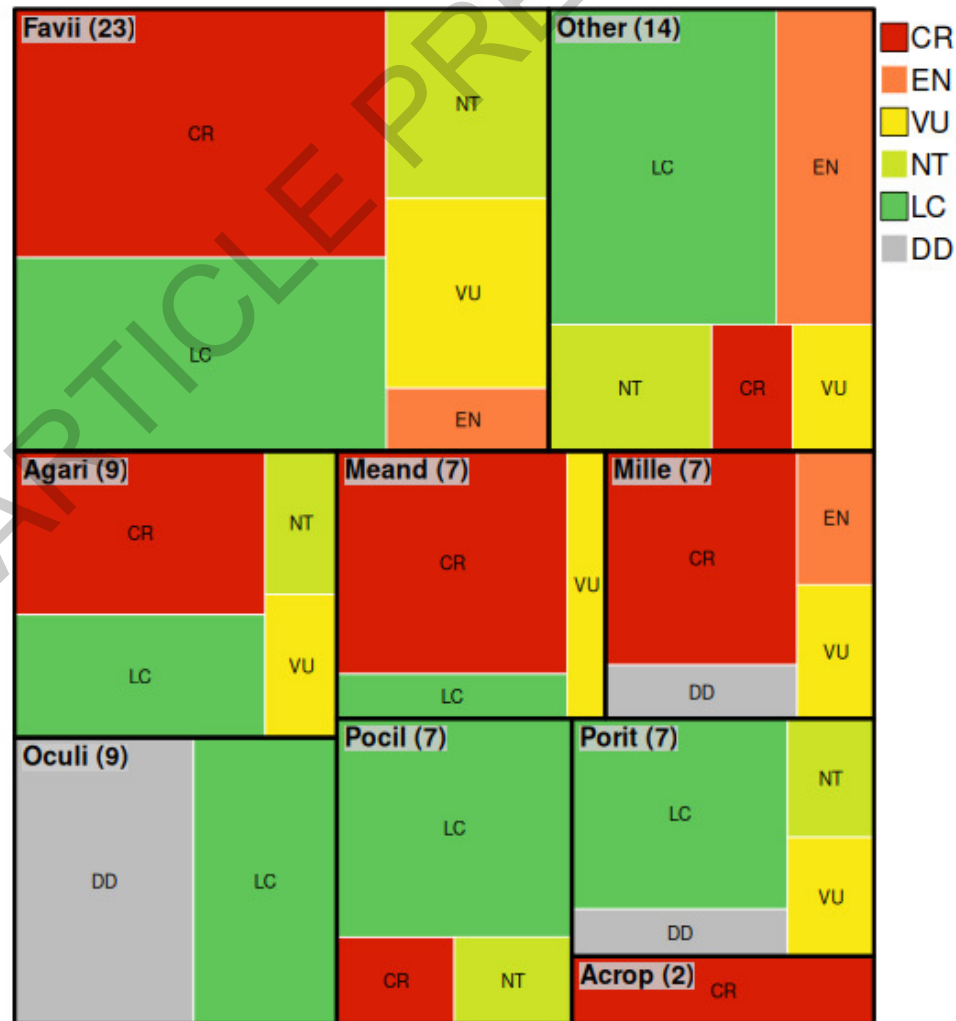
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Indo-Pacific (807)



Atlantic (85)



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### Software and code

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Data collection n/a

Data analysis Spatially explicit data was analysed and modeled in ArcGIS 10.7.1 whilst plots were built in R v 4.4.3

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|--------------------------------------------------------------------|-----|
| Reporting on sex and gender                                        | n/a |
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## Ecological, evolutionary & environmental sciences study design

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|                          |                                                                                                                                                                                                                                                                                           |
|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Study description        | The study assesses species extinction risk using the IUCN Red List of Threatened Species methodology, using data on hard coral cover on coral reefs; coral species taxonomy, distribution maps and life history traits; and sea surface temperature projections from CMIP6 climate models |
| Research sample          | shallow tropical coral species, as current in the World Register of Marine Species at the time of the study (2019-2022)                                                                                                                                                                   |
| Sampling strategy        | n/a                                                                                                                                                                                                                                                                                       |
| Data collection          | Data compiled from primary literature, experts elicitation and publicly available datasets. Coral cover change provided by UNEP's GCRMN                                                                                                                                                   |
| Timing and spatial scale | Global species ranges of reef-building corals, with historical data obtained/projected back 30 years from the present and 30 years into the future, as relevant.                                                                                                                          |
| Data exclusions          | None                                                                                                                                                                                                                                                                                      |
| Reproducibility          | The study applied the IUCN Red List of Threatened Species, which has a history of 60 years, addressing requirements for reproducibility.                                                                                                                                                  |
| Randomization            | n/a                                                                                                                                                                                                                                                                                       |
| Blinding                 | n/a                                                                                                                                                                                                                                                                                       |

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Seed stocks

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n/a

Authentication

n/a