Assessing risk of ecosystem collapse in a changing climate

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Abstract

Climate change has pervasive impacts on Earth's ecosystems, but the diversity and complexity of ecosystems makes estimating the severity of impacts and the resulting risk of collapse difficult. In this perspective, we conceptualise the challenge of understanding how climate change alters ecosystems, and how to reliably measure those changes in ecosystem risk assessments, focussing on the IUCN Red List of Ecosystems. We propose solutions to resolve these challenges – using diverse teams, conceptual models, diverse using data sources including projections, learning from analogous ecosystems, and evaluating uncertainties – and we identify research gaps to bridge these challenges. Together, these solutions will improve our capacity to produce reliable assessments of collapse risk under climate change to inform timely and effective ecosystem conservation.

Main text

Earth's climate system is shifting due to rising greenhouse gas emissions[1], triggering changes in average and extreme environmental conditions[1]. These changes are affecting human systems and ecosystems[2] (underlined words defined in Appendix 1 Glossary), including shifts in reproductive phenology [3], coastal inundation from sea level rise[4], rising sea surface temperatures in marine ecosystems[5], and declining snowfalls in alpine regions[6]. Climate change is expected to become the largest driver of ecosystem degradation this decade[7] and will exacerbate the effects of other threats (e.g., habitat loss, invasive species)[7]. Identifying climate change impacts on ecosystem components, processes and function is therefore a fundamental challenge. Our capacity to quantify the status of Earth's ecosystems has recently improved with the publication of the Global Ecosystem Typology[8,9] and the IUCN Red List of Ecosystem (RLE)[10], the global standard for assessing the risk of collapse for all ecosystem types. These risk assessments that identify and monitor ecosystem-specific symptoms of degradation are a promising tool for navigating ecosystem complexity and estimating collapse risk[11].

Risk assessments are used to estimate the probability of large, detrimental changes to a system or feature, such as species extinction or ecosystem collapse[10]. They are often summarised into lists of at-risk species and ecosystems that can inform priority setting, reserve design, mitigation strategies, state-of-the-environment reporting, and limits for developments and exploitation[12]. Climate change must be addressed in risk assessments to ensure a realistic appraisal of risk and to support informed decisions for policy, conservation, and management[13].

Much research has estimated the influence of climate change on species extinction risk. Studies often use accepted extinction risk frameworks, such the IUCN Red List of Threatened Species[14,15], to evaluate vulnerability or sensitivity to climate change[13], timing of impacts, and effects on distributions and demographic processes[16,17]. There are fewer comparable analyses linking climate change projections to ecosystem-level collapse risk[18–20]. Estimating ecosystem-level impacts has challenges, including incorporating relevant complexity, insufficient knowledge of the mechanisms of change and interactions at ecosystem scales, differences in impacts among ecosystem types[21], and uncertainties in measuring impacts.

The RLE risk assessment framework is well suited to capturing the risks of climate change through the application of five criteria (A-E), each focused on a different symptom of collapse (Figure 1); the criteria assess changes over historic, recent and future timeframes (via criteria A, C-E) across multiple pathways that climate change may affect ecosystems – distributional, environmental, and biological[22]. The capacity and capability to conduct RLE assessments is increasing[23], with over 4000 ecosystem types assessed worldwide. This number will doubtlessly rise now that the RLE is a headline indicator for the Kunming-Montreal global biodiversity framework[24]; signatory countries should implement the RLE to report against that headline indicator. Many RLE assessments have addressed climate change, making a synthesis of lessons learned timely to inform future assessments. Using these, we scrutinise the range of approaches used, examine additional approaches, and provide recommendations for including climate change impacts in ecosystem risk assessments.

We address two key questions for improving the reliability of ecosystem risk assessments: 1) How will climate change affect ecosystem features and processes; and 2) how can we accurately predict and measure these impacts? We describe key challenges across the five steps of a risk assessment protocol: 1) understanding climate change impacts on ecosystems, 2) selecting indicators of degradation, 3) defining ecosystem collapse thresholds, 4) collating available datasets, and 5) estimating and reporting risk based on the RLE criteria (A-E). We then provide potential solutions to these challenges and recognise ongoing knowledge gaps, with the aim of improving reliability and consistency of risk assessments to support informed policy and conservation decision making under a changing climate. Although we focus on RLE assessments, the ideas apply to other environmental risk assessment frameworks (e.g.,[25-26]) and to ecosystem-based approaches such as ecosystem accounting[27].

Challenges to incorporating climate change in ecosystem risk assessment

The threat to ecosystems from climate change is complex because impacts manifest through multiple drivers and pathways, and interact with other threats in ways specific to each ecosystem type[28] (Figure 1). Consequently, there is no one-size-fits-all approach to incorporating climate change into ecosystem risk assessments. We address our two key questions by examining the uncertainty in how to understand and estimate or measure ecosystem-specific responses, and examine how these challenges propagate through the five steps in an assessment (Box 1).

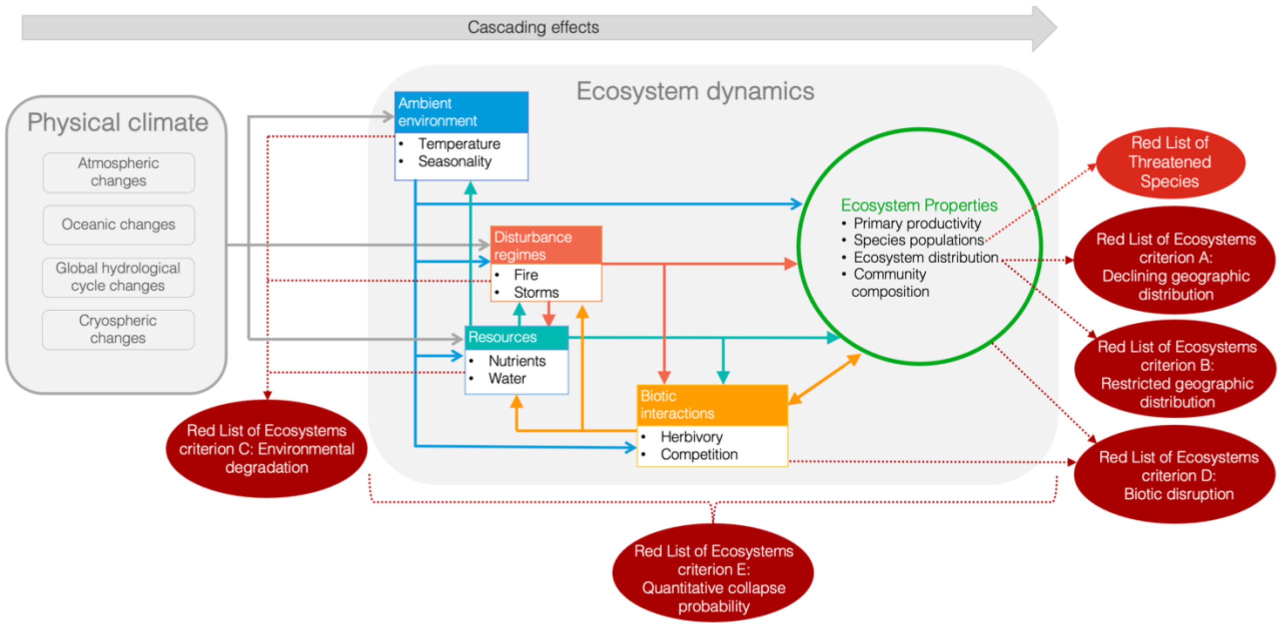


Figure 1 | Changes in the physical climate due to human-induced climate change can have cascading effects on ecosystem dynamics. Climatic changes alter the ambient abiotic environment, disturbance regimes and resources within ecosystems, driving changes in the biotic interactions and ecosystem properties (examples of relevant ecosystem processes, properties, and dynamics are provided as dot points but are not exhaustive). The Red List of Threatened Species captures changes in species populations and distributions, whereas the Red List of Ecosystems (RLE; darker red) can capture the impacts of climate-driven changes across all facets of the ecosystem type via the five criteria (A-E; darker red). Based on Keith et al.[9]

Box 1 | Synthesis of the challenges and solutions for capturing the impacts of climate change for each step in the Red List of Ecosystems method, alongside general guidance that applies across all steps.

Red List of Ecosystems steps

General: Assemble multidisciplinary teams and local experts to draw various expertise in defining ecosystems, setting collapse thresholds, and compiling and using various data sources

1) Understanding climate change impacts on the ecosystem

Task: Defining how climate change will alter key features and processes in the ecosystem description

Challenges:
- Which, how, and when ecosystem features and processes may be affected by and respond to climate change may be unclear
- Difficult to predict the adaptive capacity of ecosystems to environmental changes
- Interactions and dependencies may manifest in the impacts of climate change and of other threats on an ecosystem

Solutions:
- Develop conceptual model/s to explore different hypotheses for climate change impacts and highlighting uncertainty
- Identify sentinel variables that can trigger reassessment if change (and thus risk) is more pronounced than expected
- Examine data and conceptual models for relevant functional groups, analogous ecosystems, or climate analogues where data are lacking
- Consider and capture potential adaptive capacity in conceptual model

2) Selecting indicators of degradation

Task: Selecting indicators that reliably represent how climate change will alter key features and processes to assess under Criterion C (environmental degradation) and D (biotic disruption)

Challenges:
- Identifying which indicators to use to capture collapse risk from climate change due to uncertainty in how climate change will manifest (see 1)
- Generic indicators may be unreliable as different ecosystems will be affected in various ways
- Bias towards availability of environmental vs. biotic indicators (see 4)

Solutions:
- Use conceptual models (see 1), quantitative mechanistic models, and sensitivity analysis to guide selection
- Examine analogous ecosystems and other RLE assessments for relevant indicators
- Assess multiple indicators to capture variability in ecosystem responses and pathways to collapse
- Document, evaluate and report limitations of all possible relevant indicators
- Consult local experts

3) Defining ecosystem collapse thresholds

Task: Defining collapsed states for an ecosystem and thresholds for each indicator under climate change

Challenges:
- Unknown adaptive capacity of ecosystems may alter current collapse thresholds
- Difficult to explicitly link coarse-scale abiotic indicators to collapsed states, especially in small or patchy ecosystems

Solutions:
- Link environmental changes to species physiological tolerances or ecosystem distribution limits, including collapsed parts of the distribution
- Use long-term monitoring and experimental studies to test and/or identify possible thresholds, such as mesocosms, natural experiments
- Use plausible range of collapse thresholds, specifying upper and lower bounds with a best estimate

4) Collating available datasets

Task: Gather spatial and temporal datasets that capture the impact of past or predicted future impacts of climate change

Challenges:
- Timeseries data of recent change are often short, spatially patchy, incomplete, or biased to certain indicators (especially environmental), species, or regions
- Extrapolating current trends forward may be unreliable
- Difficult to reliably link coarse, uncertainty model outputs to changes in specific ecosystems, features, and processes
- Reliability of ecosystem simulation model outputs can be affected by the data inputs and model structure and parameterisation, especially if based on current ecosystem dynamics (see 1)

Solutions:
- Extrapolate forward current trends using sub-criterion 2b, where appropriate
- Use experimental studies to identify potential ecosystem responses and timeframes
- Use expert and local knowledge, data from species Red List assessments (including population models), and information on historical climates (as analogues) to fill gaps in published studies
- Use multiple global circulation models, climate projections (including relevant downscaled projections) to capture alternative futures

5) Estimating risk and reporting outcomes

Task: Use data to apply the criteria to estimate the risk of ecosystem collapse due to climate change

Challenges:
- Many sources of uncertainty to capture and report on

Solutions:
- Report all assumptions, reasoning, and types of uncertainty
- Report uncertainty in risk category using plausible bounds
- Conduct sensitivity analysis of models and report results from multiple models, ecological models, emissions scenarios, and model runs as plausible bounds of collapse risk

Step 1 – Understanding climate change impacts on the ecosystem

The first step in an RLE assessment is describing the ecosystem type of interest – detailing characteristic abiotic and biotic features and processes, and identifying the cause-and-effect links between threats and ecosystem responses[29] (Box 1). This involves synthesising understanding of how climatic changes may alter characteristic features and processes and cause the ecosystem to move towards (or away from) collapse. Three substantial issues include uncertain and variable ecosystem responses to climate change, their adaptive capacity, and interactions between threats.

Responses of ecosystem features and processes. Climate-induced ecosystem responses may be non-linear, and can occur slowly or abruptly due to time lags and threshold effects[30,31], making them challenging to predict[30]. Collapse risk may be underestimated if declines are forecast inaccurately. Models, experiments, and observations have revealed climate change impacts on ecosystems for decades. Yet estimating future biotic changes based on past or current conditions may be unreliable as past relationships may not hold under new conditions[30,32]. Climate change can alter ecological interactions, causing cascading impacts throughout the community[33]. For instance, species that track suitable climates will likely experience altered ecological interactions as environmental conditions change[13], and species' capacity to shift their ranges will depend on the prevailing climate and biotic interactions (e.g., competition)[34]. Although field observations can help identify range shifts, the effects of novel species on ecosystems are difficult to forecast. Many regions may experience novel climates, which may amplify changes in community compositions[32].

Adaptive capacity of ecosystems. Adaptive capacity is the latent potential of an ecosystem to alter its resilience in response to change[35]. Much work has been done to understand whether, how and to what extent some ecosystems can adapt to changing climates. For example, corals with algal symbionts tolerant of warmer water are more abundant in reefs affected by recent climate change, an adaptive shift that may support resistance to future thermal stress[36]. However, the adaptive capacity of many ecosystems remains unclear; the dispersal and adaptive capacity of species may interact, causing unexpected effects on an ecosystems' ability to maintain biodiversity[17]. The lack of published research focussed on validating the predicted relationships between climatic change and specific ecosystem responses is a considerable factor limiting reliable risk assessments. For example, high uncertainty in the presence and magnitude of adaptive responses to environmental changes has meant that the impacts of these threats remain unevaluated or data deficient in many RLE assessments (e.g., oyster reefs in Australia[37]).

Interactions and dependencies among threats. The safe operating space for ecosystems (i.e., levels of stressors within which an ecosystem can persist) is normally determined for each stressor[38]. Yet interactions and synergies among threats[38] may exacerbate their individual impacts[39]. For example, interactions between sea surface temperatures and ocean acidification have reduced metabolic rates and activity of a top predator (jumbo squid, *Dosidicus gigas*), altering predator-prey interactions in the Eastern Pacific Ocean[40]. Changes to ecosystem resilience from processes such as habitat loss or overexploitation[41] can also heighten the impacts of climate change, (e.g., impacts are amplified in degraded wetlands or those modified by land-use change)[4]. Multi-layered dependencies among threats are likely, as climate change may reduce the environmental suitability for a particular ecosystem type while increasing suitability for other land or resource uses. For example, sea ice loss will shrink some cryogenic ecosystems but may increase human access to oil reserves[42]. The impacts of such interacting threats can vary depending on a species position in its environmental niche; for example, vertebrate species abundance declined faster in areas undergoing habitat loss that neared their high temperature threshold limit[43]. Therefore, understanding the current condition and threats affecting an ecosystem is vital when estimating the risks posed by climate change.

Step 2 – Selecting indicators of degradation

Indicators are used in the RLE to measure past change or predict future change in an ecosystem type's environmental properties (criterion C) and biotic features, processes, and interactions (criterion D) (Figure 1). Indicators must be ecologically relevant to the ecosystem type, convey proximity to collapse, and, when assessing climate impacts, be sensitive to threats from climate change[44]. The diversity of responses to climate change across ecosystem types can make indicator selection challenging.

Diversity in symptoms of climate change. Selecting reliable indicators of risk under climate change is hampered by the range and uncertainty of ecosystem responses[45] to future local environmental conditions (see *Understanding climate change impacts on ecosystems*), which are less clear than global trends[1]. Collapse can manifest via diverse symptoms among and within ecosystems (Figure 2). Thus, generic indicators of condition that are relatively simple to estimate (e.g., area, species richness, annual rainfall) may be insensitive or inadequate to reliably measure ecosystem state[10] within and across ecosystem types. For instance, taxonomic and functional diversity has increased in wetter forests but decreased in drier forests in Ghana, West Africa, since the 1980s[46]. Further, the extent of Mountain Ash (*Eucalyptus regnans*) forest in Australia has not changed over the past 50 years, yet the ecosystem type is Critically Endangered due to the loss of old-growth areas and hollow-bearing trees required to support fauna[47]. This necessitates use of ecosystem-specific indicators matched with ecosystem-specific understanding of the direction of impact. There are also differences in data availability for various types of indicators; future projections are more readily available for environmental conditions than for biotic features and processes[48], limiting the capacity to assess collapse risk due to biotic change (see *Collating available datasets*).

Step 3 – Defining ecosystem collapse thresholds

Collapse occurs when the defining environmental and biotic features and processes of an ecosystem change so that characteristic native biota cannot be sustained[49], and is replaced by a different ecosystem type[49]. A collapse threshold must be set for each indicator of collapse – this threshold represents a value that, once exceeded (i.e., sufficient change has occurred), the ecosystem transitions into a collapsed state (Box 1)[10]. Setting collapse thresholds is one way that the RLE facilitates assessors to consider how climatic drivers can affect an ecosystem. Yet linking environmental or biotic changes to ecosystem collapse is the primary issue for conceptualising and quantifying ecosystem collapse under climate change.

Linking change to collapse*.* Defining collapse thresholds requires understanding the environmental and biotic conditions of various collapsed states of an ecosystem[49]. Yet uncertainty in how ecosystems will respond and their capacity to adapt to climatic changes[17] impairs our ability to set reliable collapse thresholds. The level of change an ecosystem can cope with before shifting into a collapsed state may vary in the future as species adapt, so thresholds based on current understanding of ecosystem responses may not be robust. Data are also more commonly available for environmental indicators (via climate projections) than for biotic indicators, which are more difficult to reliably predict (Table 1). Yet linking environmental data to collapsed states can be challenging, especially where data are coarse. For instance, estimating collapse risk from changes in future fire regimes using fire danger ratings requires knowledge of the link between fire danger rating and incidence of fire in an ecosystem type[50]; this may be especially difficult for small, patchy ecosystems.

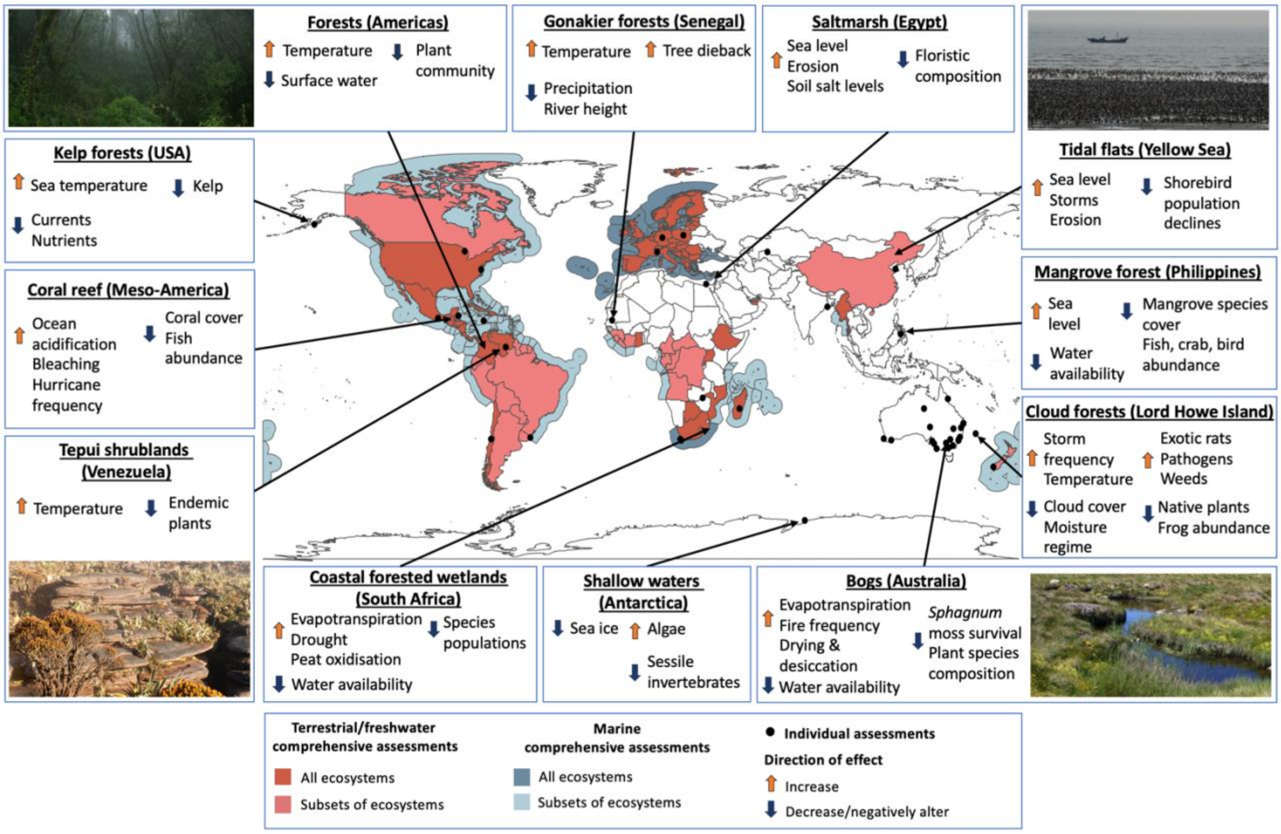


Figure 2 | Examples of different symptoms of climate change among various types of marine, freshwater, and terrestrial ecosystems with changes in environmental conditions on the left and biota on the right. The map shows the current coverage of Red List of Ecosystems assessments, including individual assessments (dots) and comprehensive national or regional assessments (coloured regions). See Appendix 2 for full list of references. Source photos (clockwise from top left): Forests (Jose Rafael Ferrer-Paris), Tidal flats (Nicholas J. Murray), Bogs (Joslin L. Moore), and Tepui shrublands (Marek Arcimowicz).

Table 1 | Examples of indicators and approaches used to assess the impacts of climate change in IUCN Red List of Ecosystems assessments for criteria A, C and D. Realms are based on the Global Ecosystem Typology[9]. ROC: recent rate of change. References noted using letters; full references in Appendix 3.

Realm	Area (criterion A)	Environmental conditions (criterion C)	Biota (criterion D)
Terrestrial	Extent of forests (extrapolated ROC)[a] Suitable habitat extent of shrubland (bioclimatic modelling)[b]	Snowpack depth in snowpatch herbfield (extrapolated ROC)[c] Surface water extent in forests (extrapolated ROC)[a] Climatic suitability in forests and woodlands (bioclimatic modelling)[a,d,e] Frequency of cloud cover in forests (extrapolated ROC)[f] Water table depth in shrublands (projections)[g] Water stress/water balance in terrestrial systems (projections)[h] Soil water deficit and soil carbon in a river basin (extrapolated ROC)[i] Water availability in terrestrial systems (projections)[j,k]	Shrub cover in snowpatch herbfields (extrapolated ROC)[c] Hollow-bearing trees in forests (modelled fire and logging regimes)[d] Weed invasion in shrublands (extrapolated ROC)[g] Dispersal and pollination in terrestrial systems (distribution models)[j,k] Productivity and vegetation condition in river basin (extrapolated ROC)[i]
Freshwater	Extent of a lake (extrapolated ROC)[l]		
Marine	Live coral cover extent of a coral reef (ecosystem simulation model[m]; survey data[o]) Seagrass extent in a seagrasses (extrapolated ROC)[n]	Sea surface temperature to estimate mass bleaching/thermal stress in a coral reef (projections)[m,o] Aragonite concentration to estimate ocean acidification in a coral reef (projections)[m] Hurricane frequency/intensity in a coral reef (projections)[m] Sea level rise in seagrasses and intertidal rocky shores (projections)[n,p] Sea ice breakout date in Antarctic marine invertebrate communities (satellite data)[q] Rainfall, storm frequency, sea level rise in oyster reefs (projections)[r]	Live coral cover in a coral reef (ecosystem simulation model[m]; survey data[o]) Herbivorous fish biomass or abundance in a coral reef (ecosystem simulation model[m]; survey data[o]) Piscivorous fish biomass or abundance in a coral reef (ecosystem simulation model[m]; survey data[o]) Algae:coral cover ratio (survey data)[o] Algal/invertebrate abundance for Antarctic marine animal forest (survey data) [q] Oyster abundance in oyster reefs (survey data)[r]
Terrestrial-Freshwater	Suitable habitat extent of riverine forest or shrublands (bioclimatic modelling)[b]	Saltwater intrusion from sea level rise in wetlands (projections)[b] Habitat suitability – flood extent and climate of riverine forest, wetlands and shrublands (bioclimatic modelling)[b]	Bird abundance/breeding activity in wetlands (inferred same as recent trend)[b] Waterbird assemblage responses in wetlands (survey data)[b]
Freshwater-Marine		Barrage flow volume of coastal wetlands (ecosystem simulation model)[b] Salinity of coastal wetlands (ecosystem simulation model)[b]	

Marine-Freshwater-Terrestrial	Foundation species extent in saltmarshes and mangroves (extrapolated ROC)[n,s]	Sea level rise in saltmarshes and mangroves (projections)[n]

Step 4 – Collating available datasets

The RLE requires past and future timeseries data for each indicator to assess ecosystem trajectories relative to collapse thresholds (Box 1). The RLE can accommodate data from a range of sources and of varying quality[10], including information from scientific literature, reports, experts, historical accounts, maps, satellite imagery, Indigenous Knowledge, or other sources. We outline three major challenges to collating and using datasets to support assessments incorporating climate change impacts.

Measuring past functional change. Recent impacts of climate change can be measured or estimated using existing datasets (Table 1)[22]. Impacts over the past 50 years may be assessed using empirical timeseries, where available. However, these timeseries often span < 50 years or are incomplete, patchy, and biased towards types of variables, species, or regions[51–53]. For example, long-term monitoring is often more feasible for environmental than biotic variables, resulting in a bias towards assessing indicators of environmental conditions [54,55].

Extrapolating current trends. Current trends can be extrapolated (with confidence intervals) to estimate future impacts of climate change (Table 1), where the recent rate of change will likely continue (e.g., assuming a linear change in snowpack depth in snowpatch herbfields[56]). However, due to uncertainty in future climate-driven changes, assuming a particular rate of change may be inaccurate or produce uninformatively wide uncertainty bounds. Under-estimating risk may delay critical action, whereas over-estimating risk may divert resources from more at-risk ecosystem types.

Forecasting with models. Climate projections from global circulation models provide information on temperature, precipitation and wind, plus other environment conditions based on known relationships (e.g., between air temperatures and sea surface temperatures)[57]. However, climate projections are typically made at coarse spatial resolutions[1], making it challenging to identify changes specific to an ecosystem type, particularly those strongly affected by microclimates (e.g., aspect and topography for snowpatch herbfields[56]). Further, the magnitude and rate of climate change diverges across emission scenarios due to highly uncertain socio-economic factors (e.g., population growth, lifestyle, energy use and policy)[1]. The projections from each circulation model can also be strongly affected by the model structure and parameterisation[58,59], while confidence in projections also differs among variables, with temperature being more predictable than rainfall[58]. It is therefore difficult to confidently identify the direction and severity of ecosystem response to climate change using climate projections.

Ecological simulation models can be used to estimate impacts on biota (e.g., changes in foundation species using species distribution models[60]) and the probability of ecosystem collapse (RLE criterion E, Figure 1)[61] based on changes in environmental conditions, indirect impacts of climate change on land-use change[62], and other threats[44]. Yet the efficacy of simulation models depends on the evidence informing the ecological processes (including the resolution of the climate data[58]), dependencies and assumptions underpinning model structure. Estimating biotic change is challenging as it relies on understanding species responses to potentially novel environments and altered species interactions (see *Climate change impacts on ecosystems*). The model type also influences the reliability of future projections; mechanistic models are considered more robust to prediction outside the range of their training data than statistical models[63].

Step 5 – Estimating risk and reporting outcomes

The final step in an RLE assessment involves using indicators to estimate proximity to collapse and reporting the outcome. One key issue is accounting for uncertainties in the assessment.

Reporting uncertainties. Capturing uncertainties in predictions of future climate conditions is a prime concern in IPCC assessments – all inferences include a qualifier of confidence[64]. Many types of uncertainty are reducible with more data or knowledge (e.g., process and model uncertainty) and others are not (e.g., variability uncertainty)[65,66]. Some uncertainties will reduce as climate change plays out and impacts become clearer. But climate change will not have a single endpoint in time – impacts will continue to occur, and ecosystems will continue to change, at least until ecosystems equilibrate if and when net zero emissions are reached. Eliminating all uncertainties is impossible – assumptions and uncertainty, along with subjective judgements in selecting future climate scenarios, indictors, models, and collapse thresholds, are inevitable in estimating the future. Many of these challenges are dealt with in the above four steps as dealing with uncertainty is key in risk assessments.

Recommendations for navigating climate risks in ecosystem risk assessment

Here we recommend approaches to address the above challenges across the five steps of RLE assessments that we identified. Our intention is to outline methods from across relevant disciplines and synthesise those in the context of RLE assessments.

Step 1 – Conceptualising climate change impacts. Several approaches support dealing with uncertainty and complexity in identifying ecosystem responses to climate change and interacting threats (Box 1). Conceptual models are excellent tools for describing how ecosystems function based on available evidence (Box 2)[8]. These relatively simple qualitative models can underpin quantitative analysis. Uncertainty in how climate may affect ecosystem processes and how interactions may occur can be captured explicitly in conceptual models, drawing on expert knowledge and synthesis of available evidence. For example, multiple conceptual models can depict different hypotheses for mechanisms underpinning climate change impacts, highlighting uncertainty using dashed lines[22]. Different pathways as alternative probabilities could be incorporated in a model (e.g., Bayesian belief network). New approaches such as causal networks can estimate how mechanisms may interact to increase risk[67]. The level of certainty in the postulated relationships can be quantified using relevant data from similar ecosystem types or structured expert elicitation[68]. Where conceptual or simulation models have captured multiple plausible mechanisms, sentinel indicators could be established to understand which pathways manifest through time and may trigger reassessment if they register greater risk than first thought. Overall, conceptual models can provide a robust evidence-base for statistical and mechanistic models by allowing alternative scenarios of change to be explored, highlighting unidentified assumptions, and generating testable hypotheses[69].

Monitoring, experiments, and modelling are valuable approaches for predicting ecosystem responses to climate change and other interacting threats[70] but most ecosystem types are data poor. Risk assessments and related decisions need to be made with imperfect understanding[65] and can be supported by a range of approaches. Data and knowledge from analogous ecosystem types (such as those in the same functional group in the Global Ecosystem Typology[8,9]) may provide a useful supplement where data are lacking. The assembly model from the relevant functional group may provide a useful starting point for creating a conceptual model of features, interactions, and threat pathways of climate change impacts. Assessors can examine regions with similar forecast climates (i.e., climate analogues)[71], such as using the Analogue Atlas database[72] (https://plus2c.org). Similarly, space-for-time substitution, using natural climatic gradients, has been demonstrated to be a plausible proxy for climate effects in similar environments elsewhere[73].

Adaptive capacity represents one source of uncertainty associated with risk outcomes. The effects of climate change have predominantly been evaluated in RLE assessments by assuming no adaptative responses[74], yet adaptive capacity would likely lower estimated levels of risk. The adaptive capacity of ecosystems may be evaluated based on variables critical to ecosystem functioning[17,35] and quantified though hypothesis testing[75], particularly for foundation species (e.g., hard corals in coral reefs[76]). But often the adaptive capacity will be unknown, and should be treated as another plausible mechanism, to be captured in the approaches outlined above. For example, components or mechanisms (e.g., ecological memory, cross-scale interactions, functional redundancy, positive feedbacks)[35] and their dynamic links can be integrated to conceptual ecosystem models to improve understanding of ecosystem functioning and aid selection of appropriate indicators, although care is needed to avoid unnecessary complexity and maintain parsimony.

Step 2 – Identifying indicators. The RLE outlines how to identify indicators linked to ecosystem functioning[22], starting with developing a conceptual model to inform the selection[44,47] and exploring indicators used in analogous systems (Table 1). This approach can pinpoint indicators likely to be most sensitive to climate change or capture climate-induced adaptions, and can be reasonably monitored to detect future change (see [44]). Quantitative mechanistic models that predict change under different climate scenarios can inform the most suitable indicators for detecting changes in risk[44]; these have been used to analyse risks to species[15] but are currently only available for a few ecosystem types. Sensitivity analyses can identify indicators or assumptions that are most likely to affect assessment outcomes[44,77,78] and can drive further research or data collection. Assessment of multiple ecosystem-specific indicators can provide multiple lines of evidence of collapse risk, while capturing the variability in ecosystem responses and uncertainty in future change[54,79]. Data limitations may necessitate trade-offs between indicators more directly relevant to functional changes but supported by minimal or unreliable data, and proximal or generic indicators with greater data availability; the limitations of each indicator should be reported alongside uncertainty in the resulting risk category (via plausible bounds). Local knowledge, including Indigenous People and Local Communities (IPLC), could be consulted to assist with development of realistic indicators relevant to a given ecosystem.

Step 3 – Setting collapse thresholds. Collapse thresholds can be defined for environmental changes by examining the physiological tolerances of key native biota, informed by population theory[44,80], species vulnerability to environmental changes[13,15,81], and data collated in relevant species Red List assessments[13]. For example, in seagrass meadows, a collapse threshold for dissolved oxygen levels may be based on hypoxia tolerance for seagrass[81]. Environmental collapse thresholds can also be based on an ecosystem's distribution limits (e.g., geographical limits of foundation species[82]), assuming alignment of realised and fundamental niches, and areas where the ecosystem has locally collapsed. Experimental studies can assist in developing a causal understanding of changes in environmental conditions and ecosystem collapse[83]. An alternative option to develop collapse thresholds could involve (data permitting) exploring responses of key biota to environmental change at the leading edge, core, and lagging edge of an ecosystem type's distribution[84]. This may allow a comparison of areas that are more and less tolerant of environmental change. Ultimately, uncertainty in collapse thresholds is likely; reporting multiple plausible collapse thresholds can explicitly capture this uncertainty (e.g., a best estimate with upper and lower bounds). For example, separate collapse thresholds were used to capture scenarios where coral could and could not adapt to ocean warming to avoid coral bleaching[44].

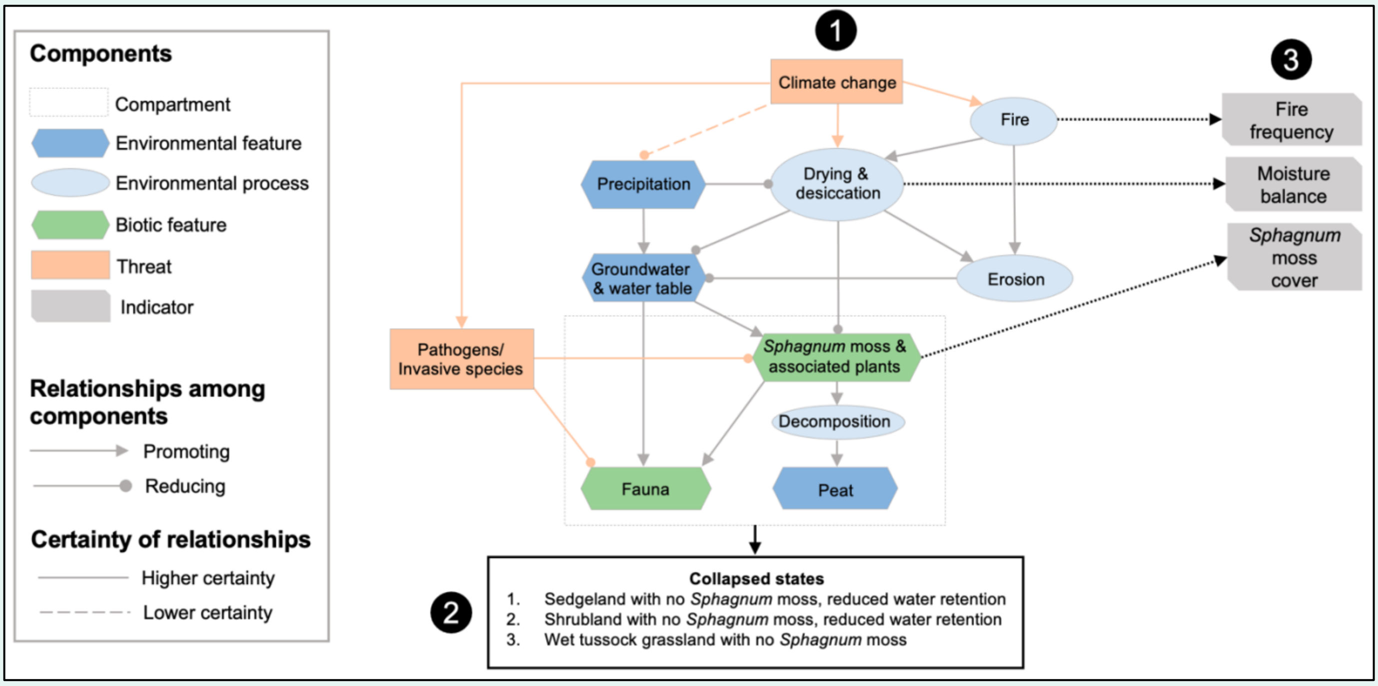
Box 2 | Using conceptual models to capture climate-driven threats in ecosystem risk assessment.

An example of a conceptual model developed collaboratively by multiple experts for the Red List of Ecosystems assessment of alpine peatlands across Australia[85] to show how they can be valuable tool for ecosystem risk assessment in the context of climate change.

1. Visualising links. Developing a conceptual model forces assessors to explicitly state the impacts of key threats (orange shapes) on environmental and biotic features (dark blue and green shapes) and processes (light blue shapes) in the ecosystem type and the cascading effects throughout the system. Assessors can directly depict the direction of impact (promoting or reducing) and the certainty in the relationships, whether qualitative (e.g., using different line types for certain or uncertain relationship; see figure) or quantitative (e.g., elicited from experts), thus highlighting the possible pathways of decline that require greater elucidation.

2. Defining collapse. Once the relationships are finalised, the model can be used to help define climate-change driven degraded and collapsed states. This can occur by examining the pathways of threat (orange links) due to various climatic changes and conceptualising how these will degrade the environmental and biotic components (blue and green shapes), and what the endpoint of each degradation pathway will look like. For example, drying and desiccation may increase due to warmer temperatures, less precipitation, and increased frequency of fires under climate change. These changes will likely decrease the water retained in the system and moss cover, altering peat-formation processes. This may allow dry-adapted shrubland plant species to encroach, causing a shift to a shrubland ecosystem.

3. Selecting indicators. Clearly depicting the key ecosystem components and the pathways towards collapse can support identification of critical indicators of decline (grey shapes). Here, drying of this characteristically water-logged ecosystem is a key pathway in which peatlands can collapse. Therefore, selecting indicators that capture changes in moisture levels may provide a useful indication of ecosystem condition and progress towards collapse.



Conceptual model for a bog ecosystem in the alpine and subalpine regions across Australia showing the (1) key features and processes, and impact points of climate change, (2) identified collapsed states, and (3) indicators of decline. Simplified version based on Regan et al.[85].

Step 4 – Identifying useful datasets and tools. Numerous approaches have proved useful for estimating future climate change impacts (Table 1). Recent trends can be extrapolated in RLE assessments to estimate future change, for example, over the 50-year window covering the past, present and future (sub-criterion 2b for criteria A, C, D), where appropriate[10,77]. Experimental studies, as outlined above, may provide insights by constructing likely future conditions and evaluating ecosystem responses[86]. The vast knowledge bank and tools collated for species risk assessments can be harnessed to support RLE assessments. For instance, over 150,300 species have been assessed under the IUCN Red List of Threatened Species (as of May 2023)[87], capturing information including estimates of vulnerability to climate change and changes in species populations or distributions[5,88,89]. Information on ecosystem engineers, keystone species or foundation species may be particularly useful where species decline is explicitly linked to collapse (e.g., mangroves[90], seagrasses[91], coral[5]), recognising that the likelihood of a single species causing an ecosystem's collapse may be uncertain. Finally, information on historical climates can be used as analogues for climate change to understand potential shifts in ecosystems based on changes in suitable habitat[92].

It is important to think critically about which models and scenarios are most appropriate for the target ecosystem types and how these will be analysed (see *Estimating and reporting uncertainties*). Multiple or ensemble global circulation models and appropriate climate projections could be used to understand the range of the potential futures[16,93]. Assessors may choose to use a multi-model mean or present results from multiple models individually. The latter may be most appropriate for ecosystem types where climate extremes and seasonality are important[58]. Projections can be downscaled to finer spatial resolutions via dynamical downscaling into regional climate models, statistical downscaling, or simple scaling, but care must be taken to avoid misinterpreting the accuracy and precision of the data[58] when interpreting the results in the context of risk. The relative importance of spatial uncertainty in datasets may depend on the scale of the ecosystem type classification[58]; some ecosystem types are assessed at broad scale, therefore coarser resolution datasets may have less impact on collapse risk than for finely defined ecosystem types.

Expert judgements have long been used to estimate ecological variables where empirical data are lacking[94], including in risk assessments for species[95], ecosystems[96] and ecosystem services[97]. Capitalising on the wealth of knowledge and experience of experts is likely to be critical to capturing climate change impacts in risk assessments[98]. Expert judgements (informed by available evidence) are pivotal in RLE assessments, including in constructing conceptual models, selecting indicators, defining collapse thresholds, and determining the relevance of datasets. Using expert judgements to estimate ecological variables requires the same scrutiny afforded to empirical data to ensure its reliability. It is best done using a structured approach (e.g., IDEA protocol[68]) that aggregates estimates from numerous experts and captures the degree of certainty[99].

Available data and expert opinion can then be used to underpin relationships between ecosystem dynamics and projected environmental changes in process-based, mechanistic simulation, statistical or climate envelope models[100]. For example, mechanistic spatial modelling approaches have been encouraged for extinction risk assessments and may be useful for ecosystem risk assessment; these approaches better capture processes (e.g., physiology, dispersal, demography and biotic interactions) and have better predictive potential when extrapolating to conditions outside those in their training data, including novel conditions under climate change[63].

Step 5 – Estimating and reporting uncertainties. Capturing uncertainty is important to allow comparisons between older and newer assessments as climate change projections and ecosystem science in general rapidly evolves. When dealing with future projections and predictions, it is vital to consider, capture and report on the types and extent of uncertainty and consider how these affect the risk of collapse for the ecosystem type. To ensure assessments are transparent and repeatable, assessors should explicitly report all assumptions and reasoning, data quality, and plausible upper and lower bounds around a most likely risk category to reflect uncertainties in the data[22] (Box 1).

Approaches to capturing uncertainty are well established and becoming more accessible for risk assessment as guidelines develop, including examples of assessments that manage and report uncertainties well[44,47]. Where possible, collapse risk should be calculated using multiple relevant climate models, ecological models, emission scenarios (from low to high), and model realisations (runs) to provide a plausible range of collapse risk that explicitly captures the uncertainty in future change[58,93]. Conducting sensitivity analyses can quantify some uncertainties by estimating change under a range of alternate scenarios of environmental changes (scenario sensitivity)[61], using a range of data sources from local weather stations to global projections (data sensitivity)[101], or using multiple ecosystem models that represent alternate ecosystem responses (ecosystem model sensitivity)[61]. Sensitivity analyses can also identify the components to which collapse risk is most sensitive, thereby highlighting components that can be preferentially monitored. Quantifying the agreement in spatial and temporal predictions from each scenario, model, and model run can show points of consensus and difference among predictions, and to understand which type of uncertainty most affects differences in predicted ecosystem changes[58,93] and thus collapse risk.

By communicating multiple types of uncertainty, end-users can evaluate the consequences of that uncertainty for their purposes and their tolerance for adverse outcomes. Ultimately, the risk categories used in RLE assessments are coarse, providing a buffer to some level of uncertainty in our capacity to estimate future changes under climate change.

Conclusions and outlook

A major challenge posed by climate change is the uncertainty in how the climate will change, and how ecosystems will respond. The RLE is well suited to capturing the threats from climate change on ecosystems (Figure 1) because of its versatility to assess any ecosystem type, handle varied availability of data and knowledge, and assess change over different timeframes[10]. Yet challenges remain in adequately representing uncertainty. The diagnostic process of defining ecosystem dynamics, selecting indicators, and setting collapse thresholds is essentially the same, regardless of the threats affecting the ecosystem type[10]. The practical solutions presented here help overcome many challenges hindering reliable, comprehensive ecosystem risk assessments capturing the threats from climate change: using innovative approaches to capture multiple plausible climate response pathways, how to use diverse data sources and deal with data-poor ecosystem types, creative use of sensitivity analyses, and evaluating and reporting uncertainties.

The uncertainty in forecasting ecosystem change under a changing climate requires a multidisciplinary approach. Assembling multidisciplinary teams with a broad range of experience in target ecosystems can enhance the capacity to produce assessments that adequately capture the ecosystem dynamics. For example, gathering experts in remote sensing products, ecological specialists, those with modelling and uncertainty expertise would facilitate a robust understanding of ecosystem dynamics, how indicators and threats may vary or be measured, and how to generate bounds on future risk for diverse indicators. Enhancing collaborations among diverse experts may increase the accessibility of datasets; for example access to ecosystem-specific climate predictions can be a major barrier because of infrequent collaboration among ecosystem experts and climate modellers[102]. Enhancing knowledge sharing and using diverse information sources will be essential to manage perceived data gaps that might otherwise limit our capacity to estimate collapse risk under climate change.

Long-term monitoring data are required to support revised assessments every 5-10 years that report whether the predicted changes manifested. This underlines the importance of developing, implementing, and resourcing such programs. The suggestions above, including the use of sensitivity analyses and sentinel variables, are designed to make this recommendation of reassessments tractable because enhancing knowledge of ecosystem organisation, drivers, and dynamics are critical to developing plausible predictions about climate change responses and corresponding collapse risk. Further research is also needed to address and acknowledge the uncertainties in global and regional climate models, particularly for uncertain variables such as rainfall.

Key unresolved issues remain a challenge for ecosystem risk assessments. Firstly, while we focus on extant ecosystems, novel ecosystems may arise as suitable conditions overlap among ecosystems[32]. Novel ecosystems may represent depauperate versions of existing ecosystem types (e.g., with new species assemblages), collapsed states of other ecosystem types, or completely novel assemblages of species and processes (i.e., new ecosystem types). Judgements are required to decide whether the novel ecosystems lie within the variations of the ecosystem under assessment, or represent transition into a new ecosystem type, and collapse of the previous ecosystem type. Current management focus to retain existing ecosystems can be assisted by accurately capturing collapse risk, and thus direct attention to high-risk ecosystems where interventions may slow or prevent transition to a novel ecosystem. Secondly, climate change will likely have cascading effects on systems, whereby climatic changes have flow-on effects within and between systems along impact chains[2]. Ideally, this should be captured in the conceptual modelling to show which features may be affected directly or indirectly. Yet our capacity to confidently detect and attribute impacts on ecosystems to climate change decreases further along the impact chain[2]. Nonetheless, the RLE focuses on symptoms of collapse[10], so attributing the change to a specific threat may be less important than detecting change to the ecosystem (which may be caused by multiple threats) and relating it to collapse.

Despite inherent uncertainty in ecosystem responses to climate change, risk assessments can inform management to prioritise investments and planning to prevent collapse. Capturing climate-driven risk is critical to inform policy, prioritisation for biodiversity and ecosystem conservation, and potential risks to vital ecosystem services[97]. There are clear implications that climate change increases the risk of collapse for particular ecosystem types, and thus impacts social-ecological systems[7], including ecosystem services, human wellbeing and economic value derived from those systems. Risk-based approaches highlight the urgent imperative and return-on-investment for climate change mitigation, can inform selection of the most effective ecosystem-specific strategies for enhancing ecosystem resilience, and help secure a sustainable trajectory for future generations.

Supplementary information

Appendix 1 – Glossary of terms
Appendix 2 – Reference list from Figure 2
Appendix 3 – Reference list from Table 1

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