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OPINION

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Combating ecosystem collapse from the tropics to the Antarctic

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Abstract

Globally, collapse of ecosystems—potentially irreversible change to ecosystem structure, composition and function—imperils biodiversity, human health and well-being. We examine the current state and recent trajectories of 19 ecosystems, spanning 58° of latitude across 7.7 M km^2, from Australia's coral reefs to terrestrial Antarctica. Pressures from global climate change and regional human impacts, occurring as chronic 'presses' and/or acute 'pulses', drive ecosystem collapse. Ecosystem responses to 5–17 pressures were categorised as four collapse profiles—abrupt, smooth, stepped and fluctuating. The manifestation of widespread ecosystem collapse is a stark warning of the necessity to take action. We present a three-step assessment and management framework (3As Pathway *Awareness*, *Anticipation* and *Action*) to aid strategic and effective mitigation to alleviate further degradation to help secure our future.

KEYWORDS
adaptive management, climate change, ecosystem collapse, human impacts, pressures

1 | INTRODUCTION

"The biosphere, upon which humanity depends, is being altered to an unparalleled degree across all spatial scales" (Brondizio et al., 2019). Humans have directly modified 77% of the land surface and 87% of oceans (Watson et al., 2018). As a result, an estimated 30% of global land area is degraded, directly affecting three billion people (Arneth et al., 2019; Brooks et al., 2019; Nkonya et al., 2016). Ecosystems are deteriorating globally, and species extinction rates are strongly correlated with both climate change and the human footprint (Ceballos et al., 2020; Keith et al., 2013). One third of species at high risk of extinction are imperilled by habitat degradation (Brondizio et al., 2019). The endpoint of disruption and degradation of ecosystems is potentially or actually irreversible collapse. We define collapse as a change from a baseline state beyond the point where an ecosystem has lost key defining features and functions, and is characterised by declining spatial extent, increased environmental degradation, decreases in, or loss of, key species, disruption of biotic processes, and ultimately loss of ecosystem services and functions (Bland et al., 2017, 2018; Brondizio et al., 2019; Duke et al., 2007; Keith et al., 2013; Sato & Lindenmayer, 2018). We consider a regime shift (see Biggs et al., 2018; Crépin et al., 2012; Levin & Möllmann, 2015; Rocha et al., 2015) to be an ecosystem collapse if there is a strong component of loss and potential or actual hysteresis, and/or limited capacity to recover. The need to understand and forestall collapse is the foundation for effective conservation action and management, and the target of global programmes such as the IUCN Red List of Ecosystems (Keith et al., 2013; Levin & Möllmann, 2015; Sato & Lindenmayer, 2018). Detecting thresholds (Ratajczak et al., 2017), identifying ecosystems approaching ecological collapse, and documenting how altered processes are driving its progression and outcomes, is a prerequisite for taking timely and appropriate action to mitigate and adapt to this risk.

We assessed evidence of collapse in 19 ecosystems (both terrestrial and marine) along a 58° latitudinal gradient for which major signals of change have been reported. These 19 ecosystems cover ~1.5% of the Earth's surface (>7.7 million km^2), extending from northern Australia to coastal Antarctica, from deserts to mountains to rainforests, to freshwater and marine biomes, all of which have equivalents elsewhere in the world (Figure 1; Table S1). We collated evidence of past (baseline) and current states of each ecosystem spanning at least the last ~200 years, focusing on change over the last 30 years. For each ecosystem, we applied a set of four a priori collapse criteria (see Methods S1) to describe the extent and nature of transformation, and the possibility for recovery to the defined baseline state. The drivers of collapse were characterised by their scale (time and/or space) and origin (global climate change or regional human impacts). We also identified pressures (also termed drivers, see Biggs et al., 2018; Rocha et al., 2015; Figure 1b), categorising them into chronic stresses or 'presses' (e.g. climate trends, habitat loss, invasive species and pollution) or acute effects or 'pulses' (e.g. extreme events—storms, heatwaves and wildfires; sensu Crépin et al., 2012; Ratajczak et al., 2017). The same pressure type can occur as both press (e.g. increasing air or sea temperatures) and pulse (e.g. heatwaves), with potential changes in pulse frequency, severity, extent and duration (Figure 2a).

To identify emergent patterns of ecosystem collapse, we first constructed four broad archetypal temporal trajectories, hereafter

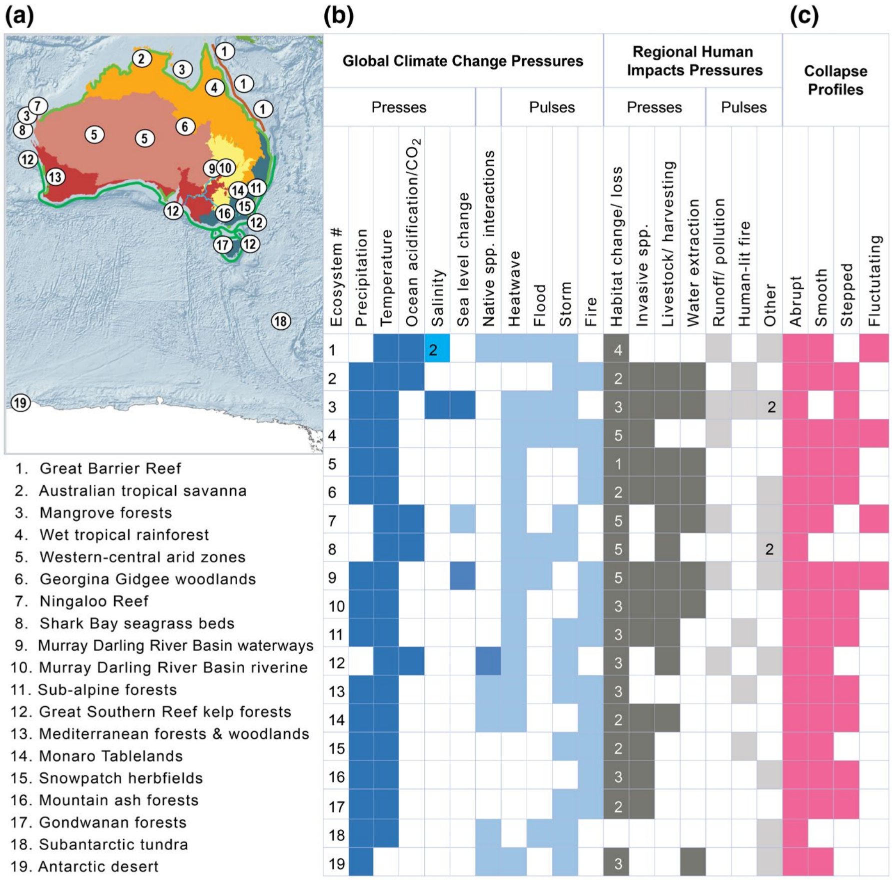

FIGURE 1 Locations and pressures of ecosystem change. (a) Map showing focal ecosystems (westernmost site in Antarctica is not shown) and geographical coverage of broad biomes (coloured areas from Ecoregions, 2017). Coloured lines indicate the extent of the marine ecosystems included in this study. (b) Pressures on each ecosystem are: global—precipitation (changes in, including drought); temperature (increase in mean air or sea surface); ocean acidification and CO_2 (air) increase; salinity increase in water or soil; sea level change; heatwave (marine or terrestrial); flood; bushfire; negative native species interactions (either a press—dark blue, both—mid blue, or pulse—light blue); regional—habitat loss or major detrimental change; invasive non-native species; livestock and harvesting (of wild populations); loss of available water due to water extraction for human use; run-off and/or associated pollution; human-ignited fire; others including trampling, dust, roads, etc. (either a press—dark grey or pulse—light grey). If the categories contained more than one pressure, the numbers are shown. (c) Collapse profiles found within ecosystems (see Figure 2 for profile shapes). Data and sources supporting these summaries are listed in Table S1

collectively termed 'collapse profiles'. We defined four profiles: abrupt, smooth, stepped and fluctuating, based on ecological theory and empirical observation and experimentation (Crépin et al., 2012; Petraitis, 2013; Scheffer et al., 2012; see Figure 2a,b). The collapse profiles illustrate potential ecosystem responses to key changes and the ability to withstand stress (i.e. the capacity to absorb pressure), and can provide insights into recovery potential (likely capacity of the ecosystem to return to its baseline state when the pressure subsides). Using information on environmental change across the last 30 years, we categorised the observed changes in each ecosystem to a collapse profile (e.g. Figure 2c). Assessments are based on quantitative information, as well as on inference from multiple lines of evidence. Ecosystem variables used to define collapse profiles were selected by experts as being representative (Table S1).

The 19 ecosystems presented have collapsed or are collapsing according to our four criteria (see Table S1 for details). None has collapsed across the entire distribution, but for all there is evidence of local collapse. Rapid change (months to years) has occurred in several cases (Figure 2c, Table S1). We identified 17 pressure types affecting the 19 ecosystems (Figure 1). The key global climate change presses are changes in temperature (18 ecosystems) and precipitation (15 ecosystems), and key pulses are heatwaves (14 ecosystems), storms (13 ecosystems) and fires (12 ecosystems). In addition, each ecosystem experienced up to 10 (median 6) regional human impact pressures (presses and/or pulses) (see Figure 1). Habitat modification or destruction has occurred in 18 ecosystems, often at substantial levels, but over a relatively small spatial scale in the Antarctic ecosystem. Run-off with associated pollutants was the most common single human impact pulse (6 ecosystems).

In recent years, pressures have become more severe, widespread and more frequent. Nine ecosystems have recently experienced presses or pulses unprecedented either in severity or on spatial scale, relative to historic records (Table S1). For example, heatwaves spanning >300,000 km^2 affected marine and terrestrial ecosystems simultaneously in Western Australia in 2010/11. They delivered sea surface temperatures 2–2.5°C above the long-term average,

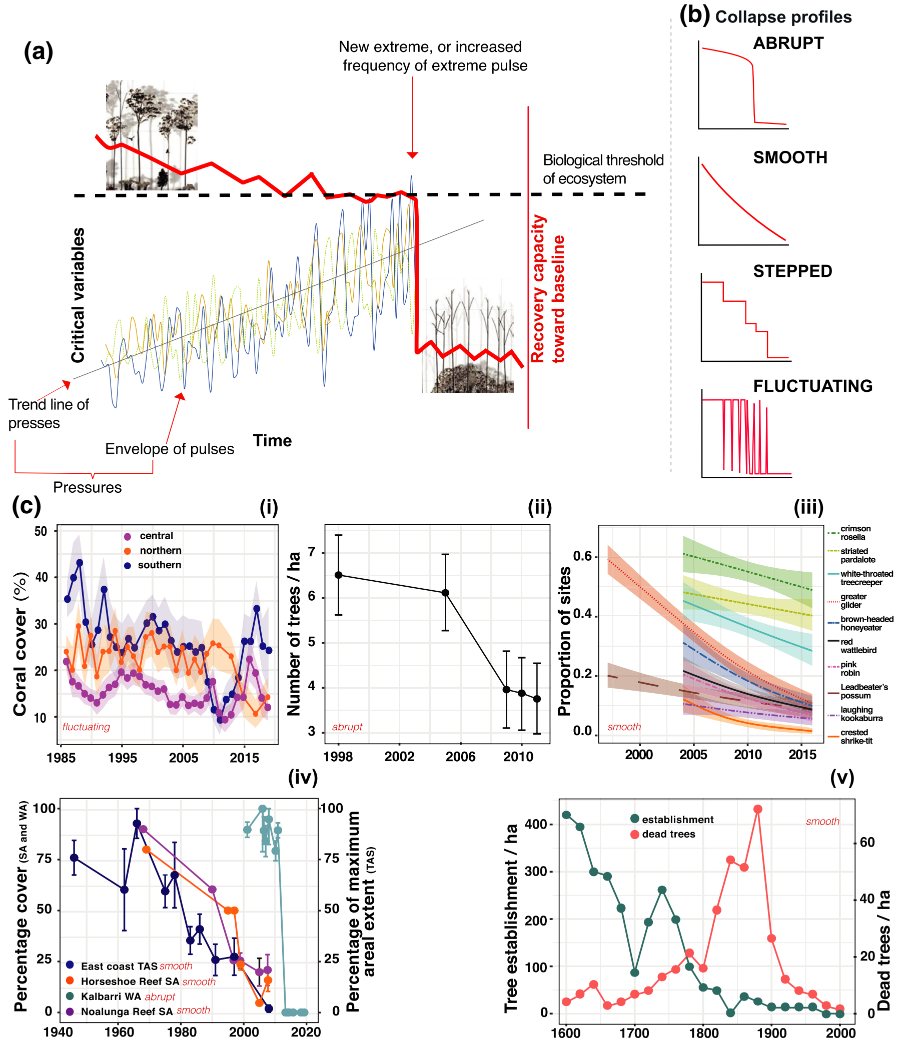

FIGURE 2 Ecosystem collapse trajectories. (a) Hypothetical trajectory for ecosystem collapse. *Y*-axis (left side): change in three hypothetical environmental variables (dotted green, orange and blue). Orange and blue are generally synchronous, and green is antagonistic. The trend line of presses is the mean for one variable. Variability illustrates the envelope of acute pulses; the blue variable exceeds a biological threshold prior to a change in ecosystem state. *Y*-axis (right side): measure of recovery capacity towards the baseline. The red line in (a) exemplifies an ABRUPT ecosystem collapse. (b) Four archetypal temporal trajectories of ecosystem collapse profiles. (c) Examples of collapse profiles: (i) fluctuating change in loss of hard coral cover on the northern, middle and southern Great Barrier Reef (#1); (ii) abrupt change in the abundance of large, old-cavity trees in the Mountain Ash ecosystem (#15); (iii) smooth change in modelled presence/absence of tree cavity-dependent species from 1997 to 2016; (iv) smooth decadal changes in Great Southern reef kelp forests (#12); east coast Tasmania: mean cover of giant kelp (*Macrocystis pyrifera*), averaged over seven sites with per-site values calculated relative to maximum cover observed at each site from 1946 to 2007 (figure adapted from Steneck & Johnson, 2013; data are means ± SE). For Horseshoe and Noarlunga reefs, the values are percentage of reef covered by all canopy-forming kelp species (figure adapted from Connell et al., 2008). Kalbarri, WA: percentage cover of *Ecklonia radiata* across three reefs in the Kalbarri region (figure adapted from Wernberg et al., 2016); (v) reconstructed establishment dates (trees/ha) in the Gondwanan conifer forest (#17) during ca. 1600–2000 AD, and smooth change of reconstructed fire-kill estimated dates (*Athrotaxis selaginoides* minimum mortality dates; dead trees/ha; data sources in methods)

causing widespread loss of kelp, affecting 36% of the local seagrass meadows, and causing the death of 90% of the dominant seagrass *Amphibolis antarctica* in Shark Bay (Arias-Ortiz et al., 2018; Ruthrof et al., 2018). Since then, no new *A. antarctica* seedlings have grown (van Keulen, 2019), and a transplant intervention has shown limited success (Kendrick et al., 2019). Whether the seagrass meadow ecosystem will recover is unknown, and the potential long-term impact on its habitat-dependent species, including commercially important species, remains to be determined. Some pressures occurred repeatedly in rapid succession. For example, a record-breaking, extensive marine heatwave occured again along the coast of Western Australia in November 2019, and was followed by further warming in December 2019; early impacts included fish, mollusc and crustacean kills and coral bleaching (Ceranic, 2019).

All ecosystems are experiencing 6–17 pressures (median 11); 12 are experiencing 10 or more pressures often simultaneously.

Interactions between concurrent pressures can be additive, synergistic or antagonistic (sensu Ratajczak et al., 2018). Additive or synergistic pressures that intensify impacts occurred commonly across ecosystems. Increasing air temperature (press) coupled with heatwaves, droughts and/or storms (pulses) culminated in extreme fire events in nine ecosystems (see Figure 1). The 2019/20 marine heatwave on the west coast of Australia was accompanied by an unprecedented, continent-wide land heatwave (18 December 2019: the hottest Australia-wide [area averaged] day on record, 41.88°C; Bureau of Meteorology, 2020). This extreme heat contributed to the highest average Forest Fire Danger Index on record (a measure of fire weather conditions) across the majority of the Australian continent. Severe drought exacerbated these conditions, leading to widespread fires at an unprecedented scale (18.6 million ha; Richards et al., 2020), particularly in eastern temperate forests, and producing 434 million tonnes of CO_2 (Werner & Lyons, 2020). Severe fire-weather conditions also created the largest recorded, single forest fire in the country (Boer et al., 2020). These fires affected #2 Australian tropical savannah, #9 Murray-Darling Basin waterways, #11 Montane and subalpine forests, #13 Mediterranean forests and woodlands, #15 Snow patch herbfields and #16 Mountain ash forest ecosystems. Although the Tasmanian Gondwanan conifer communities (#17) were spared (having previously been affected by severe fire in 2016), ~50% of Australia's other Gondwanan relict forests were affected by these fires (Kooyman et al., 2020). The affected communities comprise the greatest concentration of threatened rainforest species in Australia, and core areas may never have previously experienced fire (Styger et al., 2018). The confluence of pulsed heat, drought and fire also altered local weather conditions creating dry lightning storms, exacerbating conditions. Dry lightning frequency has increased in Tasmania since the beginning of the 21st century (Styger et al., 2018), and dry lightning also primarily ignited the devastating large fires in remote areas of eastern Australia in 2019/20 (Nguyen et al., 2020). The impact of multiple pressures within and the concurrence of multiple pressures across ecosystems undergoing detrimental, major structural and functional change is occurring synchronously elsewhere in the world (Biggs et al., 2018; Crépin et al., 2012; Ratajczak et al., 2017; Rocha et al., 2015; Turner et al., 2020).

While antagonistic pressures (attenuated changes with multiple pressures) are more difficult to identify, switching of the relative contribution of individual pressures emerged. On subantarctic Macquarie Island, the relative influence of individual pressures varied over time switching from drought-induced stress to pathogen-dominated collapse, within a single decade. While we have not yet determined the extent of interdependencies between ecosystems that share pressures, for example between #9 Murray Darling River Basin waterways and #10 Murray Darling River Basin riverine ecosystems, such interdependencies have been identified in regime shifts elsewhere (Rocha et al., 2015).

All 19 ecosystems showed at least one collapse profile across their range (Figures 1 and 2), the types of which depended on the nature and scale of the pressures involved. Only two ecosystems were characterised by single collapse profiles (#8 Shark Bay seagrasses; #18 Subantarctic tundra), while the remaining exhibited different collapse profiles in various parts of their range (e.g. #1 Great Barrier Reef; Lam et al., 2018; MacNeil et al., 2019; Wolff et al., 2018). All ecosystems experienced change that matched an abrupt collapse profile, but in 79% of cases, these changes happened at local scales (e.g. fish deaths in several waterways leading to substantial loss of biodiversity, #9 Murray Darling River Basin waterways; Moritz et al., 2019). The remaining ecosystems (#3 Mangrove forests, #8 Shark Bay seagrass beds, #17 Gondwanan conifer forest and #18 Subantarctic tundra) changed abruptly at the regional scale. In three of these, Mangrove forests, Shark Bay seagrass beds and Gondwanan conifer forest, abrupt change was attributed to multiple pressures combined with an exceptional pulsed extreme event (e.g. marine heatwaves + cyclones + floods). Ten abrupt changes were associated with fires, usually accompanied or preceded by extreme heat and/or drought. Another abrupt change, the mass dieback of mangroves in northern Australia, was uniquely associated with a temporary 20-cm drop in sea level brought on by a severe El Niño event that altered regional wind conditions (Duke et al., 2017). In 16 ecosystems, smooth collapse profiles occurred at a regional scale, six of which were associated with long-term temperature changes or changes in precipitation (e.g. drought). Twelve ecosystems had a stepped profile, and in 10 of these ecosystems, change was associated with land clearing for livestock grazing (Table S1).

Our analysis clearly demonstrates the widespread and rapid collapse, and in some cases the irreversible transition rather than gradual change at a regional scale. Different collapse profiles, combined with ecological knowledge, can provide insights relevant to different temporal and spatial recovery and the effectiveness of management actions (see Table S1). For example, patches of Mountain ash forest (#16: abrupt collapse from fire, and stepped collapse due to long-term logging—Figure 2c ii) may require a century or longer to recover to old-growth status. In comparison, recovery of populations of some mammal or bird species may occur within 10–20 years if suitable habitat were to be generated and maintained (e.g. through the provision of appropriately designed, placed and managed nest boxes; Wolanski et al., 2004; see Figure 2c iii). Similarly, fluctuations in ecosystem state, such as loss of corals from crown of thorn outbreaks linked to agricultural and urban run-off after storms (#1 Great Barrier Reef), may provide windows of opportunity in which to optimise management outcomes.

In the past, collapse of ecosystems was linked to poor ecological management, loss of ecological resilience, and poor mitigation of systemic risks to civilisations (Cumming & Peterson, 2017). Since 2009, the concept of planetary boundaries (Rockström et al., 2009; Steffen et al., 2015) has helped to identify targets for achieving a 'safe space' for all humanity without destabilising critical planetary processes. Collapsing ecosystems are a dire warning that nations face urgent and enormous challenges in managing the natural capital that is manifest in each ecosystem's biodiversity, and that sustains human health and well-being. With the advent of the Sustainable

Development Goals (United Nations, 2019) and the undertakings of the Paris Climate Agreement from 2016, there is an increasing expectation that urgent action will occur, despite indications that current progress is falling well short of meeting targets (Allen et al., 2018; Arneth et al., 2019; United Nations Environment Program, 2019). Global policies and actions must deliver an estimated 7.6% emissions reduction every year between 2020 and 2030 to limit global warming to <1.5°C above pre-industrial levels (Peters et al., 2020). However, even the most ambitious national climate policies fall well short of this target, and a collective fivefold increase in global commitment is probably required. Emissions continued to rise (0.6%) in 2019 (Climate Action Tracker, 2019), but dropped 7% in 2020 due to COVID-19 pandemic-imposed restrictions (Forster et al., 2020). However, this unprecedented fall in CO_2 emissions is unlikely to have a beneficial long-term effect, unless green technology and policy lead the economic recovery (Rockström et al., 2009). Currently, the 1.5°C goal is almost certain to be exceeded, and the 2°C target embodied in the Paris Agreement seems unlikely to be met. The IPCC's Special 1.5°C report estimated two to three times as many species are likely to be lost at 2°C compared to 1.5°C, and that the amount of the Earth's land area where ecosystems will shift to a new biome would increase 1.86 times (Allen et al., 2018; Climate Action Tracker, 2019).

Protected areas often proposed as a means for conserving and managing ecosystems and their services (Hannah et al., 2007) are not immune to collapse: 10 of our examples fall under international or national management systems, and seven are World Heritage Areas (see Table S1). Due to the ubiquitous nature of global climate pressures, even remote and protected ecosystems are not immune to collapse despite their formal protection status (e.g. Antarctica, subantarctic Macquarie Island, northern Great Barrier Reef, the Wet Tropics and Tasmanian Gondwanan conifer forests; Driscoll et al., 2018).

Effective management of collapsing ecosystems is essential for the ecological sustainability of the environment to support both people's health and livelihoods and whole ecosystem biodiversity. Managing physical environmental degradation is difficult and complex, and can only be successful when diverse segments of the community can be motivated to overcome issue fatigue and feelings of failure (Kerr, 2009; Morrison et al., 2018). Furthermore, in contrast to ecosystem change with a smooth collapse profile, abrupt change can come as a surprise because changes in feedbacks within ecosystems can go unnoticed (Crépin et al., 2012). Building on decades of conservation decision-science (Game et al., 2013; Possingham et al., 2015; Prober et al., 2019), we propose the 3As Pathway to provide clear understanding and guidance for the pathways, and reasoning for policy and management interventions (Figure 3). This pathway combines adaptive management steps prior to collapse (*Awareness* and *Anticipation*) with *Action* choices to avoid, reduce or mitigate impact from press and pulse pressures. We expand on frameworks that are binary—shift back towards favourable conditions or adjust to new conditions (e.g. Crépin et al., 2012)—and build on adaptive strategies that focus on resistance, resilience and realignment options (Aplet & McKinley, 2017; Millar et al., 2007; Stein et al., 2014; Stephenson & Millar, 2012) to provide a simple, top-level mnemonic to aid decision-making.

The first step, *Awareness*, is to acknowledge the importance of appropriate biodiversity, and to recognise where biodiversity and ecosystem services need protection (Keith et al., 2017). For example, the ancestral, fire-sensitive Gondwanan conifer forests (#17) have been identified by the Tasmanian Parks and Wildlife service as a high priority for protection from fires compared with adjacent button-grass moorlands that can recover more readily after wildfire (see Case Study, Table S1). The second step, *Anticipation*, is to identify the risks of current and future pressures adversely affecting ecosystems, and to recognise how close ecosystems may be to thresholds and major change (Ratajczak et al., 2017; Turner, 1984). Certain tools can provide early warning and mitigation of risks; these include vulnerability assessments (Weißhuhn et al., 2018) which focus on the detection of potentially damaging changes in functional capabilities, and threat web analysis (Geary et al., 2019) that identify co-occurring and interacting pressures and threats, and visualise these as networks. The third step, *Action*, requires pragmatic interventions at the regional or local (community) level, where they can be achieved most practically, whilst recognising the major challenge is to manage the dynamic risks posed by long-term, global climate change (Allen et al., 2018).

Action steps first focus on reducing the pressures to avoid or lessen their adverse impacts on ecosystems. However, planning must be undertaken to prepare for and/or respond to future change. When pressures are actively managed but damage still occurs, or pressures cannot be managed at a local or regional level, a second step may be required, depending on the extent and irreversibility of damage (see Figures 3 and 4; Table S1). Some ecosystems recover autonomously (*Recover*) or respond to evidence-based assisted restoration (Johnson et al., 2017; Moreno-Mateos et al., 2015; Suding et al., 2015), for example active seeding (*Restore*). Where environments appear to have irreversibly changed (e.g. due to climate change, invasive species or soil loss), recovery or restoration to a prior state may not be feasible (Johnson et al., 2017). In this case, there are three choices: take *No action* and accept collapse and its consequences, such as biodiversity loss, reduced ecosystem services and consequences for human health and livelihoods; *Renovate* (change some ecosystem elements to suit the new pressure(s) (Prober et al., 2019) or *Adapt*. *Renovate* is distinct from *Restore* in that it involves purposefully introducing modifications to a particular element of the ecosystem, for example, replacing Alpine Ash canopy (ecosystem #11, Table S1) with fire-adapted hybrids that can tolerate increased fire frequency. *Adapt* is a complex process that changes major ecosystem elements, and/or potentially requires the building of novel ecosystems (Bowman et al., 2017). For example, previously existing species may be replaced by species with completely different ecosystem functions but will thrive under the new conditions. In ecosystem management, adaptation involves managing for a fundamentally altered ecosystem state by recognising and characterising a ‘new’ set of ecological values, and managing to conserve those new values. The more complex an action choice is, the higher the costs both financially and ecologically, and the greater the possibility that mitigation will fail (Figure 3). Table S1 provides potential action pathways for all example ecosystems, and includes a case study of a post hoc application of the 3As Pathway with regard to protecting the Gondwanan conifer forests from fire in 2019.

In the near future, even apparently resilient ecosystems are likely to suffer collapse if the intensity and frequency of pressures increase (Oliver et al., 2015). Therefore, many ecosystems may need to be actively managed to maintain their health—not just those that are collapsing. This is highlighted by the unprecedented 2019/20 bushfires that spanned winter to summer, and burned >4.3 million ha of eastern Australian temperate forests (Nolan et al., 2020). Anticipating and preparing for future change is necessary for all ecosystems. In stark contrast to that need, a major synthesis of on-ground management (across 500 studies, see Prober et al., 2019) documented only 11% of ecological recommendations for climate adaptation actions for biodiversity and ecosystems were underpinned by empirical evidence, highlighting that there is a critical need to integrate science and management more effectively to improve management of at-risk ecosystems. For example, the lesson emerging after the Australian 2019/20 fires is that forest ecosystems at risk from altered fire regimes require management based on applied research (McCaw, 2013), because popular mitigation approaches (such as prescribed burns) may prove ineffective or even exacerbate the problem if feedbacks are not correctly identified (Kitzberger et al., 2012). Research efforts should consider and adapt, where possible, Indigenous cultural and ecological knowledge of fire management to design field trials for the establishment of management guidelines for sustainable burning patterns (e.g. Marsden-Smedley & Kirkpatrick, 2000; Trauernicht et al., 2015).

Ongoing research will improve the understanding of rates of degradation and thresholds for ecosystem collapse, and the potential role of using collapse profiles to help diagnose ecosystem change and as tools for action selection, but must be coupled with concurrent on-ground action. The rapidity of change observed in several ecosystems is motivation to implement the precautionary principle and take action to reduce pressures across ecosystems. In the face of uncertainty, we cannot wait for perfect quantitative evidence to characterise fully the trajectories of collapse; qualitative signals from multiple lines of evidence through inductive reasoning, expert elicitation and modelling can deliver valuable insights. Wider application of structured approaches to collate and interpret such a weight of evidence, as demonstrated in this study or the Red List of Ecosystems (Bland et al., 2017, 2018; Keith et al., 2013), will identify ecosystems at risk, and inform management priorities with greater speed to avoid collapse. It is also important to ascertain where uncertainties impede policy and management decisions, rather than to assume that better evidence will lead to better decisions (Canessa et al., 2015). Adaptive management principles and practices (e.g. Cynefin Framework, 2013; Open Standards for Conservation, 2019) will strengthen actions and catalyse more responsive policy change, but must include monitoring programmes that incorporate action trigger points. Given that we still lack fundamental biological and ecological data for many valuable ecosystems, seeking such understanding in parallel to pursuing the 3As Pathway will be of utmost importance. If we choose not to act, we must accept loss and a myriad of often unforeseen consequences (Figure 3).

Our study reveals the manifestation of widespread, pervasive environmental degradation, and highlights global climate and regional human pressures acting together to erode biodiversity. The pressures identified are individually recognisable and universal in

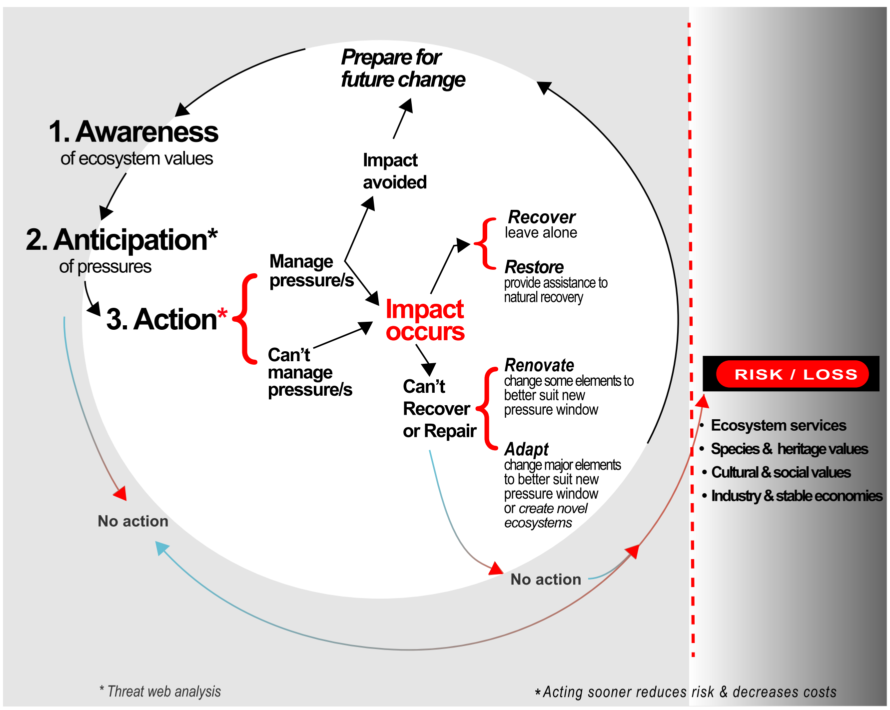

FIGURE 3 The 3As Pathway. *Awareness*, *Anticipation* and *Action* pathway for guiding strategic and effective threat abatement and ecosystem management. Anticipation can be enhanced with early warning tools such as vulnerability assessments and threat web analysis of the network of co-occurring pressures. Avoid impact implies actions directed at relatively healthy ecosystems or parts of ecosystems

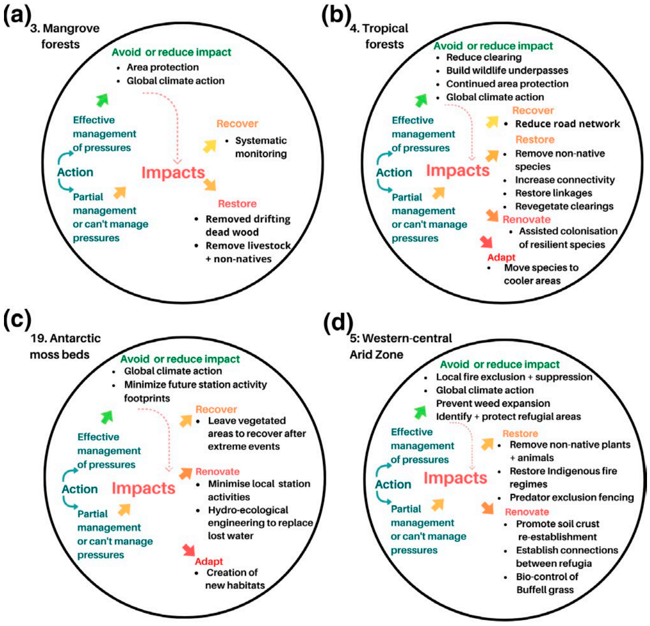

FIGURE 4 Examples of potential *Action* steps from the 3As Pathway for four ecosystems in sequential order from attempting to manage pressures to consequential actions to deal with impacts. Application of the pathways is based on consideration of the collapse profiles combined with ecological knowledge for each system. (a) #3 Mangrove forests, (b) #4 Tropical rainforests, (c) #19 Antarctic moss beds and (d) #5 Western-central Arid Zone showing a range of *Avoid*, *Recover*, *Restore*, *Renovate* and *Adapt* actions. The more complex ecosystems (b, c) have a greater number of potential actions

nature and impact (Pereira et al., 2010, 2012). *Urgent* global recognition is required of both collapsing ecosystems and their detrimental consequences (Ripple et al., 2017), especially in political and decision-making domains. The pressures identified here contribute to ecosystem collapse but have broader implications for humanity. For instance, major disruption of food production (Mehrabi, 2020) and shortages of safe drinking water pose challenges for health and well-being, and have serious security implications (Arneth et al., 2019; Food & Agricultural Organization, 2016; Le Billion, 2013). Pivotal for the future of life on Earth is a reduction of pressures that lead to ecosystem collapse (but also see Driscoll et al., 2018), some of which can only be achieved through significant change in our collective behaviours. For example, the COVID-19 pandemic and associated reductions in global activities, resulting in a temporary daily reduction of 17% (11%–25%) in CO_2 emissions (January–April 2020), has demonstrated the scale of change required annually to achieve the 20% reduction needed to meet the 1.5°C Paris Climate Agreement (Le Quéré et al., 2020). However, this pandemic has also demonstrated what is collectively possible when scientific expertise informs, and when there is political and societal will to act decisively for the common good. Widespread adoption of effective risk-management measures such as our proposed 3As Pathway provide a means to alleviate further ecosystem collapse, thereby helping to secure our collective future.

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CONFLICT OF INTEREST

The authors declare no competing interests.

AUTHOR CONTRIBUTIONS

Dana M. Bergstrom, Justine D. Shaw and Lesley Hughes conceptualised the project, presented at the conference, initial workshop and acquired funding. Dana M. Bergstrom, Barbara C. Wienecke, John van den Hoff, Lesley Hughes, Justine D. Shaw, Tracy D. Ainsworth, Christopher M. Baker, Lucie Bland, David M. J. S. Bowman, Josep G. Canadell, Katherine A. Dafforn, Michael H. Depledge, Catherine R. Dickson, Norman C. Duke, Kate J. Helmstedt, Craig R. Johnson, David B. Lindenmayer, Melodie A. McGeoch, Rachel Morgain, Emily Nicholson, Ben Raymond, Sharon A. Robinson, Jonathan S. Stark, Toby Travers, Rowan Trebilco and Kristen J. Williams contributed to idea formulation and the initial workshop. Dana M. Bergstrom, Barbara C. Wienecke, John van den Hoff and Lesley Hughes compiled the extended data table. Lesley Hughes, Justine D. Shaw, Tracy D. Ainsworth, David M. J. S. Bowman, Katherine A. Dafforn, Catherine R. Dickson, Norman C. Duke, Craig R. Johnson, Andrés Holz, David B. Lindenmayer, Melodie A. McGeoch, Suzanne M. Prober, Sharon A. Robinson, Samantha A. Setterfield, Kristen J. Williams and Phillip J. Zylstra provided expert input into the data collation, and all authors contributed to the review of the data. Dana M. Bergstrom, Barbara C. Wienecke, Lucie Bland, Andrew J. Constable, Emily Nicholson and Ben Raymond created the a priori collapse criteria. Justine D. Shaw, Tracy D. Ainsworth, Christopher M. Baker, Kate J. Helmstedt, Jessica Melbourne-Thomas, Ben Raymond, Jonathan S. Stark and Rowan Trebilco applied the criteria to the dataset. Dana M. Bergstrom, Barbara C. Wienecke and John van den Hoff analysed the data. Delphi F. L. Ward assembled the collapse profiles. Dana M. Bergstrom, Barbara C. Wienecke, John van den Hoff, Justine D. Shaw, Jessica Melbourne-Thomas and Ben Raymond applied the collapse profiles to the data. Dana M. Bergstrom drafted all figures with input from Ben Raymond, David B. Lindenmayer, Andrés Holz, Jonathan S. Stark, Rachel Morgain, and Toby Travers; Craig R. Johnson assembled literature data for Figure 2c. Dana M. Bergstrom, Barbara C. Wienecke, John van den Hoff, Justine D. Shaw, Lesley Hughes, David B. Lindenmayer and Melodie A. McGeoch drafted the manuscript, and all authors contributed to the writing of the manuscript.

DATA AVAILABILITY STATEMENT

All data are provided in the extensive Supporting Information.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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Combating ecosystem collapse from the tropics to the Antarctic

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Methods

With support from the Australian Academy of Sciences, two authors (DMB and JDS) initiated the *Boden Research Conference: Ecological Surprises and Rapid Collapse of Ecosystems in a Changing World* held in Canberra Australia, May 2018. All abstracts were accepted, resulting in 50 presentations among 85 participants. Following the conference, a smaller workshop attended by 24 participants was held to consider the span of ecosystems showing evidence of substantial change across a broad range of regional Australian, Subantarctic and Australian Antarctic Territory ecosystems, and to examine patterns of collapse within a suite of exemplar ecosystems.

Five participants (DMB, BCW, LH, JvdH, PZ) undertook searches of academic and grey literature using the search engines Scopus, Web of Science, Google and Google Scholar, and of media. Search terms included, but were not limited to, 'collapse', 'change', 'rapid', 'climate change', 'extreme', 'regime shift', 'loss'. For example, one search contained the following: "Australia" OR "Australian"; AND ecosyst* OR communit* OR marine OR woodland OR forest OR reef OR seagrass OR kelp OR shrub* or desert OR rainforest; AND collaps* OR “ecological shift*” OR regime shift*OR phase shift* OR state shift* OR catastrophic shift* OR “community shift*” OR abrupt shift* OR catastrophic chang* OR abrupt chang* OR “state chang*” OR trophic cascad* OR alternat* stat* OR hysteresis OR tipping point* OR reference point*OR distrib* shift* OR altitud* shift* OR elevation* shift* OR biome* shift* OR biome* replac* OR “vegetation* shift*”. Of principal importance was information on baseline and present states for each ecosystem spanning the last 200 years, but with a focus on change in the last 30 years.

Additional information, such as current mitigation and challenges, potential amelioration and actions, and socioeconomic consequences, were also tabulated (see table S1 for these categories). In total, 610 sources were used in populating table S1. From this information, 20 candidate ecosystems were identified and matched to biomes (see Fig. 1 in main text, and tables below). The map in Fig. 1 was based on https://ecoregions2017.appspot.com/. Australian mangrove forests, coastal and marine ecosystems were added to Fig. 1 based on descriptions at https://www.worldwildlife.org/biomes. Mangrove forests were mapped according to known distributions at http://www.mesa.edu.au/mangroves/mangroves01.asp.

Ecosystems experts then reviewed and amended the data collated (DMB, DBL, TDA, DMJSB, KAD, CRD, NCD, CRJ, MAG, SMO, EGR, SAR, KXR, SAS, GMWW, KJWW, JDS). For each ecosystem, we applied a set of *a priori* collapse criteria to determine whether the ecosystem in question showed evidence for collapse or was tending towards collapse. Ecosystems that did not meet criteria were excluded (n = 1). For the remaining 19 ecosystems (Methods Table 1, A–C), the extent and nature of ecosystem transformation was described and the likelihood of recovery to the defined baseline state assessed. Collapse criteria, established by DMB, BCW, JDS, AC, LB and EN, were based on Keith et al., 2013; Bland et al., 2017; Bland et al., 2018 and Rowland et al., 2018 (listed below).

Criteria:

1) That ecosystem structure, function and/or composition has transformed from what was a base state to a new state.

2) There is a time series of data spanning ≥10 years with change in that period.

3) There is empirical quantitative evidence in the literature documenting change. Quantitative evidence was deemed adequate if there was found to be a clear understanding of at least one of the following:

i) the baseline state (i.e., an account of the ecosystem prior to change) and the new state were described,

ii) the direction of change/s.

4) There is quantitative and/or qualitative evidence that the scale of the change is of sufficient magnitude to support the notion that the likelihood of recovery to the base state is low. Evidence was deemed adequate if it showed at least one of the following:

i) substantive reduction in population size and distribution of keystone species,

ii) substantive change in ecosystem biomass,

iii) substantive change in the status of ecosystem engineers,

iv) substantive change in population size of characteristic species, and/or

v) loss of ecosystem function or/and services.

Authors who had not contributed to data collation or establishing the collapse criteria led the evaluation of the data set against the collapse criteria.

Two drivers of change were recognised, and characterised by scale and origin: (i) global climate change or (ii) regional human impacts. We also identified 17 pressures within the two drivers (main text Fig. 1B), categorizing them into chronic presses (e.g., climate trends, habitat loss, invasive species) or acute pulses (e.g., extreme events - storms, heatwaves, and wildfires). Our use of the terms “press” and “pulse” follows (Harris et al., 2018). To aid identification of emergent ecosystem response to pressures, we first constructed four archetypal temporal trajectories of ecosystem collapse (hereafter collectively termed ‘collapse profiles’) described as: abrupt, smooth, stepped, and fluctuating. These profiles were based on ecological theory, experimentation and observation (see Petraitis, 2013; Scheffer et al., 2012; Dakos et al., 2013; main text Fig. 2, A and B). An abrupt collapse describes a very sudden (days to sub-decade) shift from baseline state to a new state. Smooth is gradual change from a baseline state to a new state over decadal time scales. Stepped collapse involves a shift from a baseline state to a new state via a sequence of discrete rapid shifts, with periods of relative stability between shifts, and fluctuating involves oscillation away from a base state until eventual collapse. In the latter case, flickering (see Dakos et al., 2013) was identified as a possible profile. However, this proved difficult to assess in practice given lack of certainty in presence of hysteresis and with time series that were relatively short given the temporal scale of the fluctuations. Nevertheless, knowing that ecosystem state could fluctuate on approach to a transition proved useful for categorising systems which did not have a more typical profile of collapse (e.g., abrupt, smooth). We therefore retained the profile, but called it fluctuating to distinguish it from cases where there is evidence the system is shifting between alternative stable states. The narratives were examined by a subset of the authors (DMB, BCW, JvdH, JS, JMT, BR) and profiles were assigned based on regional and local state changes. The terms ‘regional’ and ‘local’ were defined to mean “across the entire spatial extent of an ecosystem”, and “a contiguous patch within an ecosystem”, respectively. Examples of collapse are given in table S1 for each ecosystem. Based on expert elicitation, we carefully distinguished between short-term perturbation (i.e., with capacity to recover to a base state) and collapsed or collapsing. For example, fire is common in many Australian ecosystems, but repeated fires at frequencies shorter that recovery intervals can alter species composition and function.

Data from selected publications were synthesized for Figure 2C to generate collapse profiles. Graphs in Fig. 2C were adapted from the following sources: (i) A.I.M.S. (2019); (ii) and (iii) Lindenmayer & Sato (2018) and Lindenmayer & Taylor (2020); (iv) Tasmania (Stenecke et al., 2014) where data were averaged over 7 sites with per-site values calculated relative to the maximum cover that was observed at each site over the period 1946–2007; South Australia (Connell et al., 2008), Western Australia (Wernberg et al., 2016; Holz et al., 2020).

We assembled current and potential mitigation measures and identified the following categories of action: Recover (leave alone to natural processes), Restore (provide assistance to natural recovery), Renovate (change some elements to better suit a new pressure window), and Adapt (change major elements to better suit a new pressure window or create novel assemblages). We also added the category Avoid (actions that prevent negative impacts of still relatively intact parts of large ecosystems). This allowed the development of the *Awareness–Anticipation–Action* framework (main text Fig. 3) for future action. A *post-hoc* case study of this framework was developed for one ecosystem (Gondwanan conifer forests #17). This case study was built on first hand experience by one of our authors (STB) of fire fighting during the 2016 and 2019 fires in this ecosystem.

Methods Table 1A. Number of study ecosystems represented within each global *terrestrial* biome (after Dinerstein et al., 2017); for ecosystem reference number see Fig. 1 in main text.

Biome	Number of study ecosystems within this biome	Ecosystem reference number
Tropical and Subtropical Grasslands, Savannas and Shrublands	1	2
Mangroves	1	3
Tropical and Subtropical Moist Broadleaf Forests	1	4
Deserts and Xeric Shrublands	2	5, 6
Temperate Broadleaf and Mixed Forests	4	11, 14, 16, 17
Mediterranean Forests, Woodlands and Scrub	1	13
Montane Grasslands and Shrublands	1	15
Tundra	1	18
Rock and Ice	1	19
Tropical and Subtropical Dry Broadleaf Forests	0	
Flooded Grasslands and Savannas	0	
Temperate Conifer Forests	0	
Temperate Grasslands, Savannas and Shrublands	0	
Tropical and Subtropical Coniferous Forests	0	
Boreal Forests/Taiga	0	
Total	13	

Methods Table 1B. Number study ecosystems represented within each global *freshwater* biome; for ecosystem reference number see Fig. 2 main text.

Biome	Number of study ecosystems in this biome	Ecosystem reference number
Large river	1	10
Large river headwater	0	
Large river delta	0	
Small river	0	
Large lake	0	
Small lake	0	
Xeric basin	0	
Total	1	

Methods Table 1C. Number of study ecosystems represented within each global *marine coastal* and *shelf-based* biomes; for ecosystem reference number see Fig. 2 main text.

Biome	Number of study ecosystems in this biome	Ecosystem reference number
Temperate shelves and seas	2	8, 12
Tropical coral	2	1, 7
Polar	0	
Total	4	

Definitions of terms used in the work

Collapse profiles (may occur at regional and/or local scales):

Abrupt: no major signs of change in baseline state (although some possible degradation) followed by abrupt state change. Temporal scale of overall change: months to decade.

Smooth: gradual change from baseline state to new state. Temporal scale of overall change: decades.

Stepped: stepwise changes from baseline state in response to discrete pressures to new states. Individual step changes occur abruptly, but are smaller in scale than in the Abrupt profile and are separated by periods of relatively stable state. Temporal scale of individual step changes: months to years. Temporal scale of overall change: decades.

Fluctuating: relatively rapid, fluctuation between baseline state and alternative state through time, until the new state eventually persists. Temporal scale of individual 'fluctutations': months/years. Temporal scale of overall change: decades

Keystone species is one that has a disproportionately large effect on its natural environment relative to its abundance.

Ecosystem engineer is any organism that creates, maintains or significantly modifies a habitat.

Substantive change is notably large in magnitude (size, amount, or extent), such that the change can be considered to a new state.

Chronic presses are long-term, sustained perturbations (temporal scale of months to decades).

Acute pulses are short-term perturbations that not sustained over time but may repeat periodically (temporal scale of days to months).

Regional refers to changes across the entire spatial extent of an ecosystem.

Local refers to changes in a contiguous patch within an ecosystem.

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Data

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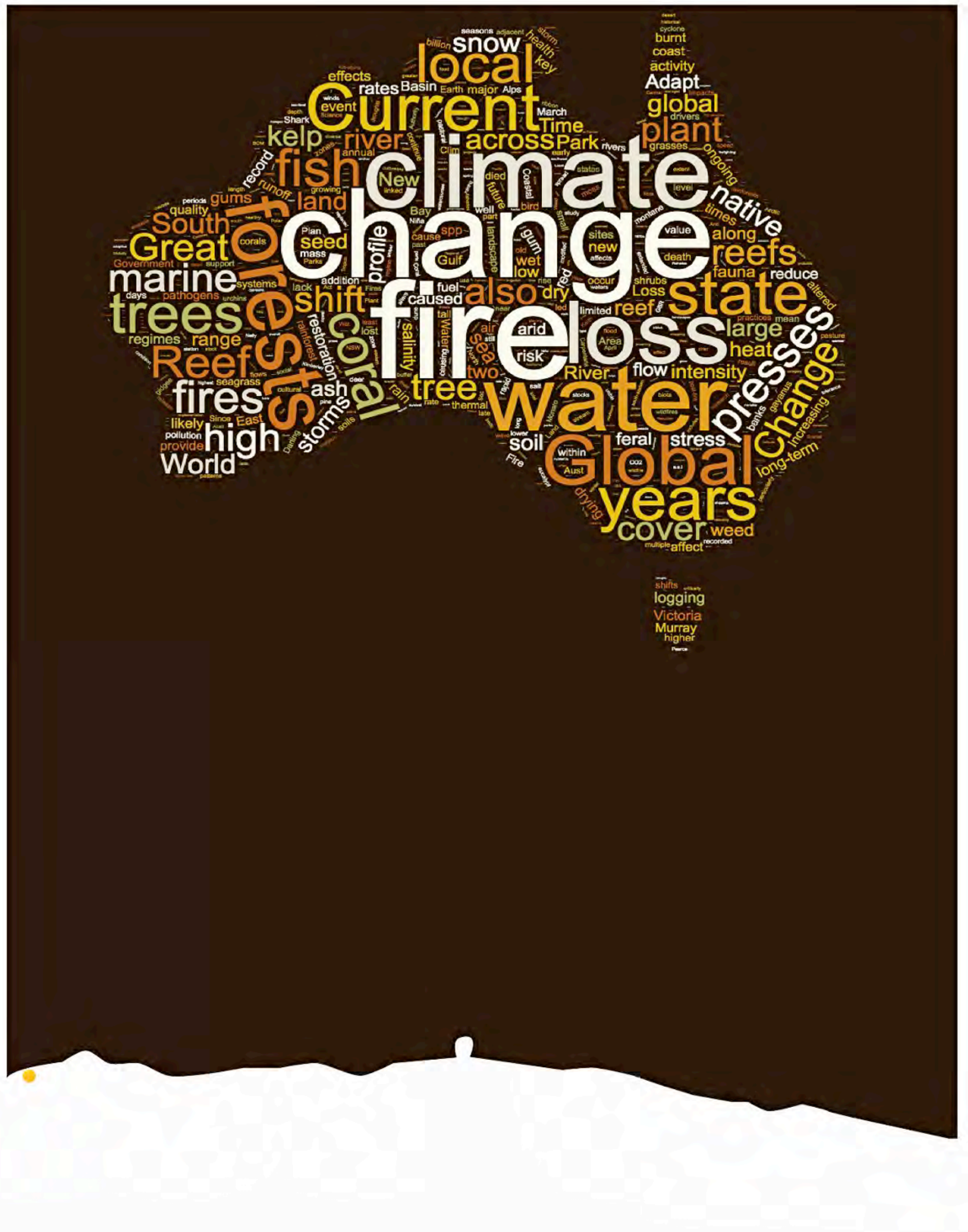

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Summary of key climate change patterns

Australia

Air temperature

- Since 1910 when records began, temperatures over land have increased on average by >1° C. The seven years from 2013 to 2019 are among Australia's 10 warmest recorded. In 2018, the mean temperature averaged across the continent was 1.14° C higher than the average for 1961–1990[1]; in 2019, Australia's average temperature was 1.52° C above the long-term average[3]. In 2018 and 2019, average temperatures were 0.77° C and 0.86° C, respectively, above the average of the preceding decade[1,2].

Recent temperature anomalies

- In 2019, the annual mean temperatures across Australia were the highest on record for nearly all states. The heat persisted throughout the year, and February, April, July, October and November temperatures reached in the highest ten of the respective months. January, March and December had record high temperatures with mean anomalies of 2.90° C, 2.08° C and 3.21° C above average, respectively[3–5].
- Globally, five recent years (2015–2019) have been the warmest on record. 2019 was the warmest year for Australia[2].

Rainfall

- Since the 1970s, rainfall has increased during the wet season in northern Australia. In large areas of northern, central and central-western Australia, wet season (October to April) rainfall has increased substantially (above average to highest on record) since 2000. But in the south-western and south-eastern parts of the continent where most irrigated and non-irrigated cropping occurs, >40% of rainfall is received during winter (April to October). In these regions, rainfall has decreased during the austral winter; in vast areas, rainfall ranged from below average to the lowest on record over the 20 years from 1999–2018[1].
- Southern Australia has experienced a large-scale change in rainfall for several decades. In the period 1999–2018, rainfall had decreased by ~11% compared to the long term average. Particularly severe and persistent drought conditions were experienced from late 1996–2010 ('Millennium Drought'), when annual rainfall was particularly low, especially in winter in most of southern Australia. Water resources were drawn down and land and vegetation dried out.

  Rainfall deficiencies experienced in 2019 were akin to the worst conditions during the Millennium Drought[2]. Over much of Australia, rainfall was below or very much below average. Precipitation across Australia reached a record low with only 277.6 mm, i.e. 40% less than the long term average (1961–1990) of 465.2 mm and 12% less than the previous record in 1902 (314.5 mm)[2].
- There are indications that more rain falls as heavy rainfall. The intensity of extreme rain days (>90th percentile for 24 h rainfall)[6] are likely to increase[2]. Hourly extreme rain events often associated with flash flooding have increased by >7%. Each degree of warming is predicted to increase the total rainfall on heavy rain days by ~7%[1].

Fire

- The number of extreme fire weather days and the length of the fire season across large parts of Australia have increased since the 1950s. In many regions with fire risk, the fire season commenced earlier in spring and ended later in autumn. In July–August 2018, particularly severe fire conditions occurred in large areas of eastern Australia, and major fires started in August (2–3 months earlier than usual)[1]. The combination of dry, warm and windy conditions in the 2019-20 summer generated severe fire weather in eastern Australia[2,7]. This fire weather is more commonly generating thunderstorms and dry lightening within fire smoke plumes[7].

Stream flows

- Stream flows have increased in the northern parts of Australia since the 1970s but decreased across southern Australia. Water storage in the northern Murray-Darling Basin were lower than during the Millennium Drought and were <7% capacity[2].

Snow depth

- Since the 1950s, there has been a decrease in snow depth and a reduction in the areas covered by snow in alpine regions[1].

Sea surface temperature

- Since 1910, sea-surface temperatures (SST) in Australian waters have warmed by ~1º C[1]. Above average SSTs have been recorded each year since 1995, and have been particularly high for the most recent decade when 8 of the 10 warmest years occurred. The frequency and duration of marine heatwaves are increasing[2,6].

Sea level

- Globally, sea levels have increased by >20 cm since 1880, and 3.2 cm per decade since 1993[1]. Around

Australia, rates of sea level rise vary annually and by location. From 1993 to 2017, sea level rose well above the global average (7–9 cm per decade) in the Gulf of Carpentaria in the north and along the south-eastern coast. Along the southern and north-eastern coast, sea level rise was about the global average[1].

Coastal erosion

- Potentially erosion will cause the loss of >11,400 km of sandy beaches or ~50% of Australia's sandy coastline by 2100[8].

Acidification

- The pH of waters has decreased from 8.18 to <8.07 in 2017. Thus, ocean acidity has increased by >30% since the 1880s, at a rate ten times faster than in the last 300 million years[1]. Regionally the values vary; the pH decreased more in the waters south of Western Australia and the Great Australian Bight than in the northern waters[1].

Compounding extreme events

- Climate change is influencing the frequency, magnitude and impact of extreme weather events, and their affects can be compounded. Naturally occurring variability, expressed as an extreme positive Indian Ocean Dipole and atypical Antarctic stratospheric warming in the spring and summer of 2019-2020, exacerbated long-term climate trends. These combined led to severe drought, record-breaking heatwaves and fire weather[7].

Antarctic and subantarctic regions

Ice sheets

- From 1992 to 2017, Antarctic ice shelves and ice sheets lost 2,720 ± 1,390 billion tonnes contributing about 10% of global sea level rise[1].

Wind

- In the Polar region (case studies 18, 19), greenhouse gas increases and ozone loss have led to a southwards shift in the westerly jet stream resulting in altered wind and precipitation patterns and other changes to regional climate[9–12]. As a result, the polar ecosystems have become windier, drier and, in the case of coastal East Antarctica, slightly drier.

Air temperature

- Between November 2019 and February 2020, a heatwave circumnavigated Antarctica with extreme upper air temperatures at a number of localities reaching (e.g. 20.75° C at the Antarctic Peninsula and 9.2° C at Casey Station)[13].

Supplementary Data Fig. S1. Map of ecosystem regions in Australia. For details of 19 study ecosystems see table S1.

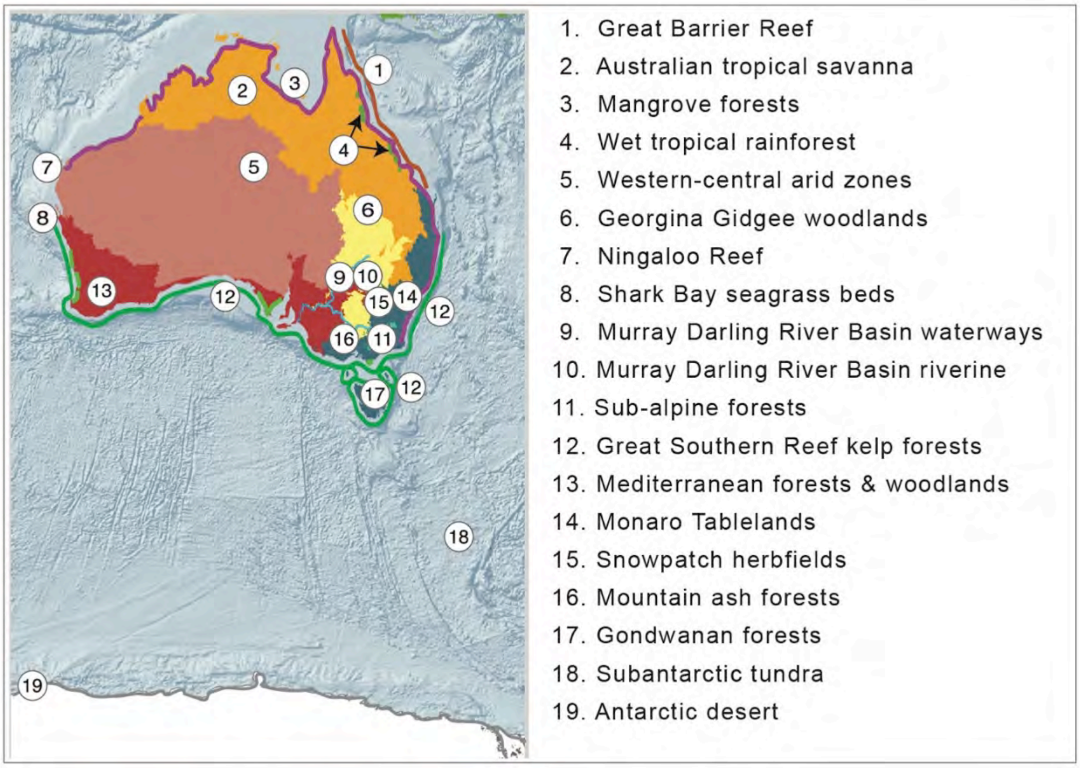

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Table S1. Change in 19 ecosystems, ordered along a north-south latitudinal gradient. (Following pages)

For each example we describe: the name of the ecosystem and a reference number that links with Fig. 1; the global biome to which the example belongs (biome terminology[1], biome global distribution[2]); the ecosystem descriptor and the latitudinal range of the ecosystem; the local action choice/s available (Avoid pressures or Recover, Restore, Renovate, Adapt after impact — see Fig. 3 in main text); the baseline state (descriptor of the ecosystem before major change occurred from ~1800 to recent times); the new state and changes to the ecosystem as found up to mid-2020; two categories of pressures (global climate change and regional human impacts), further divided into long-term presses and short-term pulses; the probable ecological trajectory in the near future (<50 years); time taken to detect the state change; collapse profiles (see online methods); social and economic costs (in Australian dollars unless indicated otherwise) of the state change; current conservation or mitigation actions and challenges with regard to the pressures; the global context of the state change; references used. Data cut-off date June 2020.

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Ecosystem	**1. Great Barrier Reef, north-eastern Australian coast (10–24°S)**
Biome	Marine: coral reefs
Action Choices	**Avoid, Recover, Restore, Renovate, Adapt**
Baseline state	The Great Barrier Reef is the world's largest coral reef system (10% of global coral reef area) extending >2,300 km (15º latitude) from the northern tip of Queensland southward to near Bundaberg; the Great Barrier Reef Marine Park (GBRMP) covers 344,400 km[1,2]. Reefs grow along a gradient of depths from shallow estuarine waters, across the continental shelf, to deeper waters off the continental shelf[2]. The Great Barrier Reef includes ~3,863 individual reefs, 900 continental islands, 300 coral cays and 150 inshore mangrove islands[3,4]. Biodiversity is very high, regionally species specific with high coral cover and abundance, as well as high abundance and diversity of reef-associated fish and invertebrates. The reef is unique in its biodiversity comprising at least 5,000 species of mollusc, 1,500 species of fish, 400 species of coral, >240 species of birds and many sponges, worms, crustaceans and anemones[5]. Variations in shelf morphology and structure of coral communities are associated with latitude (northern, central and southern reefs) and across the coast, coastal lagoon, shallow, mid to deep-water (across shelf) gradients[6].
Current state and nature of collapse or shift	The GBRMP is part of a World Heritage Area that includes islands and estuaries, and covers >348,000 km[1,2]. The United Nations Educational, Scientific and Cultural Organization (UNESCO) acknowledged the Area for its outstanding universal values and its "natural significance which is so exceptional as to transcend national boundaries and to be of common importance for present and future generations of all humanity"[7]. Local and global factors affect coral reef systems but climate change is the single greatest threat to the reef[8]. Responses to single and combined pressures in affected areas have resulted in both rapid and gradual decline in the cover (abundance) of reef-forming corals, as well as a loss of species diversity, a simplification of community structure and function, and a shift to an alternate ecosystem state, i.e. an algal-dominated ecosystem[9]. From 1985–2012, the coral cover of the Great Barrier Reef was reduced by 50.7% due to the effects of tropical cyclones, predation by crown-of-thorns starfish (*Acanthaster planci*) and coral bleaching; the latter accounted for 10% of coral cover loss[10]. By 2016, 22 of the system's 38 values had depreciated[11], and patchy collapse has occurred with high spatial and temporal exposure across the Great Barrier Reef. Prolonged periods of increased sea-surface temperatures (marine heatwaves)[12] resulted in five mass bleaching events spanning the last 22 years (1998, 2002, 2016, 2017 and 2020) causing the loss of dominant, habitat-forming coral species (e.g., *Acropora* spp.) with associated loss of biomass and rapid community changes in many areas. Severe bleaching events in two consecutive years (2016, 2017) affected two thirds of the reef's extent and led to catastrophic loss of corals. Along a 700 km stretch 67% of corals died — the greatest loss of coral on record[13]. The unprecedented bleaching event in 2016 affected 91% of reefs examined (n = 1,156) along the length of the Great Barrier Reef[14]. Anywhere

Current state and nature of collapse or shift (cont.)	from 10–51 % of life coral cover was lost; the northern reefs were more severely affected than the southern ones[15]. The bleaching event in 2020 was second only to the 2016 event and was so far the most widespread one[16]. Marine heatwaves not only cause coral mortality within days but also increase microbial activity (microbial biofilm formation) leading to the rapid dissolution of the coral skeleton[17]. From 1925 to 2016, marine heatwaves had become 34% more frequent lasting 17% longer; on a global scale, this amounts to 54% more days of marine heatwaves annually[18]. Deeper sites experience lower levels of mortality and higher rates of recovery from bleaching than shallower sites, but overall ongoing deterioration is projected[19]. Southern reefs experienced only mild bleaching such as the corals around Keppel Islands where only 21% were affected during the 2016 bleaching event[20]. After the 2016/17 bleaching event, the sound scape of fringing reefs around Lizard Island was, on average, reduced by 15 decibels due to the loss of fish and invertebrate populations. A feedback loop is exacerbating the shift to the low-fish state: reef soundscapes are no longer attractive to juvenile fish compared with the open ocean, resulting in 40% less settlement of young fish on the reefs[21]. The Great Barrier Reef has also been affected by freshwater bleaching from flooding (2008/09, 2010/11 and 2019)[22,23]. Extremely high rainfall in the 2008/09 and 2010/11 summers caused extensive flooding and freshwater inundation of nearshore reefs[24]. Major coastal flooding also occurred in February 2019, the wettest February on record. A stationary, tropical storm dropped up to 2,000 mm rain in some locations on coastal areas of North and Far North Queensland between Bowen and Cooktown. Extensive flood plumes occurred, including a major plume from the Burdekin River, which extended up to at least 60 km offshore, reaching mid- to outer-shelf reefs. By April 2019, salinity levels were still lower than the mean, and some isolated freshwater bleaching was observed[25]. Freshwater plumes lower salinity and deliver nutrients, herbicides and pesticides into the marine environment; they also deposit sediment. Nutrient and sediment loads are now five to nine times higher than during pre-European settlement[10]. More intense and frequent bleaching events render recovery of corals increasingly unlikely[8]. Furthermore, calcification rates of corals have decreased over the past 30 years limiting growth[10]. Cyclones and storms also physically damage corals. From 2014–2019, the destructive force of six tropical cyclones reached >50% of the GBR and severely diminished reef health[1]. Shallow-water regions (<15 m) with the highest light penetration have suffered the most rapid and severe change from base state due to the combined impacts of bleaching mortality and tropical cyclone damage. Near Lizard Island, the impact of two category 4 cyclones (2014, 2015) was compounded by severe bleaching (2016). This caused substantial loss of live hard coral cover, and significant loss of taxonomic diversity of herbivorous reef fish assemblages. The difference increased across a shelf gradient[26]. In recent years, >40% of coral loss at the Great Barrier Reef was due to crown-of-thorns starfish outbreaks[27]. Several factors probably lead to crown-of-thorns starfish outbreaks; the species' very high fecundity is an important factor[29]. In 2014, a cloud of crown-of-thorns starfish larvae spread several hundred kilometres south of the outbreak area[27]. Increased predation by the native starfish has been linked to post-flood phytoplankton blooms responding to nutrient enrichment from fertilisers and other pollutants in the Great Barrier Reef Lagoon[28], increased nutrient loads from upwelling, and the removal of crown-of-thorns starfish predators[29]. The various coral types respond differently to various pressures; while digitate acroporid and pocilloporid corals are mainly impacted by physical destruction, tabular and branching acroporids are most susceptible to thermal stress[30]. Overall coral cover is in decline as the intensity and frequency of disturbances are increasing and the length of potential recovery periods is decreasing. However, corals in outer shelf zones recover quicker than near-shore ones[31]. Ocean acidification is expected to limit coral growth and survival and, hence, reduces their capacity to maintain and create habitat. Reef biodiversity is expected to decrease[8]. Over the last 30,000 years, the reef proved remarkably resilient to major impacts due to sea level changes; however, given its sensitivity to increased sedimentation and poor water quality combined with mass bleaching events, it is questionable whether it will survive the coming decades[32]. Poor water quality and land-based runoff result in algal overgrowth of corals. From 2005–2015, an estimated 25 million m^3 of dredge spoil were dumped into the Great Barrier Reef

Current state and nature of collapse or shift (cont.)		World Heritage area, equivalent to the historical amount of sediment carried by 35 rivers per decade pre-European settlement[33]. Dredging and sediment disposal operations in the WHA sustain increases in suspended sediments, affecting corals, seagrasses, fish populations and other biodiversity to varying degrees. As yet, no significant coral mortality has been documented but uncertainty still exists with regard to long-term sub-lethal effects. Increased levels of artificial light and noise may significantly affect marine life[34]. Low level of disease in corals is common across the reef in most summers. Marine-bound plastic debris harbouring pathogens may make corals more susceptible to disease outbreaks[35]. Fishing (commercial and recreational) is allowed in 70% of the marine park. Concern about illegal fishing in no-take zones is increasing; offences appear to be concentrated in a small number of no-take zones [1]. Shipping plays a major part in the reef area; from 2012 –2013, 3,947 vessels made >9,600 trips in the reef area. The increase in ship traffic is an estimated at 4.8% per year[36]. Large vessels (>50 m) are monitored and travel in prescribed shipping lanes, and vessels >70 m (oil tankers, natural gas and chemical carriers) require pilots on board. From 1987 to 2009, >600 shipping incidents were reported. Major incidents are rare but chronic damage (e.g., damage caused by propellers and anchors, and contamination) has a cumulative effect over time. Strike rates of wildlife and exposure to pollution, noise and light are likely increasing as more ships arrive[36]. Where a ship collides with the reef, anti-foul paint is left behind. Active ingredients can spread from the impact site and potentially impair coral recruitment[37]. Debris derived from tourism is of concern particularly in the southern parts of the Great Barrier Reef; concentrations have been recorded highest where human visitation occurred most frequently. Non-tourism related debris was also recovered on unvisited islands[38]. Coral reefs may recover from where land-based human influences (e.g., runoff) are better controlled, and provided the intervals between disturbances are long enough to allow recovery[39]. Given the pressures on the Great Barrier Reef this is becoming increasingly more of a challenge.
Pressures	**Global climate change presses**	Long-term ocean warming, increasing thermal stress, and predicted ocean acidification.
	Global climate change pulses	Marine heatwaves, cyclone and storm events, floods. Microbial film formation after heatwaves leading to coral skeleton dissolution.
	Human presses	Poor water quality from agricultural, sediment runoff and dredge spoils, commercial and recreational fishing, tourism, boat anchor damage, coastal development and chronic pollution neat shipping lines.
	Human pulses	Oil spills and ship grounding causing contamination and physical disturbance, crown-of-thorns starfish outbreaks linked to agricultural and urban runoff after heavy rains.
Ecological impacts and trajectory		Increasing frequency and intensity of extreme events (heatwaves, storms and associated flooding) coupled with wide-reaching global climate change and regional human pressures will continue to affect the structure and function of the reef system; ongoing deterioration is projected[22,40]. Shallow reefs and the coastal Great Barrier Reef lagoon are more susceptible to long-term transformation to algal-dominant systems than deeper reefs. Increased frequency of bleaching will reduce recovery potential. Ocean acidification is projected to affect calcification rates[41], but currently thermal stress is a more important pressure[17]. The persistence of coral reefs depends on calcification rates (building of coral structure) exceeding loss of $CaCO_3$ (occurring through breakdown, export, and dissolution processes). Ocean acidification lowers the pH and reduces the rate of calcification and aragonite saturation, dissolving coral structure[42]. Calcification rates are predicted to drop by mid-century, and dissolution of coral reefs will occur in future with decreasing aragonite saturation levels[43].
Time to detection of impact		Since the 1980s, reef health has been declining; widespread and dramatic instances of bleaching and mortality are detected days / weeks / months after impact. Shallow coral bleaching is detectable within days of heat stress and remains detectable for at least four months.
Collapse profile		SMOOTH — regional, declining health[10,44] ABRUPT — local (northern sub-region), e.g., bleaching[14]

	FLUCTUATING — local (southern sub-region), e.g., repeated crown of thorns outbreaks causing loss[29]
Social and economic consequences	The Great Barrier Reef provides ~$12 trillion of ecosystem services (~$517,950 ha^{-1}) in terms of habitat for marine organisms, water quality and food. Providing >64,000 jobs, the Great Barrier Reef delivers more employment than Australia's largest companies, and contributes ~$6.4 billion per year to the Australian economy (2011/12)[45]. The value of coastal protection of 49,000 km^2 of coral reef was estimated at $438 million[46]. Shallow-water reefs are the most widely used and relied on by humans for tourism and fishing activities. Social and economic activities have very limited capacity to respond and relocate to deeper and less-affected regions. An estimated $56 billion in total (social, Indigenous, scientific, aesthetic and historic values) of World Heritage values will potentially be lost in future[45]. Annual gross value product for commercial fishing in 2018/19 was forecast to reach $181 million[1], while total expenditure of recreational fishing contributes about AU$415 million per year; the latter includes the purchase of equipment and visits to islands[47].
Current mitigation and challenges	*Current mitigation:* World Heritage status and associated management by the Great Barrier Reef Marine Park Authority. Australian and Queensland governments committed $1.9 billion and $820 million, respectively, into reef protection[48]. Water quality monitoring and restrictions on agricultural runoff — allocation of >$261 million and $471 million by Queensland and Australian governments, respectively, to improve water quality[8]. Implementation of the *Reef Blueprint: Great Barrier Reef Blue Print for Resilience*[48], and the *Reef 2050 Long-Term Sustainability Plan*[8]. Localised restoration[49]. Reef Alliance Project works with sugarcane farmers and graziers to improve farming practices across >1.8 million ha covering 33 of 35 catchments area of the reef[49]. Integrated management and zoning of the marine park[50]. *Challenges:* Land-based human activities affect reef health, and need to be managed effectively. Ongoing ocean warming is causing the increasing severity and frequency of bleaching events and ocean acidification is projected to affect calcification rates. Improving quantitative understanding of carbon chemistry. Efforts to address water quality and local pollution have shown varying degrees of success depending on the region and type of management action. Management of impacts of chronic pressures from shipping. Prevention of poaching and improving compliance with no-take fishing zones. Port developments and sediment dumping. Regional development of the Galilee Coal Basin in Queensland raises potential threats through increased port and shipping activity on and through the Great Barrier Reef.
Potential actions	AVOID: limit pollution and runoff (nutrients and sediment); global climate action. RECOVER: small reefs protected from cyclones sustain less damage than exposed sites where recovery is slower (> 5 years)[51]. Recovery is observed through long term monitoring by the Australian Institute For Marine Science (AIMS) (https://www.aims.gov.au/docs/research/monitoring/reef/latest-surveys.html). RESTORE: actively restore reef (“gardening” – growing corals in nurseries)[52]; implement assisted colonisation through coral larval restocking, selective breeding[53]; apply integrated monitoring to evaluate effects of shipping to implement best environmental practice[36]; use seawater electrolysis to improve calcification rates[52]. RENOVATE: locate and establish heat-tolerant coral genotypes; implement assisted migration of more thermally tolerant coral genotypes from northern to southern reefs[52]. ADAPT: apply local small-scale adaptation strategies (e.g., surface screens, cloud brightening)[53]; use epigenetics to enhance resistance through development of novel alleles[54].
Global context	Before the 1980s, severe bleaching events in corals were mainly local and occurred every ~25–30 years. Mass bleaching events occur now every ~6 years at regional and global scales[22]. Twenty one of 29 major global reefs were subjected to severe or repeated heat stress during 2016/17[3].

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Images L-R: Healthy reef near Heron Island, Queensland, March 2019. Collapsed reefs near Lizard Island, Queensland, February 2018. (Images: left -Charlotte Page, right - Alexander Fordyce)

Ecosystem	2. Australian Tropical Savanna, northern Australia (11–18°S)
Biome	Deserts and semi-arid areas: savanna
Action	**Avoid, Restore**
Baseline state	Australia's tropical savannas cover ~1.3 million km^2 across northern Australia from the Kimberley region of Western Australia to Queensland's tropical coast, and up to ~700 km inland[1]. Savanna woodlands and open forests overstorey is dominated by *Eucalyptus* and *Corymbia* species, while the understorey comprises mid to tall grasses[2]. From late November/early December to April/May, seasonal monsoons bring 90% of annual rain ranging from up to 2,000 mm in coastal areas to 300–400 mm farther inland[3]. However, water availability is generally limited due to the annual extended rain-free period ('dry season'), high temperatures and high evaporation rates[2]. The region includes one of the largest networks of free-flowing and least polluted rivers in the world, with the biologically most diverse and healthy aquatic ecosystems in Australia[1]. Due to their extensive size and relatively good condition, tropical savannas contain high levels of biodiversity and endemism.
Current state and nature of collapse or shift	By world standards Australian tropical savannas remain relatively intact[4,5]. However, agricultural land use is extensive and increasing. In the 2010/11 financial year, 33,700 km^2 (or 46% of the Northern Agricultural Region) and ~7,930 km^2 were used for dryland cropping and grazing, respectively, in northern Western Australia. In the Northern Territory, ~568,000 km^2 (42.2% of the Territory) is used for livestock production[6]. In Queensland, >80% of the state (or >1.38 million km^2) is dedicated to livestock production, including grazing mainly on native grassland[6,7]. In Queensland, major land clearing (50–65% of Australia's deforestation) for agriculture has been associated with land degradation and ecosystem collapse through permanent, cumulative habitat loss and erosion[8]. Clearing is expanding in the Northern Territory and the Kimberley region in Western Australia. In the Northern Territory, approvals of land clearing applications have risen nearly 10-fold in recent years[9]. The mammal fauna in northern Australia's tropical savannas is declining at an accelerating rate. For example, in Kakadu National Park, populations of several native mammal species, including threatened species such as the endangered northern quoll (*Dasyurus hallucatus*) have decreased severely and rapidly. In northern Australia, some 53 % of dasyurid species, 47 % of macropod and potoroid, 33 % of bandicoot and bilby, 33 % of possum, 30 % of rodent, and 24 % of bat species are now considered to be extinct, threatened or near threatened[10]. This is likely due to the impacts of non-native cat predation, the spread of cane toads (directly affecting carnivorous marsupials), and increased fire frequency and livestock grazing that remove habitat cover[10]. Bush fires are becoming more frequent, extensive and severe. In September 2019, ~141,800 ha burned in the Darwin region alone. Until then the average area burned in September covered ~45,500 ha. More than 160 large fires averaged 8,700 ha in size[11]. The response of vertebrates to the invasion of non-native cane toads (*Rhinella marina*) is highly species specific. Populations of predatory species such as the northern quoll declined, or have become locally extinct, in areas where they preyed on the poisonous toad. However, some quoll populations appear to have developed 'toad-smart' behaviours avoiding the toads[12]. Several snake species may have benefitted indirectly from the arrival of cane toads, possibly through the loss of large varanid (monitor) lizards that consume snakes[13]. Native frog populations face increased competition with cane toads for resources; where cane toads are present, the abundance and diversity of invertebrates is decreased[14]. Some 243 bird species occupy the tropical savannas; many are vulnerable to changes in land management and use, and climate change[15]. Responses among reptiles to habitat disturbance through grazing negatively affected ground-dwelling reptiles, while more arboreal species appeared to be more resistant. Retention of trees is vital for both types of reptiles[16]. Synergistic pressures in savannas include stochastic weather episodes[13], land clearing[8], damage by livestock and frequent fires[17], and introduced vertebrates (e.g., buffalo, cats, and cane toads)[18–20]. These factors can degrade ecosystems and increase predation pressure on native vertebrates and flora. Grazing of pastoral and non-pastoral (escaped pastoral) stock has changed vegetation structure and floristics, and curtailed food availability of

Current state and nature of collapse or shift (cont.)	native animals (e.g., Gouldian finches (*Erythrura gouldiae*)). In addition, fires of increased intensity degrade natural habitats. However, responses to fires by vertebrates are complex due to considerable variation in species' sensitivities[15,21–23]. Ecosystem state changes and habitat loss due to invasion of disturbed and undisturbed savannas has resulted from the introduction of pasture grasses that often outcompete native species[24], leading to the loss of environmental, cultural and social values[25]. Of particular concern is the high biomass gamba grass (*Andropogon gayanus*). Gamba grass is native to central Africa and was introduced to northern Australia in the 1930s in pasture grass trials. Extensive agricultural expansion in 1983–1993 was linked with the availability of commercial seed with >180 km^2 planted in Queensland. Gamba grass has established and spread rapidly in a range of habitats including riparian habitats and upland savanna[26], and along roadsides. Transportation of hay has dispersed gamba grass and other weed seeds[27]. Infested areas include 15,000 km^2 of the Northern Territory (including Litchfield National Park)[28]. There are also small infestations in World Heritage Kakadu National Park, 600 km^2 of Queensland, and limited areas in the eastern Kimberley, Western Australia[29]. Gamba grass invasion has altered fire regimes and can convert eucalypt savanna woodlands to more flammable non-native grasslands within 5–10 years[30]. Gamba grass was declared a 'weed of national significance' the Northern Territory in 2008[25]; there is a statutory weed management plan[29]. Ecosystem transformational traits of gamba grass include perennial growth form, high growth rate, high seed production (69,000–74,000 seeds m^{-2}) and seedling survival (~90%), substantial height (up to 4.1 m) and density of stands, and late dry season maturation[31]. Gamba grass has 4–10 times higher fuel loads (up to 30 t ha^{-1}) than native grasses (1–7 t ha^{-1})[32]. The dominance of gamba grass alters fire regimes (both in intensity and frequency) due to the increased biomass of highly flammable material resulting in tree mortality and reduced recruitment[33]. Fires are up to 12 times more intense (6,408 ± 4,125 kW m^{-1} of heat released than native grass fires (647 ± 184 kW m^{-1})[32,34], and the char height in gamba grass fires is significantly higher than in native grass fires (gamba grass: 8.7 m, native grasses: 1.6 m)[35]. More intense fires and greater char heights alter the vegetation structure (e.g., reduced recruitment, species abundance and species diversity; degraded canopy cover), and ecosystem processes[30,35,36]. Late maturation of gamba grass seeds shifts the fire season from early to late in the dry season consequently increasing fire temperatures due to higher fuel loads; this leads to self-perpetuating positive feedback loops. According to Indigenous rangers, gamba grass upsets the practice of "right-way fire" fuel load reduction burns[37]. Ecosystems dominated by gamba grass have reduced biodiversity of native species, and altered microclimate and ecosystem processes[38], including disruption of carbon and nitrogen cycles, e.g., through the inhibition of soil nitrification and the promotion of fire-mediated nitrogen loss[33]. Other non-native invasive plant species include grader grass (*Themeda quadrivalvis*), para grass (*Urochloa mutica*), olive hymenachne (*Hymenachne amplexicaulis*), mission grass (*Cenchrus polystachios*), and annual mission grass (*C. pedicellatum*)[39]. Other plants, such as the prickly acacia (*Acacia nilotica*) and giant sensitive tree (*Mimosa pigra*), have also degraded ecosystems through competition and habitat loss[40]. Australia's tropical savannas comprise a number of mainly free-flowing and minimally polluted (mostly nutrients from livestock) rivers. River flow is highly seasonal and, in most rivers, is followed by extended periods of little or no water flow[41]. The freshwater fish fauna is diverse (111 species) and is an integral part of freshwater foodwebs (rivers, wetlands)[3,42]. Dry season river flow and surface water persistence is crucial for the survival of freshwater ecosystems, including fish[1]. Fish abundance and distribution vary between river systems and are affected by the interannual and seasonal changes in flow regimes[42,43]. Freshwater ecosystems are threatened by increasing development of water resources for human use; flow modifications (dams, channels, reservoirs) for mining, agriculture and industrialisation all affect aquatic live and associated systems[44]. Given the enormous size and remote nature of the tropical savannas, illegal land clearing can be difficult to manage; not all cases are prosecuted. For example, in Queensland in 2019, some property owners illegally cleared native woodlands for agricultural purposes, destroying habitat of the vulnerable greater glider (*Petauroides volans*) The property owners then had to set aside 113 ha woodland for the marsupial[45,46]. In the Kimberley region, 120 ha of land sacred to the traditional owners were cleared. The responsible company was ordered to undertake remedial action[47]. Climate change is likely to change the function and structure of this complex ecosystem[48],

		including through potential changed (decreased) water availability in hotter and extended dry seasons and/or failed wet seasons, and altered fire regimes[23,49].
Pressures	**Global climate change presses**	Increased wet season rains (especially in Northern Territory); erosion[8]; increasing temperatures and changes in rainfall patterns limit distribution of native vertebrates[50]; decreased water availability in dry season[23]; higher CO_2 levels may change tree-grass structure where trees may outcompete grasses (CO_2 fertilization and woody thickening)[51];
	Global climate change pulses	Increased fire intensity and extended fire season.
	Human presses	Increasing development and land degradation (e.g., extensive cattle grazing and land clearing) leading to habitat loss; non-native plants and vertebrate species affect native populations; diversion and capture of water[10]. Increasing construction of artificial water points for livestock alter ecosystem processes and biodiversity.
	Human pulses	Altered fire regimes due to spread or non-native invasive pasture grasses.
Ecological impacts and trajectory		Several interacting pressures, such as habitat loss, non-native animal introductions, and changes in the fire regime, appear to drive the rapid and accelerating decrease in native mammal populations[52]. Gamba grass continues to expand; in 2017, only 50% of known gamba grass infested areas were actively managed around Katherine where eradication is still deemed possible[28]. Without appropriate management, gamba grass is predicted to affect 32% of Litchfield National Park by 2025, and ~50% by 2040[53]. Warmer conditions from global climate change will continue to increase fire risk; exert physiological stress of biota. Unless controlled, gamba grass has the potential to invade 380,000 km^2 of tropical savanna[35]. The length of the fire season is increasing[32]. Land clearing and irrigation are likely to increase in northern Australia for agricultural development and intensified cattle grazing[54]. These changes have the capacity to further degrade or remove substantial ecosystem components (e.g., soil structure, pollution, reduced water quality)[55].
Time to detection of impact		Decades
Collapse profile		SMOOTH — regional, e.g., grazing activity and invasion of some non-native species causing biodiversity loss[8]. STEPPED — regional, e.g., cumulative affect of land clearing, past planting of gamba grass for pasture and stepped loss of ecosystem.[33] ABRUPT — local, e.g., clearing of woodlands, escape of gamba grass into native savanna followed by changed fire regime[30]
Social and economic consequences		The extension of the fire season due to gamba grass increases the cost of fire management. For example, in the Northern Territory, the average cost of managing gamba grass wildfires is ~26 times that of equivalent areas of native grass fire. In 2012, the standby firefighting cost for 38 days of extreme fire weather was ~$450,000 in gamba grass areas (fuel load, 13 t ha^{-1}) compared to zero in native vegetation (fuel load, 6 t ha^{-1})[25]. In 2018, firefighting preparations on 29 fire ban days cost $464,000 in the Batchelor region alone. The daily cost of fighting wildfires here has increased 30-fold from 2007 to 2010 from $474–13,264[32]. Fires cause the loss of livestock and farm infrastructure (e.g., fencing), negatively impacts human health and safety, and damages residential property and infrastructure, and cultural and spiritual values[56,29]. The cost of fires to lands was estimated to be $148 million per year; loss of ecosystem services, production and pastoral lands were $113 million, $22 million and $13 million per year, respectively[57]. In 2018/19, the Northern Territory Government allocated $1.5 million for weed and fire management on Crown Land, plus $38 million for fire management and response[28]. The Federal Government budgeted $259,000 for pest and weed management. Early dry season burn-offs are part of the Australian *Carbon Farming Initiative* (a voluntary carbon offset scheme) aiming to reduce emissions from severe, late-season fires[58]. Gamba grass negatively affects the financial viability of 'savanna burning' carbon offset projects due to rising costs of weed control and the exclusion of invaded areas to be included in the scheme. Australia's savannas are cultural landscapes that support the cultural, spiritual and socio-

	economic livelihoods of Indigenous people[59–61].
Current mitigation and challenges	*Current mitigation:* protected area management including Kakadu National Park (World Heritage Area since 1981), and dedication of Indigenous protected areas within the national reserve network (https://www.niaa.gov.au/Indigenous-affairs/environment/Indigenous-protected-areas-ipas, https://www.nlc.org.au/our-land-sea/caring-for-country/Indigenous-protected-areas). Formal listing of key invasive species as Weeds of National Significance (WONS) and Key Threatening Processes under the Australian *Environmental Protection and Biodiversity Conservation Act*. The *National Gamba Grass Weed Management Plan (WMP 2018)*[29] includes a ban on further plantings, transport and sale of grass or seed, and prescribes active management of the species by all landowners and occupiers. The Northern Territory Government offers free herbicide (glyphosate), loans for spray equipment and weed management advice[62]. Savanna burning projects designed to burn vegetation early in the season to reduce fire intensity now cover 20% (380,000 km^2)[63]. The Northern Territory *Water Allocation Planning Framework* requires licenses for water extraction; 80–95% of flow of rivers is apportioned to environmental and public water needs, and water in aquifers cannot be reduced by >20%[64]. Use of satellite technology to detect illegal land clearing[65]. *Challenges:* Sparse records of trends in mammal populations across vast areas[52]. Inadequate weed and fire management. Increasing agricultural development[54]; illegal land clearing; size of area and remoteness; implementation of weed management plans; lack of access for adaptive management practices; lack of national coordination and continued land clearing. Clearing permits are often case-by-case, and cumulative impacts of extensive clearing across the four states are not accounted for. Water management and increased extraction[66]. Development of inclusive management policies[52].
Potential actions	AVOID: abandon high-risk permit system allowing gamba grass as pasture; reduce land clearing; global climate action. RESTORE: improve national coordination and investment in non-native species eradication; increase compliance and enforcement of the *Gamba Grass Weed Management Plan*[29]; apply novel spread modelling, spatial prioritisation and dynamic management techniques for control and eradication of invasive species; build exclusion fences, translocate and reintroduce threatened mammal species[10]; develop more sustainable livestock grazing and fire management practices; align management strategies with cultural practices; increase Indigenous Ranger programs to lead the management of issues, including fire management[67]. Oblige land managers to maintain biodiversity[52].
Global context	Tropical savannas cover 11.5% of Earth's terrestrial surface and occur outside Australia in South America, Africa, south east Asia and India; they are the world's 2nd most common climate type[1]. Savannas contribute ~30% of terrestrial net productivity globally[38]. In India and south east Asia, river systems in tropical savannas are highly threatened[68]. Gamba grass threatens native species in the Americas[69].

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Images clockwise L–R: Savanna in good condition with Darwin woollybutt (*Eucalpytus minata*) and screw palms (*Pandanus* sp.), Litchfield, Northern Territory, March 2019. Locally collapsed savanna with gamba grass, post fire tree mortality Rum Jungle, Northern Territory, March 2019. (Images: S. M. Prober). Gamba grass (*Andropogon gayanus*) on fire, Northern Territory. (Images: S. A. Setterfield)




Ecosystem	3. Mangrove Forests, Gulf of Carpentaria, eastern Northern Territory and north-western Queensland (15–18°S)
Biome	Tropical forests: mangroves
Action	**Avoid, Recover, Restore**
Baseline state	The Gulf of Carpentaria is a shallow (<70 m deep) coastal gulf that covers ~330,000 km^2. Several large river systems drain ~92,000 Gl into the gulf per year[1]. The Gulf has an extensive (~2,000 km) semi-arid zone of mangrove and associated ecotones (e.g., saltpan and saltmarsh) along estuarine and shoreline edges. Annual rainfall ranges from 600–900 mm in the southern parts to >2,000 mm in the north. Flooding occurs sporadically during the wet season (December to March). The regions are regularly disturbed by annual tropical cyclones. Heavy storms and tropical cyclones occur two or three times a year[2,3]. Mangroves are salt tolerant[4], and highly dependent on regular inundation by tidal waters and rainfall flows[5]. The mangrove forests of northern Australia comprise up to 41 species and are dominated by grey (*Avicennia marina*), spotted (*Rhizophora stylosa*), yellow (*Ceriops australis*), club (*Aegialitis annulata*, *A. corniculatum*) and milky mangrove (*Excoecaria agallocha*)[11,12]. However, in the southern Gulf there are <25 species due to the arid conditions, the dominant species is *Avicennia marina.* Estuarine habitats in the Gulf have high levels of faunal diversity and support many vertebrates including thousands of turtles and dugongs[3]. Mangrove forests provide vital ecosystem services, such as nursery habitats for fish and crustaceans[6], coastal protection against wave action[7], maintenance of water quality[8], and carbon storage and sequestration[9,10]. Due to the low density of the human population, the mangrove forests bordering the Gulf are still relatively unaffected by direct human activity. Some indirect effects may occur mainly through adjacent farming activities[2], and mining and port operations[3]. While the mangroves are amongst the least human impacted mangrove ecosystems globally, they are notably close to their upper tolerance limits of climatic pressures like moisture, salinity, storms and temperature conditions.
Current state and nature of collapse or shift	Analysis of satellite imagery showed that mangroves in the Gulf of Carpentaria suffered high levels of stress as indicated by a reduction in the normalised difference vegetation index (NDVI) in 2014 and early 2015 compared with the previous three years[13]. In late 2015, an unprecedented, severe, synchronous mass dieback of mangroves occurred along 1,000 km of coastline from the Roper River estuary and Numbulwar in the Northern Territory to Karumba and the Mitchell River mouth in Queensland[13]. In one month, >74 km^2 of closed-canopy mangrove forests died (6% of the total area of mangrove vegetation[3]). Nothing approaching this scale has been recorded anywhere[3]. Although the entire Gulf coast was affected (~2,000 km), response patterns varied in different catchment areas ranging from complete loss of the fringing zone along the shoreline to patches that appeared largely unaffected. Some catchments had lost up to 25% of their mangroves. Several patches of severe tree death were 100–200 m wide fringing stands — an unusual occurrence for shoreline fringing zones. Losses occurred in at least two or three species zones (mostly grey mangroves, but also spotted and yellow mangroves). Mangroves in the upper margins adjacent to saltpans and saltmarshes were also lost[3]. An unusual combination of extreme weather conditions contributed to this severe and extensive dieback. In the months leading up to the event, unprecedented high temperatures persisted in the Gulf area. In March 2015, temperatures exceeded 38.8° C for 18 consecutive days[14]. Furthermore, during the severe and prolonged drought (~10–months) preceding the dieback, rainfall was at the lowest since 1972 due to a strong El Niño event in late 2015. Unprecedented low sea levels in the equatorial western Pacific region (~20 cm lower than in normal) compounded reduced water availability from rain and groundwater. This resulted in reductions of both tidal inundation and water content in the soil[3,15] resulting in severe moisture stress. In addition, the lower water levels probably changed sediment geochemistry; normally reducing conditions switched to an oxidising state, ultimately leading to the release of bioavailable Fe^{2+}. Elevated iron concentrations in the wood of dead mangrove trees may have contributed to tree death[16]. During the three years after the 2015/16 dieback event, there was notable recovery in affected areas with significant seedling recruitment (mostly *A. marina*), consolidation of

Current state and nature of collapse or shift (cont.)		surviving undercanopy (particularly *A. annulata*), but limited resprouting of remaining canopy trees[13]. However, some mangrove stands suffered significant accumulative impacts. While these impacts were characteristically localised, the areas affected were often large. Recovering mangrove stands were then struck by two severe tropical cyclones ('Owen' in December 2018 and 'Trevor' in March 2019). Both were slow-moving category 3–4 cyclones with very destructive winds (gusts up to 137 km $h^{-1}$and 250 km h^{-1}, respectively), thunderstorms and record-breaking rainfall and flooding[17,18]. Following 'Trevor', substantial sediment outflow occurred from river systems like the Flinders on Queensland's south-eastern rim of the Gulf. The areas affected by these additional impacts were eroded and scoured of recruits and survivors. Rafts of drifting dead wood from the 2015 event uprooted trees, causing further catastrophic damage, and severely curtailed the establishment of new plants. Remaining trees were dying from buffeting damage that removed stem bark or broke stems[19]. By 2018, the exposed breathing roots of dead grey mangroves had decomposed, and likely affected nursery habitat for fish and crustaceans, reducing shoreline protection from storms and blue carbon storage in sediments. Mobilised sediments accumulated in some areas and eroded in others, further hampering recruitment and ecosystem recovery. This was compounded by rising sea levels. Loss of the mangrove ecosystem leading to local ecosystem collapse was maintained through these feedback mechanisms[19]. Mangroves along estuarine watercourses were less affected, and limited or no impacts were recorded for saltmarsh or sub-canopy mangrove species. Although the lower sea level in 2015 (pulsed event) contributed to rapid dieback, mangroves and tidal wetlands are under a chronic pressure from rising sea levels[5,22]. Sea level rise in the southern Gulf of Carpentaria is the highest in Australia (8.9 cm per decade, ~3 times the global average from 1993 to 2009)[20,21]. Sea level dependent habitats must relocate upland to survive the higher levels of inundation and erosion. This involves a balanced combination of shoreline retreat and upland encroachment. Where this balance is disrupted, as in circumstances where encroachment upland is prevented, then mangrove systems are decreasing in area, influence and value. Other pressures that exacerbate these processes include increasing temperatures and increasing cyclone intensity. Also, longer term changes in rainfall with progressively less freshwater will reduce the growth and extent of mangroves[23]. Species introduced for commercial purposes have escaped and become weeds. One of Queensland's top 20 'weeds of national significance' is the pond apple (*Annona glabra*) used as graft stock for custard apples (*Cherimoya* spp.). The pond apple is highly invasive and transforms habitats. Its ability to tolerate saline conditions enables it to outcompete mangroves[11,24]. Until recently, severe weather events like droughts and heatwaves were not considered likely pulse events on mangroves, but this view has changed with the 2015 dieback in the Gulf. Furthermore, the 2015/16 ENSO event revealed a previously unrecognised pressure. Where followed by severe tropical cyclones and flooding, the significance of accumulative pulse events has become more apparent[25]. There are few direct human influences and pressures on Gulf mangrove habitats. Mining, port activities and grazing cause relatively minor, localised impacts in this remote part of Australia. By contrast, indirect human pressures, such as non-native species like feral animals (e.g., pigs, cattle, donkeys and horses), damage mangroves, as well as saltpans, saltmarsh and adjacent savanna. The latter systems are also notably affected by pastoral activities (e.g., introductions of grazing stock and overgrazing), tree clearing, gully erosion, introduction of weeds, lighting fires and water extraction from abundant aquifers. These human pressures have a growing and accumulative influence on tidal wetlands. Equally significant are landward influences playing a strong role in these processes like feral pigs digging up seedlings, scorching by fires, and smothering by weeds — all preventing and reducing landward encroachment. Human activities also alter drainage and runoff with stream diversions and road construction.
Pressures	**Global climate change presses**	Sea level rise inducing higher levels of inundation and erosion; periodic drops in sea level; increasing temperatures, and increasing cyclone intensity. Long term changes in rainfall with progressively less freshwater will reduce the growth and extent of mangroves[24].
	Global climate change pulses	More extreme fluctuations in sea level and the occasional impacts of category 3 and 4 tropical cyclones are significant pulse events where the destructive combination of wind and waves can have devastating impacts on mangrove ecosystems[13,23]. Severe flood events cause bank erosion, habitat scouring and destruction.

	Human presses	Mining, port activities and road constructions; livestock grazing; introduction of non-native plants and animals; water extraction from aquifers and stream diversions.
	Human pulses	Human pulse impacts are likely to damage mangroves in the Gulf, but so far, these have been localised and minimal. Examples include oil and chemical spills, and possibly burning-off fires.
Ecological impacts and trajectory		Recovery of mangroves and associated ecosystem components depend on the degree of alleviation of pressures to recruitment and standing trees. Climate predictions project increasing temperatures and increasing tropical storm intensity[26]. Cyclones are also linked to extreme rainfall events. The severity of tropical cyclones and flooding may further restrict recovery and continue to damage standing trees. Forest recovery is possible in >20 years but is threatened by the increasing frequency of other extreme weather events, particularly extreme ENSO events like that in late 2015 coupled with accumulative impacts from severe tropical cyclones and flooding[13]. There is also an expected increasing demand on natural resources for human use, such as irrigation and dam constructions affecting drainage and runoff[1].
Time to detection of impact		Months. Previously, mangrove dieback in Australia had been recorded at decadal scales if at all. In late 2015, mangrove tree death took place between December 2015 and January 2016[13]. Public detection was slow and was delayed due to a lack of monitoring and the remoteness of the location. In the Gulf region, local fishermen and contractors first raised the issue in March–April 2016 before the incident was recognised by the public[3]. There is a need for more rapid detections of change in significant natural vegetated ecosystems, especially those visible from remote sensing satellites. The latter is critical for the more remote shorelines of the country.
Collapse profile		ABRUPT — regional extreme events (e.g., drop in sea level) trigger longer-term change. These can be exacerbated by the cumulative impacts of additional localised and regional extreme events, such as severe tropical cyclones and flooding. STEPPED — regional progressive pressures like stepped sea level rise coupled with localised impacts like more frequent severe cyclones cause the loss of mangroves with stepped changes; coupled with periodic pressures preventing progressive landward encroachment.
Social and economic consequences		The loss of ecosystem services (coastal protection, nutrient cycling and carbon sequestration — estimated as US$194,000 per hectare per year[26]). The total value of the Gulf fishery is nearly $30 million per year[3]. In 2017, the line fisheries in the Gulf of Carpentaria was worth $1.5 million, the inshore finfish fishery $11.9 million and the mud crab (*Sylla* spp.) fishery $12 million[27] per year. The impacts on the economy of reduced recreational fishing and remote Indigenous communities' use of mangroves for fishing have not been quantified. The loss of shoreline stability is compounded by extremely high rates of sea-level rise in the Gulf (~3 times the global average)[20,21,28].
Current mitigation and challenges		*Current mitigation:* active remote-sensing monitoring initiated by at least two agencies including the Terrestrial Ecosystem Research Network[29] and National Map (2018) with the Digital Transformation Agency, Department of Communications and Arts, and CSIRO Data61 (https://nationalmap.gov.au/). State or regional environmental management authorities have not implemented local mitigation measures. *Challenges:* the scale and remoteness of the location provide significant challenges for interventions and adaptive measures. Harsh environmental conditions, low-lying topography with a very shallow shoreline and rapid sea-level rise are also challenges. Development of national legislation and policy framework for the protection of mangroves.
Potential actions		AVOID: increase protection of mangrove ecosystem through protected area network; include mangroves in marine spatial planning; increase public awareness of value and importance of mangrove forests[30]; global climate action. Increase condition monitoring and intervention by community groups and Indigenous rangers[31]. Conduct environmental impact assessments for infrastructure and development projects[32]. RECOVER: implement standard, systematic and regular monitoring of shorelines by local Indigenous rangers to identify changes in the system and recommend pressure reduction activities if needed[31], especially in remote regions. RESTORE: Remove drifting dead wood to prevent damage to roots and emerging

	seedlings. Model the impact of pastoral groundwater usage on local stream flow and salinity to inform mitigation actions. Introduce specific intervention measures including improved local land use management of agricultural and non-native animals and plants, and fires, to reduce impacts on sensitive mangrove areas, especially during specific vulnerable times[13]. Reduce or remove local and adjacent press such as trampling by livestock and non-native animals. Lewis[32] suggested a 5-step process that can be applied to this region: i. understand reproductive patterns, distribution of propagules and seedling survival at a given site; ii. Examine hydrology of existing mangrove forests to determine pressures; iii. Assess environmental changes that prevent secondary succession naturally, iv. Natural recruitment of propagules provided appropriate hydrology exists; v. Only actively cultivate and plant seedlings when steps i – iv have not led to sufficient natural recruitment.
Global context	At the same time as the dieback in the Gulf of Carpentaria, a notable dieback also occurred in Mangrove Bay, Western Australia, where sea levels had dropped as well[33]. Mangroves also died in Kakadu National Park[34], but under different circumstances, demonstrating the importance of recognising and interpreting specific indicators and factors in the identification of the cause for the particular, altered environmental conditions. Mangroves cover >14,000 million ha in 123 countries[35,36]. Mangroves are declining at a rate three to five times faster than the overall rate of forest loss[37]. At the current rate, mangrove forests may become functionally extinct in ~100 years[38]. Globally, 1–2% of mangroves are disappearing each year, and in 26 out of 123 countries they are already critically endangered, even approaching extinction[39]. Their ecosystem services (e.g., coastal protection and carbon storage) have been estimated at ~\$3,000–13,000 ha^{-1} per year; globally, they provide minimally US\$1.6 billion each year in ecosystem services[38]. Land use changes devastate mangrove forests; emissions from deforestation of mangrove systems comprise about one fifth of global emissions with an associated cost of US\$6–42 billion per year[30]. Mangrove forests can also provide substantial income from fisheries to local communities. For example, in the Gulf of California mangroves provide approximately US\$19 million per year to local fishers[30]. Mangroves are also vital for food and provide a wide diversity of forest products and ecosystem services, such as carbon sequestration, coastal protection and stabilisation, maintenance of water quality, and cultural and spiritual values[30]. Globally, a net loss in mangrove ecosystems is due to human activities, such as timber harvest for domestic uses, urbanisation and encroaching coastal development. Conflicting public perceptions about mangroves result in deliberate damage in some areas[30,40]. Low frequency-high intensity weather events have caused about 70% of reported natural losses of mangroves[25]. In Mexico, inland shifts in mangrove and saltmarsh ecotones are associated with extreme weather events and rising sea levels. Mangrove expansion at the expense of saltmarsh is associated with warmer and/or wetter conditions and mangrove retreat is associated with severe frosts and/or drought[41]. Development of national legislation and policy framework for the protection of mangroves[33]. However, implementation of frameworks and ensuring compliance are needed. No less than 11 international treaties and agreements were devised to offer some protection to mangroves. Yet, although some of these have been in force for >50 years mangrove forests are still declining albeit at a slower rate than in previous decades[33,38]. Because of their ability to sequester CO_2 include mangroves into emissions trading schemes[33]. In several south-east Asian countries, mangrove restoration projects have been successfully implemented[42]. The approach taken was based on the *Community-Based Ecological Mangrove Restoration* (CBEMR) method developed by R. R. Lewis[32] and promoted by the Mangrove Action Project (https://mangroveactionproject.org/).

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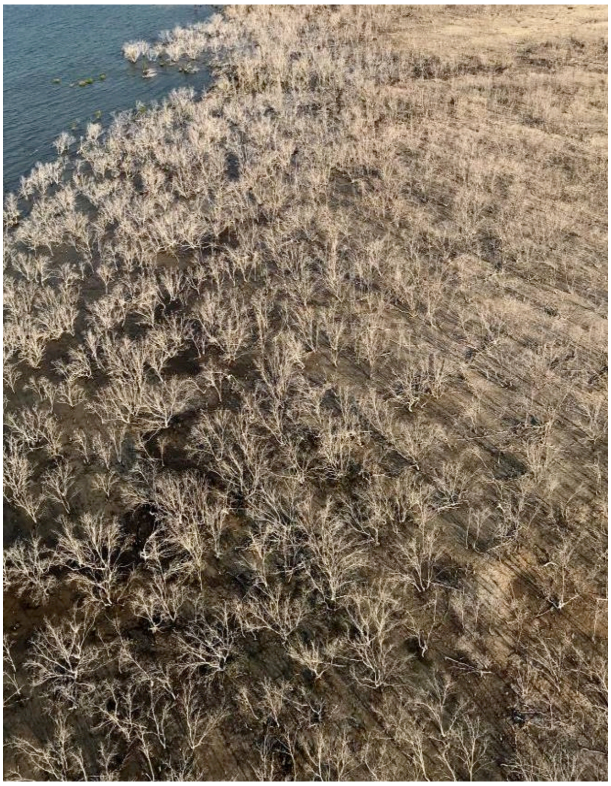
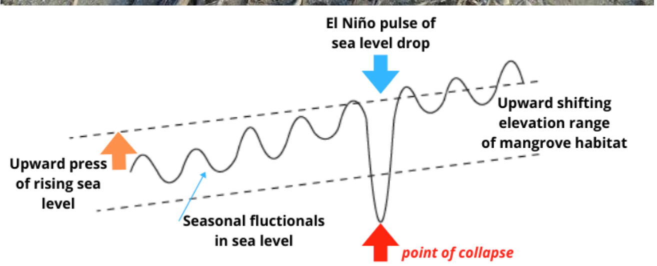
Images clockwise L–R: Three years post dieback, dead mangroves have broken and become driftwood that now rafts buffeting and destroying survivors and new recruits across the broad tidal mud banks. In 2018, the areas impacted by the 2015 mass dieback remain stark and relatively devoid of wildlife. (Images: N. C. Duke). Mechanistic model of sea level change.





Ecosystem	4. Wet Tropical Rainforest, North Queensland (15–19°S)
Biome	Tropical rainforests
Action	**Avoid, Recover, Restore, Renovate, Adapt**
Baseline state	Tropical rainforests line the northeast coast of Australia across 450 km from Townsville to Cooktown. Extensive, mixed wet tropical rainforest cover ~1.85 million ha, and stretch from the coastal lowlands to highlands 1,000 m a.s.l. where some peaks are >1,600 m high[1]. It is a biodiversity hotspot with very high species diversity (>3,000 vascular plant species), and phylogenetic richness and very high levels of endemism (>700 plants and 88 vertebrate species). Many plant and animal communities have ancient Gondwanan heritage[2]. The tropical rainforest make up only 0.12% of Australia's landmass, but the area has the greatest faunal and floral biodiversity comprising 65% of Australia's fern species, 60% of butterflies, 50% of birds, 41% of freshwater fish, 36% of mammals, 30% of orchids, 29% of frogs, and 23% of reptile species[1]. Some 66 vertebrate species are unique to the area[1]. The ecosystem is the primary habitat for many threatened species; of the 693 vertebrate species occurring here, 190 are of significant conservation value and together with rare plants (n = 80) and plants of ancient heritage (n = 16) contribute to the Outstanding Universal Values of the Wet Tropics World Heritage Area. The biodiversity is greatly dependent upon the wet tropics region as long-term evolutionary refuge[1]. The Wet Tropical Rainforest is an important carbon sink, protects a great multitude of species and is important for water and soil conservation[1]. The rainforests are also home to 18 Aboriginal tribes who have occupied this land for thousands of years providing food, shelter and medicine. The Traditional owners have strong cultural and spiritual ties to this land that forms part of their identity[1]. Some 180,000 ha are national parks, and ~500,000 ha are state forests. More than 100,000 ha are timber reserves and another 100,000 ha comprise leasehold and vacant crown or federally owned land. Most of the latter is used by the Australian defence forces[3]. Part of the wet tropical rainforest (894,420 ha) is within the Wet Tropics World Heritage Area (Cooktown to Townsville)[4].
Current state and nature of collapse or shift	Populations of many endemic, rainforest specialists are in decline. At least four frog species are endangered, and the distribution and abundance of ~50% of rainforest birds has changed in accordance with climate change induced variations[1]. Climate change poses the greatest threat to this region. Air temperatures and the frequency of heatwaves associated with global climate change are increasing, and the extent of cool, moist upland refugia is declining[5]. Many rainforest specialists have low levels of resilience to climate change, which makes them vulnerable to extinction; impacts of climate change predicted for vertebrates appear to be occurring sooner than expected and are more severe than forecast[1]. Reductions in the populations of rainforest specialists (especially rainforest obligates) have occurred, in addition to changed species distribution and phenology, community structure, and ecological dynamics[6,7]. There has been an upslope shift of 28 of the 56 rainforest bird species, often associated with declines in overall population size (e.g., 30% decline in populations of the topknot pigeon (*Lopholaimus antarcticus*)[8]. Two possum species (*Hemibelideus lemuroides* and *Pseudochirulus herbertensis*) have disappeared from habitats below 600 m a.s.l.[6]. Heatwaves with extreme temperatures exceeding the upper thermal limits of species are occurring[6]. For example, in 2005, *H. lemuroides* possum populations on Mount Lewis were not detected for seven years following extreme heat conditions[6]. In November 2018, about a third of the entire population of spectacled flying foxes (*Pteropus conspicillatus*) died; this was the first mass death of the species in northern Queensland[9]. Increased rainfall intensity and four major storms in 13 years (category 4 cyclones in 2006 and 2011 and flooding tropical storms in 2018 and 2019) have caused repeated structural damage and loss in rainforests habitats. In 2019, an active monsoon trough and slow-moving tropical low dropped 200–2,000 mm of rain on coastal areas of North and Far North Queensland[10]. Water levels in the Daintree River were 9 m above the long-term mean. Storm surges inundated littoral rainforests[10]. In March 2019, the Iron Range rainforest was hit by Cyclone Trevor and sustained serious damage; habitat food resources were destroyed[11]. Loss of the tree canopy makes the habitat hotter and more prone to fire. In 2006 and 2011, flooding wiped out local populations of dusky rats (*Rattus colletti*),

Current state and nature of collapse or shift (cont.)		creating famine for their main predator, the water python (*Liasis fuscus*), in seven out of eight years[12]. In 2006, a cyclone killed 35% of the regional cassowary (*Casuarius casuarius*) population. Cars and dogs killed many more when the birds emerging from destroyed forests[13]. Riparian vegetation was damaged by wind, flooding and subsequent weed invasions. More than 500 weed species including 10 transformer species have been recorded in 64% of littoral rainforests[14]. Other areas are also severely impacted by weeds, especially smothering non-native vines and lianas. A positive feedback exists between forest fragmentation, cyclone damage, opening up rainforests and weed establishment leading to increased local degradation and loss of diversity, and increased homogenisation at the landscape and regional level[7,15]. The Wet Tropics are predicted to experience longer dry season with more variable rainfall, and more frequent cyclones and flooding rains. Temperatures are expected to raise 0.5–1.4° C by 2030[16]. Substantial and widespread change to this ecosystem and its biodiversity associated with regional human impacts is a chronic pressure[17]. Tourism and an expanding urban human population and associated infrastructure are exerting pressures including habitat fragmentation and loss, increased runoff and pollution[18]. Extreme temperatures increase evaporation; the length and severity of dry seasons are also increasing. Historically, fire has not been a threat to rainforests due to their high moisture content. However, in December 2018, unprecedented conditions led to extreme bushfires that burned 250 ha of mature rainforest in Japoon National Park (https://www.theguardian.com/australia-news/2019/nov/24/world-heritage-queensland-rainforest-burned-for-10-days-and-almost-no-one-noticed). In combination with damage from high intensity cyclones that potentially produce fuel and open the tree canopy, these factors are likely to increase the fire risk to rainforests[1].
Pressures	**Global climate change presses**	Increasing temperature; more severe and frequent extreme events (e.g., droughts).
	Global climate change pulses	Heatwaves (longer, hotter and more frequent); flooding rains; cyclones; fires on fringes, and increased fire risk.
	Human presses	Degradation of natural habitats by clearing leading to erosion; expanding tourism, regional population increase, and associated infrastructure; weeds and non-native animals; pollution; increased erosion from human-altered landscapes.
	Human pulses	Unknown.
Ecological impacts and trajectory		Climate change effects are likely to be compounded by other pressures including the fragmentation of habitats, especially in the uplands. A predicted increase in temperature and increased severity and frequency of heatwaves will cause the loss of key habitat types, significant population declines and potential local or global extinctions in upland and mountain areas with limited adaptive opportunities for species to distribute elsewhere[6]. Fires are expected to increasingly affect rainforest habitats. Further impacts will increase with the frequency of extreme events (heatwaves and tropical storms). Cyclones are expected to become more frequent and severe, reducing recovering times in between these extreme events, resulting in further loss of biodiversity, ecosystem structure and function[5]. Human impacts will increase with more activity in the region.
Time to detection of impact		Decades
Collapse profile		STEPPED — regional, e.g., habitat fragmentation and habitat loss[1,19] ABRUPT — local, e.g., heatwaves[6] FLUCTUATING — local, e.g., from repeated extreme storms[12,13] SMOOTH — local, e.g., from sustained increase in air temperature[5]
Social and economic consequences		Tropical rainforests are culturally significant for rainforest Indigenous tribal groups, which have unique traditional practices. The area is culturally rich and home to 18 Indigenous peoples of eight language groups. Native title covers 87.5% of the World Heritage area[17]. Tourism supports ~5 million visitors per year, and directly contributes >$400 million per year to regional economies. Overall, the economic benefit, directly and indirectly, of the local environment was estimated at >$5.2 billion per year in 2015, including ecosystem services (e.g., carbon sequestration), biodiversity protection, and conservation of soil and

	water[1]. Extreme events (heatwaves, fires, floods and severe storms) will also affect human health[20].
Current mitigation and challenges	*Current mitigation:* the existence of the Wet Tropics World Heritage area reserves (85% of the area in >30 parks) with associated conservation strategy and supportive research. The *Making Connections* program (https://www.wettropics.gov.au/cfoc) to restore connections between remnant patches and increase habitats by tree planting, weed removal, corridor re-establishment and riverine restoration[4]. Implementation of the Climate Adaptation Plan for the Wet Tropics 21. *Challenges:* the complexity of the landscape is a considerable challenge with regard to mitigating pressures. Other challenges include the restricted elevational limits of many species that limit the potential for range shifts to cooler areas, especially associated with upper thermal (lethal) temperatures being reached for some species during heatwave conditions; the high level of endemism (localised distributions); the different state-based forest management strategies; and the arrival of aggressive, transformational non-native yellow crazy ants (*Anoplolepis gracilipes*) in some regions[22]. Targeted, region-wide and systematic long-term monitoring is currently lacking. Control measures of invasive species have been successful in local areas but are difficult and costly to implement across the entire region[1].
Potential actions	AVOID: identify and protect still existing, high priority refugia and improve management[1]; manage fire around rainforest perimeters; reduce land clearing; construct road overpasses and underpasses for wildlife; prevent pathogen transport; global climate action. RECOVER: leave forests to recover after storms. RESTORE: increase connectivity by expanding the protected area network[23]; conduct research into genetic adaptive potential[1]; reduce current road network; expand conservation areas[19]. Secure and restore refugia and linkages; revegetate cleared areas such as electricity corridors; remove non-native species. RENOVATE: implement assisted colonization potentially with more resilient species[1]. ADAPT: apply *ex situ* conservation planning (e.g., germplasm storage and captive breeding)[1]; deliberately move species upwards or southward to cooler environments.
Global context	Tropical rainforest are home to >60% of known species but cover only 7% of Earth's surface[24]. Worldwide, the extent and health of tropical forests is threatened due to global climate change bringing more frequent and severe fires[25]. Other pressures include industrial logging, conversion to agricultural land and plantations for biofuel, invasive species, demand for wood, and the increasing numbers of roads[7]. These threats are leading to the loss of biodiversity and ecosystem function.

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Image clockwise from left top: Healthy littoral rainforest, Daintree River, north Queensland (Image: Moremilu Pixabay). Intact tropical rainforest, Cape Tribulation, North Queensland, and with cyclone damage 1999. Images taken from canopy crane. (Images: D. M. Bergstrom)

Ecosystem	5. Western-central Arid Zones (15–31°S)
Biome	Deserts and xeric shrublands
Action	**Avoid, Restore, Renovate**
Baseline state	The arid zone covers 3.3 million km^2 (~43% of Australia) across four states and the Northern Territory. Annual rainfall is unpredictable, episodic but overall low (100–500 mm rain per year)[1]. Its climate is heterogeneous and its topography is characterised by a low profile (<300 m a.s.l.) interrupted by various mountainous regions (>1,000 m a.s.l.), such as the Flinders Ranges (South Australia), the Central Ranges (Northern Territory) and the Hamersley Range (Western Australia)[1]. The diverse plant communities range from woodlands to shrublands, grasslands, rangelands and desert dunes[2]. These ecosystems include hummock grasslands, mulga (*Acacia aneura sens. lat.*) woodlands and chenopod shrublands[3]. The biotic soil crusts (lichens, bryophytes, algae, cyanobacteria, bacteria and fungi) stabilise dune and arid topsoils during periods of drought, and influence water filtration and runoff, as well as soil erosion and deposition[3]. Freshwater systems through the arid zone include subterranean aquifers, relict streams, stream pools, isolated rock holes, clay pans and temporary lakes, and they provide important spatial and temporal refugia for flora and fauna. The communities inhabiting freshwater habitats are highly isolated and dependent on groundwater, particularly subterranean communities occupying aquifers[1]. Surface freshwater habitats include discharge springs mainly fed by the Great Artesian Basin, one of the world's largest underground reservoirs, which extends across 22% of the Australian continent[4]. Riverine waterholes of varying sizes (50 m to 20 km long) include permanent and ephemeral waterbodies[1].
Current state and nature of collapse or shift	A decade-scale megadrought markedly changed the arid zone (Australian Federation Drought 1891−1903) and shaped the current arid zone[5]. Widespread pastoral activities have altered ecosystems from their initial states, including habitat loss, changes in habitat structure and community composition[3] and reduction in small mammals[6]. Livestock trampling of delicate biotic soil crusts disrupts arid soil and dune stability reducing water infiltration, and increases susceptibility to erosion[3]. Non-native plant species have frequently been planted deliberately as pasture or shade trees; subsequently their seeds escaped or were transported by machinery and vehicles into new areas[2]. Not all introduced plans are invasive, but those species that are have played a key role in ecosystem changes in the arid zone. The total number of non-native plant species is poorly documented, but includes 206 species in the Great Western Woodlands (sub-ecosystem) alone[7], and 260 species in the southern Northern Territory[4], with some of these introduced >200 years ago. Importantly, these include transformer plant species, such as buffel grasses (*Cenchrus ciliaris* and *C. pennisetiformis*), rosy dock (*Rumex vesicaria*) and athel pine (*Tamarix aphylla*) that alter ecosystem structure and functions. Athel pines — frequently planted as shade trees near outback homesteads — rapidly invaded riparian ecosystems, areas with the highest species diversity and productivity in arid Australia[2]. In 1974, one source of this invasion was floods along the Finke River, Northern Territory, which rapidly spread seeds along the shores of the 600 km long river[2]. Buffel grass species, the most threatening of the non-native, transformer species, have invaded extensive areas of the Northern Territory, Queensland, Western Australia and South Australia, and are spreading into New South Wales and Victoria. Buffel grass was planted as a dust suppressor in the Northern Territory in the 1970s, and is deliberately grown for pasture because of high drought tolerance and resilience to heavy grazing. However, buffel grass leads to substantial ecosystem degradation, including habitat loss, biodiversity decline and alteration to fire regimes (frequency and intensity)[8,2]. In 2001 and 2011/12, extreme rainfall linked to La Niña events resulted in exceptional growth of buffel grass, providing fuel for severe fires in those years[9]. More recently, in January 2019, 100 km of the length of Tjoritja /West MacDonnell National Park were burned. More frequent and intense fires reach into the canopy and cause the loss of trees, shrubs and native grasses. This has led to local ecosystem state change with reduced species diversity. In particular, rainfall cycles combined with buffel grass invasion are affecting persistence of trees such as bootlace oak (*Hakea lorea*) [10,11]. Other ecosystems are similarly affected by increasing extent of intense fires potentially associated with climate change; for example, increased wildfire intensity has increased positive fire feedbacks in

Current state and nature of collapse or shift (cont.)		obligate seeder eucalypt woodlands in the Great Western Woodlands, reducing re-development of old-growth woodlands[12]. Extreme heatwaves are another driver of change in these already extreme environments, increasing likelihood of species reaching physiological limits and ecosystems reaching tipping points[13]. Modelling has shown that soil moisture is strongly negatively correlated with heatwaves in the arid zone[14], leading to interaction between drought and heat stress. The summer of 2018/19 was Australia's hottest summer on record (2.14° C above average of 1961–1990), and was also the driest for areas of southern Queensland, New South Wales, Western Australia and parts of South Australia[15]. Accordingly, tree mortality is increasingly reported (e.g., the widespread *Acacia aneura* sens. lat., and the rare and threatened purple-wood wattle (*Acacia carneourum*)[10]. Similarly, experimental studies on domesticated zebra finches (*Aeniopygia guttata)* demonstrate that exposure to heatwave conditions alters sperm morphology, and thus detrimentally affects breeding success[16]. Above ground freshwater habitats depend on infrequent but at times intense rain events that can cause flooding. During periods of extreme heat and long drought, the availability of aquatic refugia and habitats is also greatly reduced[1]. Water extraction and the provision of artificial water sources have mixed effects: creation of novel habitat (e.g., wetlands); increased availability of water for native fauna and associated ecological changes (e.g., range extension of some species); change of local native plant assemblages; a suite of negative impacts including extreme local ecosystem degradation from associated livestock trampling, and provision of water to support local non-native herbivores[3]. Non-native vertebrates have had major negative impacts on ecosystem structure and function, and have led to loss of species diversity, especially through predation of native mammals and birds[3,6,17]. Eleven species of non-native herbivores and predators have established themselves in the semiarid and arid zone including cattle (*Bos taurus*), goat (*Capra bircus*), camels (*Camelus dromedaries*), cat (*Felis catus*), canids (*Vulpus vulpus* and *Canis* spp.), and pig (*Sus scrofa*)[18]. Their impacts on native populations and the environment depend on their population densities and level of ecosystem resilience. Trampling and overgrazing has led to soil damage and changes in vegetation structure (e.g., lack seedling regeneration), increased erosion, habitat loss of reptiles and small mammals, and predation on native species and livestock[18].
Pressures	**Global climate change presses**	Increased variability in rainfall where dry seasons are more prolonged and more severe; a potential for a greening of the desert in some regions[19,20]. More energetic weather systems cause frequent rain in arid and semi-arid regions; combined with the ambient CO_2 fertilization effect[21], this can contribute to increased fire frequency and intensity.
	Global climate change pulses	Increasing temperatures; increased duration and frequency of extreme heatwaves; increased flooding rains and frequency of cyclones; increased fire frequency and enhanced buffel grass-fire cycle.
	Human presses	Vegetation clearing and associated loss of habitat; invasive introduced plants contributing to habitat change; introduced mammals; extensive rangeland grazing by hooved livestock; artificial watering points contributing to land degradation[3,9,18].
	Human pulses	Unknown.
Ecological impacts and trajectory		Arid regions are projected to warm proportionally faster than coastal areas[1,20]. For example, in Alice Springs (Northern Territory), annual maximal temperatures have risen by 2° C since 1900. In the past 30 years, the region has experienced more hot days than previously (49 days with >38° C compared to 41 days prior to 1988)[22]. More frequent hot days, increased evapotranspiration. Although rainfall has increased by 13% over the past 30 years, the monthly water balance in negative[22]. In combination with invasive species and other human presses, ecological impacts of these climatic changes are expected to include: shifts in composition and distribution of ecological communities[19]; increased tree and bird mortality, loss of long-unburned habitat[8,10,12]; reduced aquatic refugia[1,19]; increased intensity of rainfall events and more intense storms leading to greater interannual variability in productivity and carbon cycling[23], and more pronounced boom and bust dynamics such as increases in raptors in response to rodent flushes after intense rain events[24]. Response of non-native plants to climate change is expected to be species specific. For example, models suggest that buffel grass could become established in ~68% of the Australian continent or 5.3 million km^2 [25], but suitability in central Australia could decline with increasingly hot summers under climate change[26].

Time to detection of impact	Months to centuries
Collapse profile	SMOOTH — regional, e.g., pastoral activity and invasive biota out-compete native species STEPPED — regional, e.g., clearing and planting of buffel grass, buffel grass invasion with human disturbances destroy habitat ABRUPT — local, e.g., loss of overstorey with heatwaves, drought and/or change in fire regime
Social and economic consequences	Dust storms, soil erosion, widespread fires, feral animals and loss of pasture, livestock and property can impact directly on human health (e.g., through dust and fire risks - including impacts on the major cities in eastern Australia.); and on human and economic well-being through reduced stock carrying capacity, loss of income and livelihoods, and potential desertification of arable lands[5,9]. Buffel grass also affects Indigenous communities such as Anangu Pitjantjatjara Yankunytjatjara in central Australia through the reduction in the availability of natural resources ("bush tucker") and water[27]. Travelling Indigenous people who use waterholes are at risk from faecal contamination of water sources by feral camels; the presence of feral camels may also prevent a waterhole from re-filling. Grazing and trampling by livestock and feral hoofed herbivores affect the vegetation surrounding waterholes and may alter drainage patterns[28].
Current mitigation and challenges	*Current mitigation:* The Australian Weed Strategy (https://weeds.org.au/) identified 32 Weeds of National Significance including athel pine and African boxthorn (*Lycium ferocissimum*) in the arid zone. Federal and state governments develop weed management plans and strategies[2]. Some areas in the Western Central Arid Zone are Indigenous Protected Areas (IPA) managed by Indigenous rangers and communities to 'better care for country'. Some areas such as the Matuwa Kurrara Kurrara IPA comprise former pastoral properties[29]. The current 76 IPAs cover a total area of >67.3 million ha; individual IPAs vary greatly in size; e.g., Tjwanpa IPA is 4,500 ha and managed by women rangers who implement control measures for fire, weed and feral animals, while Birriliburu IPA covers 6.6 million ha (https://www.niaa.gov.au/). In October 2019, the Australian Government announced an expansion of the IPA network to >100 million ha[30]. Indigenous Protected Areas combine biodiversity conservation, culture and livelihood objectives, and include resources for Indigenous Ranger Programs[31]. State- and national-based weed management strategies including containment, mechanical and (potentially) biological control and eradication programs (e.g., specific threat abatement advice for buffel grass in response to listing of the threatening process 'Novel biota and their impact on biodiversity' under the Environment Protection and Biodiversity Conservation Act 1999. This includes calls for surveillance, containment, and restrictions on further development for agriculture[32]. Fencing of areas can exclude predators potentially creating refuges for threatened mammals, at least in the short term. Currently on mainland Australia, there are 19 fenced off areas covering in total 350 km^2 from where predators are effectively excluded. The areas are small (0.5–123 km^2) and spread across the continent. Another 1080 km^2 are fenced off but do not exclude non-native predators[33]. Initiation of a $19 million camel control program[34]. *Challenges:* highly variable environmental conditions and the vastness of the region; high levels of uncertainty about the impacts of climate change[9,10]; difficulties in accurately determining the distribution of invasive species, inadequate capacity to control invasive transformer species, many of which are already widespread (buffel grass, camels, cats) and for plants, can have long-lived seed banks. There are no official quarantine actions to protect arid regions although some states (e.g., Western Australia); limit plant introductions. Buffel grass is still promoted as pasture grass[2], and for erosion control and mine site rehabilitation[35]. Planning for the potential impacts of a megadrought should be considered[5].
Potential actions	AVOID: prevent future expansion of notorious weeds into undeveloped areas; identify and protect freshwater and terrestrial refugia and their connections at a landscape scale; exert local fire control; global climate action. Add buffel grass to the list of Weeds of National Significance. RESTORE: establish fenced exclusions areas to allow endangered vertebrate populations to recover; return to ecosystem-appropriate fire regimes, e.g., through investment in Indigenous ranger programs; control non-native predators and herbivores, and non-native

Potential actions (cont.)	plant species; set up predator exclusion areas; provide incentives to enable sustainable livestock grazing intensities; prioritise conservation measures; manage access to artificial water; promote soil crust restoration: implement major biological control program directed at control/ eradication of buffel grass. RENOVATE: monitor key aquatic systems to ascertain the extent of refugia-microclimate decoupling from larger-scale regional climatic change, and prepare to establish better suited ecotypes or species;
Global context	Various species native to Australia are well established on other continents. The eastern cotton bush (*Maireana brevifolia*) has become an established weed in the Middle East, Chile and the Canary Islands[35]. In South Africa, four saltbush (*Atriplex*) spp. introduced as fodder for the dry season have become notorious, established weeds where they escaped cultivation[37]. The giant reed (*Arundo donax*) possibly native to the Mediterranean region has invaded riparian regions worldwide (including in arid zones) where it replaces the native vegetation. Popular for its multitude of uses it has been cultivated in plantations in various countries, but where it escapes and invades native ecosystems it has ecological and environmental impacts. In California, it is listed as one of the five most invasive species degrading natural ecosystems[37]. Buffel grasses have replaced natural vegetation cleared for pastures from the warm temperate to the tropical regions of the Americas. Originally deliberately planted, they spread uncontrolled into forests, savannas, grasslands and arid zones[38]. The CO_2 fertilisation effect in arid and semi-arid (rain-limited) regions is already evident and monitored[23]. This is a potential new, extensive carbon sink linked to moisture pulses (although a carbon source in subsequent dry seasons)[23].

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Images clockwise L–R: Healthy mulga (*Acacia aneura)* arid zone woodland, Boolardy Station, Western Australia, July 2016. Collapsed mulga arid zone woodland, Boolardy Station Western Australia, November 2018. Heavily grazed by cattle. Dying mulga after severe summer heatwave, Newman, Western Australia, April 2019. (Images: S. M. Prober). Hughes River, Tjoritja /West MacDonnell National Park, January 2017 and February 2019. (Images: fionawalshecology.com)

Ecosystem		**6. Georgina Gidgee Woodlands**, central Australia (19–28°S)
Biome		Arid and semi-arid area: acacia woodlands
Action		**Avoid, Recover, Restore, Renovate, Adapt**
Baseline state		The Georgina Gidgee Woodland in central Australia is a patchy but widespread woodland located in arid to semi-arid eastern Australia[1]. The pre-European settlement ecosystem extent is unknown but was larger than present. The keystone tree Georgina gidgee (*Acacia georginae*) dominates low open woodlands. It usually grows in clay depressions between spinifex grass (*Triodia basedowii*) dunes and along watercourses[1]. Georgina gidgee trees are long-lived (~200 years) with infrequent episodic recruitment in wet years. Rainfall is highly variable; extended periods of without any rainfall are interrupted by periods of heavy falls[2]. Woodlands support perennial flowering shrubs, grasses and diverse fauna, including small mammals, kangaroos, reptiles, ants, bats and ~80 bird species, especially during resource pulses[1,3,4].
Current state and nature of collapse or shift		The arid zone was markedly changed by a decade-scale megadrought (Australian Federation Drought 1891–1903)[5]. This would have shaped the current distribution of Georgina Gidgee Woodlands. Past, large-scale harvesting for fence posts, and clearing have affected Georgina gidgee woodlands. In the Brigalow Belt in Queensland, areas covered by gidgee and brigalow (*A. harpophylla*) were cut back from 8.5 million ha to 1.1 million ha by 1999[6]. In addition, wildfires kill juvenile trees. The loss of keystone trees alters ecosystem structure. Currently, there is still extensive loss of the ecosystem through pastoral activity. Declines are occurring in ~73% (~473,900 km^2) of the geographic range[1]. Livestock and camels reduce native vertebrate and plant diversity and abundance through grazing, trampling and eutrophication[7]. Trees are also removed for firewood and fencing[1]. Increases in non-native plants and vertebrate herbivores and non-native predators (e.g., cats, goats, horses and foxes) affect cover, the understorey and associated animal species[1]. Increased fire impact is occurring from invasion by the introduced, highly flammable buffel grass[6,8]. There is a positive feedback loop: buffel grass invasion is aided by fire, but buffel grass increases the fuel load on the ground that in turn increases the fire risk[9]. The patchiness of wind erosion is a natural part of the ecosystem but more energetic climate systems reduce patchiness and promote landscape-scale erosion and deposition, which may alter the system's drivers. Exposure of stored seed due to wind erosion can lead to pulse recruitment events but also makes seeds vulnerable to predation. Reduction of local water resources and damage from livestock is occurring around artificial watering points as per #5 Western-central arid zone. Vehicle tracks over dunes and across clay pans cause hydrological change and compact spinifex (*Triodia basdowii*) hummocks[1].
Pressures	**Global climate change presses**	Reduced rainfall; ongoing warming and increased extreme temperatures; hydrological change[10].
	Global climate change pulses	Altered fire regimes[11]; increases in extreme fire weather[12]; more frequent and prolonged droughts[13].
	Human presses	Georgina gidgee harvesting[1]; land clearing (Georgina gidgee seedpods are poisonous to cattle); non-native herbivores and predators[1]; livestock grazing[7]; artificial watering points and hydrological change[14].
	Human pulses	Use of fallen trees for firewood and vehicle tracks through dune systems[1].
Ecological impacts and trajectory		Assessed as vulnerable under future climate projections[1]. The ecosystem is projected to be heading towards collapse with the loss of stable open woodlands and associated ecosystem services. Without significant intervention, the system will cascade into desertification.
Time to detection of impact		Decades
Collapse profile		SMOOTH — regional, e.g., pastoral activity and invasive biota[1] STEPPED — regional, e.g., clearing or increases in more prolonged droughts[1] ABRUPT — local, e.g., loss of ecosystem with changes in fire regime[1]

Social and economic consequences	Desertification of rangelands, loss of shade for cattle, loss of water catchment surface for refilling the artesian basin, and loss of ecosystem function associated with ancient dune stabilisation, increased prevalence of regional dust storms, including impacts on the major cities in eastern Australia.
Current mitigation and challenges	*Current mitigation:* reserves, introduction of firebreaks; fuel reduction strategies (including intensive grazing); landscape-level exclusion of fire, minimisation of topsoil disturbance and stock exclusion. The ecosystem is assessed as Vulnerable under the IUCN Red List of Ecosystems criteria[15]. *Challenges:* long-term strategies needed to control effectively invasive species; increasing intensity of temperature/drought regimes combined with unprecedented fire events and top soil disturbance resulting in neighbouring dune mobilisation, smothering recovery and transforming the system to novel wind-driven dunes. Improved understanding of the response of Georgina Gidgee Woodland to extreme temperature events, extreme rainfall events and prolonged drought[1] is needed.
Potential actions	AVOID: formally protect high value areas (e.g., Ethabuka and Cravens Peak Nature Reserves, Munga Thirri National Park); global climate action. RECOVER: Maintain boundary fences of reserves. On pastoral properties, fence off selected woodland areas to encourage regeneration of *Acacia georginae* trees and associated understorey species; regulate removal of wood for fires or fencing[1]. RESTORE: remove non-native plant species to reduce fire risk[6]. Remove non-native animals[16]; manage stocking rates including destocking, and removal of feral herbivores (e.g., camels) to reduce total grazing pressure[7]. Stabilise dunes and restore hydrological processes (clay pans around which gidgee woodlands exist have an important function; without trees, these would likely experience more sheet flooding and erosion). Undertake fine-scale spatial mapping of woodland extent and condition to investigate the potential for dispersal and the patterns of recruitment across the geographic range[1]; RENOVATE: investigate the role of altered hydrology on the distribution[1] to allow for plantings of Gidgee into new, suitable areas. ADAPT: investigate the genetic structure of populations and explore options for establishing new locations at southern end of the range where suitable habitat will remain under future climate projections[1].
Global context	Woodlands in arid and semi-arid regions (dryland forests) are under-appreciated globally, making changes in distribution hard to track as they typically lack adequate baseline mapping products. Moreover, many dryland forests decline in abundance and function before there is a noticeable decline in extent[17]. For example, there has been a significant reduction in tree cover in some African semi-arid and tropical dry regions due to expanding agriculture, despite some villagers maintaining trees on farmland[18]. In Kenya, uncontrolled production of charcoal degrades woodlands, causing a loss of livelihoods. In Morocco, argan (*Argania spinose*) woodlands declined 44.5% from 1970 to 2007[19].

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Images clockwise L–R: Georgina gidgee (*Acacia georginae*) stand good condition, November 2007. Browsed Georgina gidgee sapling, November 2006. Cattle seeking shade with browse line and no branches in lower part of Georgina gidgee tree, and removed understory. (Images: G. M. Wardle)

Ecosystem		7. Ningaloo Reef (and adjacent areas), northern Western Australia (21–24°S)
Biome		Marine: coral reefs
Action		**Avoid, Recover, Restore, Renovate, Adapt**
Baseline state		Ningaloo Reef is part of the Ningaloo Coast World Heritage Area inscribed in 2011 and comprises 604 km^2 of terrestrial and marine components at the western side of North West Cape[1]. Ningaloo Reef is highly biodiverse with ~ 217 reef-building coral species, representing 54 genera and 15 families; >500 fish species, 650 mollusc species, 600 crustacean species, >1,000 species of marine algae, and 155 sponge species[2,3]. At Ningaloo Reef, regional coral cover ranges from 3 to 44%. Presently, corals of the family Acroporidae and Poritidae dominate all but the most inshore of reefs at Ningaloo Reef[4]. The reefs constitute biologically important areas for a multitude of spectacular species, such as seabirds, sharks, whales, dolphins, marine turtles and dugongs (*Dugong dugong*). Whale sharks (*Rhincodon typus*) aggregate annually at Ningaloo, and humpback whales (*Megaptera novaeangliae*) migrate through the area to their northern breeding grounds. The Ningaloo Coast is a principal nesting site for three marine turtle species listed under the *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC), including the endangered loggerhead turtle[5]. The reefs of northwest Australia are shallow-water tropical marine ecosystems. Habitats include fringing and barrier coral reefs, soft sediments, canyons and limestone pavements[2]. Natural impacts such as earthquakes and associated aftershocks and tsunami affect the reefs ecology[6].
Current state and nature of collapse or shift		Long-term increasing sea-surface temperatures (SST) and ocean acidification affect reefs and exacerbate damaging conditions from tropical cyclones and seasonal lows[7]. Corals become heat stressed when the local temperatures are ~1° C warmer than the highest monthly mean temperature[8]. Heat stress causing coral bleaching has emerged as a major threat to coral reefs[9]. Although the pressure (elevated SST) can be large scale, there is spatial patchiness in species responses. The magnitude varies depending on local site factors, such as taxonomic composition, localised storms, mitigating the response[10]. Bleaching events occurred at Ningaloo Reef and adjacent reefs from 1990 to 2019, two of which (2011 and 2013) were regional mass bleaching events[10,11]. The 2010/11 event coincided with a marine heatwave which lasted more than six months, and sea-surface temperatures were ~5° C above seasonal averages which caused bleaching across 12º of latitude extending to the reefs southern limits[10,12]. The heatwave was driven by one of the strongest La Niña events on record, and an unusually strong southward flow of the Leeuwin Current that delivered warm tropical waters along the coast of Western Australia. As a result coral species composition changed, and regional fish, abalone and crayfish kills occurred[10]. On the shallow-water (<5 m) Bundegi reef, coral cover decreased by 79–92% and dominant, mature (>10 cm) *Acropora* and *Montipora* species assemblages died. In other areas of Ningaloo Reef, bleaching was moderate (~20–35%)[12]. During the La Niña associated extended heatwave of 2013, 51–68% of all coral groups (hard and soft) bleached at Onslow Reef (10–15 m deep)[13]. Post-bleached coral areas were further affected by crown-of-thorns starfish (*Ananthaster planci*) predation, reducing recovery of corals[14]. Of the Western Australian reef systems, Ningaloo Reef experienced minimal coral bleaching (<10 %) in the 3rd Global Coral Bleaching Event in 2016. However, the event contributed to a further decrease in coral cover and reduction in structural complexity[11]. Predation by corallivorous gastropods (*Drupella* spp.) and disease can delay post-bleaching reef recovery[15,16]. Recurrent anoxic events, caused by the rapid decomposition of locally trapped coral spawn can also compound the resilience of coral communities[17]. Fish biomass was reduced in recreational fishing zones compared with sanctuary zones, but an overall decrease in fish biomass (up to 22%) across the marine park occurred concurrently with hard coral abundance[18]. Studies of marine megafauna found no evidence that interactions with tourists affected the likelihood of whale shark re-encounters or survival. Physical and biological environmental factors had a far greater influence on whale shark visitation rates[19,20].
Pressures	**Global climate**	Long-term sea-surface temperature increase, ocean acidification.

	change presses	
	Global climate change pulses	Rapid increases in SST due to the poleward movement of tropical water masses coincident with marine heatwaves; seasonal tropical lows and cyclonic weather. Sea-level rise and fluctuations linked to Indian Ocean Dipole[21].
	Human presses	Aquaculture (e.g., pearling); tourism; oil and gas drilling; seismic surveys; salt works; water and resource abstraction; targeted recreational fishing (e.g., spangled emperor)[22].
	Human pulses	Discharge of polluting substances from commercial shipping and recreational boating; seasonal (March to November) peaks in tourist numbers.
Ecological impacts and trajectory		Shifts in species composition towards coral species that can survive repeated thermal events[4]. Since *Acropora* species are vulnerable to bleaching, they are likely to be replaced by more tolerant species[13]. Pressure from crown-of-thorns starfish outbreaks but a concomitant 1.4–7.5 % per year change in hard coral cover[18]. Possible shift to algal dominated ecosystem[23]. The loss of key coral species impacts associated species, e.g., fish species composition recruitment and survival[18,24]. Expansion of more northerly coral species into more southerly areas has begun[11].
Time to detection of impact		Shallow coral bleaching is detectable within days of heat stress accumulation to 2° C heating weeks, and remains detectable for at least four months. Declines in deeper communities due to the gradual, cumulative impact of local pressures.
Collapse profile		SMOOTH — regional, e.g., from global sea-surface temperature rises and ocean acidification FLUCTUATING — regional, e.g., from multiple thermal stress events ABRUPT — local, change after 2010/11 extreme heatwave
Social and economic consequences		There has been a considerable loss of wilderness and natural heritage values, Indigenous native title values, cultural values and Indigenous livelihoods. Economic impacts include a reduction in fish stocks and impacts on tourism in the northwest worth ~$1.5 billion p.a. In 2016/2017, 2.3 million visitors were recorded in the area[24]. The economic damage of the December 2010 storm was estimated at $100 million.
Current mitigation and challenges		*Current mitigation:* World Heritage area, marine parks, reserves and management areas, managed fisheries and industry-managed actions[25]. *Challenges:* ongoing warming and marine heatwaves are increasing the severity, frequency and extent (hundreds to thousands of kilometres) of bleaching events. Sea-level rise, ocean acidification, storm severity, increased nutrient loads after flooding, and increased tourism are additional challenges.
Potential actions		AVOID: stringently control coastal and catchment area development, and limit activities that stress the reef (e.g., fishing, physical damage from diving, boat anchoring, runoff and construction); global climate action. RECOVER: capitalise on imminent large-scale decommissioning of nearshore oil and gas drilling platforms as structures for coral restoration, using the extensive north-to-south network of platforms to allow for the assisted migration of relevant species. RESTORE: transplant new corals to assist recruitment[26]. RENOVATE: assist migration of more thermally tolerant coral genotypes from thermally extreme to cooler reefs[27]. ADAPT: introduce more heat-tolerant corals[27]; use epigenetics to enhance resistance through development of novel alleles[28].
Global context		Coral reefs north of the Ningaloo have experienced recent abrupt (Montebello and Barrow Islands) and fluctuating (Scott Reef and Seringapatam) collapse profiles[11]. Coral reefs globally are facing multiple threats (mass bleaching, ocean acidification, increasing hurricane and cyclone intensity and severity, pollution, fishing and invasive species).

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Images left panel: Healthy coral Ningaloo reef. Top right: Plate coral storm damages (Images: John Turnbull Flickr). Bottom right: coral bleaching at Ningaloo reef. (Image: scientific editor_Flickr)

Ecosystem	**8. Shark Bay Seagrass Communities**, Western Australia (24–26°S)
Biome	Coastal marine: seagrass
Action	**Avoid, Restore, Renovate**
Baseline state	Shark Bay is a shallow, low energy marine environment, which has limited ecological connectivity with regions to the north and south[1]. Shark Bay, listed as a World Heritage Area in 1991, comprises one of world's largest (4,300 km^2) and most diverse (n = 12 species) seagrass assemblages, dominated by the temperate meadow-forming seagrasses *Amphibolis antarctica* and *Posidonia australis*[2]. *A. antarctica* is an important ecosystem engineer in this system[3,4]. The seagrass communities support an extensive food-web[5]; at the apex are resident populations of tiger sharks (*Galeocerdo cuvier*). The area also protects ~10% of the world's dugong (*Dugong dugong*) population who feeds exclusively on the seagrass meadows. Manta rays (*Manta* spp.), a globally threatened species, are also resident. Green (*Chelonia mydas*) and loggerhead (*Caretta caretta*) turtles use Shark Bay and it is an important nesting area for loggerheads. Southern right (*Eubalaena australis*) and humpback (*Megaptera novaeangliae*) whales use Shark Bay as a migratory staging post. Hypersaline (double the salinity in surrounding seawater) Hamelin Pool contains a diverse assemblage of stromatolite species (dome shaped microbial mats), which are among the oldest life forms on Earth[5]. Shark Bay is a sediment-carbon storage hotspot (a blue carbon ecosystem). Over 4,000 years of continuous seagrass growth has resulted in the accumulation of an estimated 350 million tonnes of CO_2 (or about $8.13 billion in carbon credit terms)[6,7]. In a global context, Shark Bay contains 0.65–1.3% of carbon stored in the upper 1 m of seagrass sediments[8]. The main factor controlling the water quality (e.g., temperature and salinity) of Shark Bay is climate change[9]. Additionally, in response to high rainfall (e.g., cyclones), both the Wooramel and Gascoyne rivers periodically discharge freshwater and sediments into Shark Bay[9]. At present (2020), localised sewage input from septic tanks and runoff is considered a minor factor altering water quality[9].
Current state and nature of collapse or shift	There is high confidence of a slow, long-term (over 32 years) increase in seawater temperature that has been linked with climate change[9]. That long-term trend in water temperatures has been punctuated by large positive deviations, which are linked to variability in the Southern Oscillation Index (SOI = El Niño/La Niña development and intensity)[9]. An unprecedented marine heatwave, known as the Ningaloo Niño, occurred in the summer of 2010/11 when one of the strongest positive SOI anomalies (La Niña) was recorded. Compounding this, an unusually strong southward flow of the Leeuwin Current delivered tropical water along the coast of Western Australia. Sea surface water temperatures rose to 2–3.5° C above the long-term average in late February/early March and endured for >10 weeks[10]. Anomalously high water-temperatures were also recorded across Shark Bay during the summer months of 2011/12 and 2012/13. Both heatwaves spanned 12° latitude and 1,200 km of coastline. Coincident with the 2010/11 marine heatwave, a tropical storm over the Gascoyne River catchment caused an extreme rainfall event in December, and discharged significant volumes of terrestrial sediment into Shark Bay. Localised deposits of up to 10 cm thick covered seagrass within Shark Bay, and the Wooramel River flood plume spread 10–15 km into the area[11]. This storm was one of three during the 2010/11 season. Total extent of seagrass has declined over time across areas of Shark Bay. The extent reduced overall by 21.5% from 2002 (~2,700 km^2) to 2014 (~2,110 km^2)[9]. However, a 250 km^2 area of seagrass recovered between 2014 and 2016[9]. One study summarised the same time series slightly differently[12]. The analyses showed a 313 km^2 increase in total seagrass extent from 2002 to 2010 (pre-marine heatwave), followed by a 1,069 km^2 (25%) loss from 2010 to 2014 (post-marine heatwave) and a modest recovery of 125 km^2. Following the death of seagrasses and associated disturbance of sediments, an estimated 2–9 Tg of CO_2 may have been released to the atmosphere over the following three years, a mass equivalent to 4–20% of the carbon stock in the top 1 m of sediment[8]. The change in total seagrass extent was due to major losses of the dominant species *A. antarctica,* which accounted for ~85% of cover in the mid-1980s and declined from 55% in 1996 to 1.5% in 2016[2,9,13]. Percent cover of *P. australis* remained relatively stable between

<table>
<tr><td colspan="2">Current state and nature of collapse or shift (cont.)</td><td>2002 and 2016[9,12].

While the recovery of A. antarctica has been limited, tropical early successional seagrasses (Halodule uninervis and various Halophila spp.) recovered by 2013 and exceeded pre-marine heatwave cover estimates by 2014[4,12].

In addition to the seagrass loss, benthic fish biomass declined ~40%, in shallow waters and ~27% in deep waters. Fish kills were also observed during the marine heatwave [14].

Against a background of constant tiger shark abundance[4] were post- marine heatwave falls in mega-fauna abundances and densities[15]. Sea snake (e.g., Hydrophis elegans, Disteria major, Aipysurus pooleorum) densities were most affected (a 77% decrease). Dugong density decreased by 68% (probably due to emigration). Green sea turtle (Chelonia mydas), pied cormorant (Phalacrocorax spp.) and bottlenose dolphin (Tursiops aduncus) densities decreased by 35–40%. Loggerhead turtle density remained stable.

The cumulative effects of a series of record low recruitment years (2011–2013) for scallop (Ylistrum balloti) resulted in <1% pre-marine heatwave abundances. In 2013, catch rates dropped to two scallops per nautical mile[16]. From 2014 onward, cooler water temperatures improved spawning and catch per unit effort reached pre-marine heatwave levels by 2016[16].

Marked changes in blue swimmer crab (Portunus armatus) distribution and biomass were also observed[17]. Six to 12 months after the 2010/11 marine heatwave, commercial catch rates dropped to 2% of pre-marine heatwave. November 2011 catch per unit effort decreased from an average of 1,345 to 41 kg per square nautical mile. Heat stress probably had a detrimental effect on juvenile survival[17]. Scallop fisheries were closed for ~5 years, and crab fisheries for 18 months; catch rates recovered by 2018[16].

Brown tiger (Penaeus esculentus) and western king (P. latisulcatus) prawn recruitment spiked at very high rates immediately post-marine heatwave but returned to historical levels soon after[16].

In December 2019, Shark Bay again experienced an unprecedented marine heatwave, the most widespread on record (form the Kimberley to South Australia) with temperature anomalies >2° C warmer than average for several weeks. This in combination with low tides contributed to fish, mollusc and crustacean kills and coral bleaching[18].</td></tr>
<tr><td rowspan="4">Pressures</td><td>Global climate change presses</td><td>Long-term increase in seawater temperature and acidification[19,20].</td></tr>
<tr><td>Global climate change pulses</td><td>Extreme fluctuations in water temperature (marine heatwaves) and ocean circulation linked to climate extremes (e.g., the Southern Oscillation index)[21] with predicted increases in frequency[22].

Seasonal winter rainfall with increasing variability in summer rainfall associated with cyclones. Extreme flooding associated with cyclones released very large sediment plumes from the loss of Gascoyne Catchment topsoil into certain parts of Shark Bay[9].</td></tr>
<tr><td>Human presses</td><td>Minimal[4,23]; some commercial fishing[24]; commercial activities in the Gascoyne Catchment Region including salt production and associated shipping[23]; nitrification from increasing urban and new agricultural activities[9].</td></tr>
<tr><td>Human pulses</td><td>Seasonality in tourists and recreational fishing[23].</td></tr>
<tr><td colspan="2">Ecological impacts and trajectory</td><td>Marine heatwaves affected the slow-growing late-successional P. australis and A. antarctica species, which could take decades to recover[25]. The effects were felt throughout the Shark Bay ecosystem[9,15]. Continued global warming will most probably increase the magnitude of extreme ‘Ningaloo Niño’ and extreme flood events[22].

Bottom-up and top-down processes regulate recovery. For example, loss of seagrasses can cause release of sediments and nutrients into the water column, which encourage phytoplankton blooms and further reduce water clarity forming a negative feedback loop for seagrass recovery[4]. Herbivory and bioturbation can also impede recovery[4,26].

Seagrass loss increases the exposure of organic matter in sediment. This leads to 2–4 times higher remineralization of sediment carbon relative to intact beds, and the release of millions of tons of carbon dioxide (CO_2) into the atmosphere[8].

The rapid expansion of early-successional seagrasses such as H. uninervis, a principal food of dugongs, may allow for the future return of emigrated dugongs. The survival and reproduction rates of bottlenose dolphins were greatly reduced following the marine</td></tr>
</table>

	heatwave [27]. Some commercially important invertebrate species have recovered to pre-marine heatwave catch rates[16].
Time to detection of impact	Immediate reduction in leaf biomass (continuing for several months), followed by a longer-term reduction (over several years) in belowground biomass[11]. Rapid reduction in invertebrate recruitment[16]. Estimated carbon loss occurred over several years and will continue for decades[4].
Collapse profiles	SMOOTH — decadal changes in seagrass community composition[9] ABRUPT — very rapid changes following extreme marine heatwaves and tropical storms[13]
Social and economic consequences	Shark Bay is now rated as "high" on the climate change vulnerability index for World Heritage sites[19]. Consequences include the loss of nursery and feeding grounds for marine species, including commercial and recreational fish species and dugongs. Commercial fisheries were closed for 3–5 years following the 2010/11 marine heatwave [16]. In the long-term, water temperatures as well as the frequency of marine heatwave are expected to increase; this will severely limit the time populations need to recover[16].
Current mitigation and challenges	*Current:* on-land conservation and agricultural management practices are in place to improve rangeland condition and increase vegetation cover. The site is listed as a World Heritage Area[5]; marine parks, with specified reserves and management areas[28], as well as quota managed fisheries and industry-managed actions, are also in place[24]. *Challenges:* the management of local pressures requires regulation of commercial and recreational fishing and protection of spawning stocks; continued improvement of catchment practices (including the release of new land for horticultural development) that reduce sediment and nutrient runoff, and damage from flooding; and controlling vessel activities and tourism. These management efforts will be assisted by improved understanding of the impact of heatwaves on species of commercial interest, improved stock management, and improved understanding of relative contribution of climate pressures (heatwaves in summer, warming winter temperatures due to global warming).
Potential actions	AVOID: establish seagrass-friendly moorings to reduce anchoring disturbance[30]; global climate action. RESTORE: improve land catchment management including the restoration of inland topsoil, vegetation cover and destocking. Incorporate Indigenous knowledge of restoration using seeds and viviparous seedlings[29]. Remove seagrass detritus after acute disturbances to enhance recovery[8]. Seed seagrasses. RENOVATE: provide anchoring points near donor meadows[31]. Identify stress-resistant genotypes to support assisted colonisation from other sites[32]. Develop early intervention with regard to fisheries management. Consider the practicality of seagrass transplantation[33].
Global context	Blue carbon ecosystems (seagrasses, mangroves and tidal marshes) act globally as sink for 0.08–0.22 Pg per year or 0.6–2.0% of anthropogenic CO_2 [34]. Blue carbon ecosystems are in decline worldwide from coastal development, declining water quality, erosion and fishing pressure[35]. Marine climatic changes, such as the global increase in frequency of marine heatwaves, exacerbate these threats.

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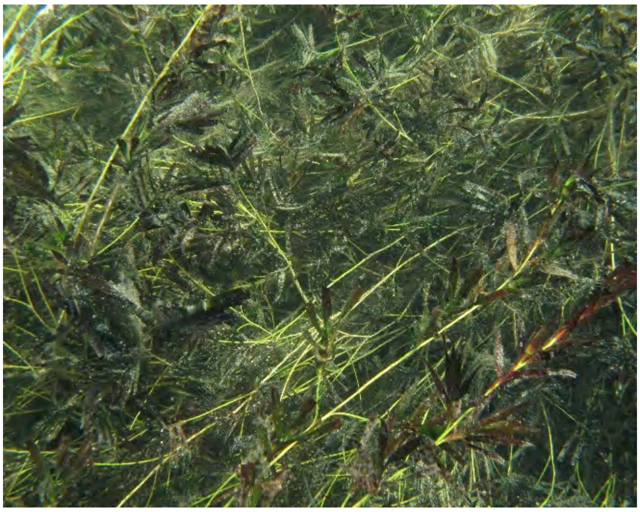
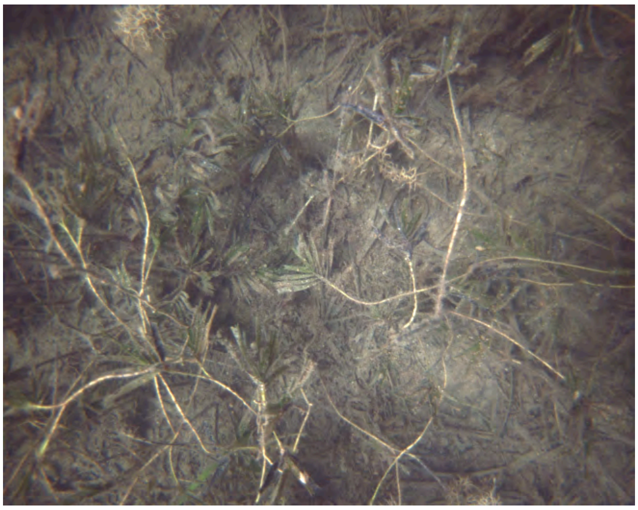
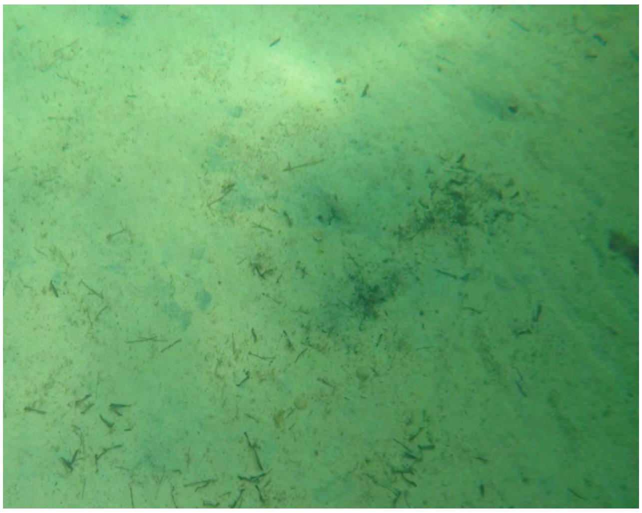
Images clockwise L–R: Sequence of loss of seagrasses in the Gladstone area, Western Australia. May 2010 (healthy), June 2012 (collapsing), March 2018 (collapsed). (Images: Simone Strydom)







Ecosystem	9. Murray Darling River Basin — waterways, New South Wales, Victoria and South Australia (24–37°S)
Biome	Freshwater: rivers, watercourses and wetlands
Action	**Avoid, Recover, Restore**
Baseline state	The Murray Darling River Basin (MDRB) is Australia's largest river system with 23 river valleys and >77,000 km of watercourses. With an area of 1 million km^2 it is also the largest catchment area in Australia[1]. The Murray-Darling river system has highly variable average annual inflows (6,740–117,900 Gl per year with an average of 32,800 Gl per year)[1]. The MDRB comprises >30,000 wetlands — among them 400 high value wetlands in Victoria alone — home to 46 species of native fish[2], and 120 species of waterbirds[3]. There are currently 16 Ramsar-registered wetlands in the MDRB[1]. The MDRB was a modestly modified river system with low-level presses and intensive pulses (cultural gathering) due to activities of local Indigenous people for at least 45,000 years[4]. Pulses included the extraction and harvesting of plant, fish and invertebrate resources and some river modifications (e.g., rocky fish traps and diversions). However, historically impact was low due to the low human population.
Current state and nature of collapse or shift	After 1830, European settlement initiated significant changes to the river system, and by now it is a highly regulated[,6]. In the late 19th century, when irrigated agriculture commenced, steps were undertaken to control river flow with the construction of weirs on tributaries to the Murray river. Flow regulation intensified from 1920 to 1940, and dams were constructed after 1950 as irrigation expanded. The biological and physical river environment was affected by the ~56% reduction in the mean annual discharge of the river system, as well as by erosion of channels, salinisation, sediment deposition and decreases in the populations of native animals and plants[7]. The pancontinental, decadal megadrought (Australian Federation Drought 1891–1903) affected at least 36% of Australia. In the Murray-Darling Basin, the annual inflow was reduced to 5,400 Gl per year and led to major fish kills, for example, in the Darling River in western NSW[8]. Nowadays, the condition of the rivers is overall poor[9]. Stream flows have declined over 40% since the mid-1990s, and in some catchments across central and Western Victoria stream flows have declined >70%[10]. Rainfall overall has reduced. In addition, annual inflow is reduced by 15% when temperature rises 1° C above the mean, even when rainfall remains unaltered[11]. In addition, the MDRB experienced severe droughts in 2001–2009, 2017–2019 and the summer of 2018/19, which was Australia's warmest and driest on record[12]. The most recent drought is considered to have been the worst in 120 years with regard to total rainfall and run off into dams and left many dam levels below 50% capacity, and some near empty[13]. Fish kills occur frequently with varying degrees of fish loss in the MDR system. Native fish populations are only 10% of pre-European numbers[14]. Since 1960 there have been 20 events with mortalities of 10,000 fish or more in the MDRB, including three events with >100,000 deaths (1998, 2004 and 2011), and four events with ~1 million deaths (1990, 2004, 2011 and 2018/2019)[15,16]. In early 2003, the entire fish population perished in 70 km of the Ovens River (Victoria). Rains following bushfires deposited sediment (up to 3.3% solids) into the river. From October 2003 to February 2004, overall fish numbers in the Gouldburn River decreased by 71% along as stretch of ~15 km of river; probably causes were a change in water temperature when water was released, and influx of herbicides[17]. In 2010/11, due to several flood events the levels of dissolved organic carbon increased leading to a reduction in dissolved O_2. In the 2018/19 summer, millions of fish died in the Darling River near the town of Menindee in four separate events. This event included substantial mortality of 20–100 year old threatened Murray cod (*Maccullochella peelii*)[15] and was the result of insufficient river flow in part due to drought, but more importantly to unsustainable water diversion for irrigation in the upstream areas[16,18]. Lack of water combining with extreme temperature variations led to poor water quality, algal blooms and hypoxia in the river[16]. Fish populations do not always recover from severe events[17]. Greatly reduced water flow during droughts also results in severe impacts at the mouth of the Murray River including extreme salinisation of the Coorong lagoon system[19]. Furthermore, post-drought flooding caused extensive hypoxic blackwater events such as in 2010/11 when ~1,800 km of the Murray River channel was affected[20].

Current state and nature of collapse or shift (cont.)		By 2001, 95% of the river had been degraded and 30% substantially modified[21]. Currently, about 3.6 million town and urban residents and ~40,000 non-irrigated farms rely on the MDRB for drinking water for humans and livestock[1]. In Victoria, substantive impacts began in the 1890s, associated with irrigation practices including the removal of structures to enhance ship traffic. Impacts expanded to other states after the Second World War. The progressive construction of 14 weirs and locks is regulating river flow and water usage[6,22]. Since 1970, most of the MDRB has been warming at a rate of 0.2–0.4° C per decade, compared to the national average of 0.15° C per decade, and 9 of the 10 hottest years in the region have occurred since 2005[22]. Introduced European carp (*Cyprinus carpio*) comprises about 90% of the current fish biomass. Carp modify the river ecosystem by stirring up mud that reduces light levels, photosynthesis, and species composition[17]. Water pumps inadvertently suck fish (100–12,000 fish per day) through onto agricultural land equating to millions of lost fish per year in the MDRB. In addition, weirs and dams restrict the migration of native fish and other fauna[14]. Low water flows, combined with high temperatures and barriers that restrict downstream flows have promoted repeated outbreaks of toxic cyanobacteria that in some years have contaminated >2,000 km of the Murray River[23,24]. In the 2019/20 summer, bushfires devastated parts of the Murray-Darling system, including the upper Murray catchment area in NSW. Once it rained, burned vegetation could no longer stop the runoff of mud and ash that were washed into waterways. The water quality deteriorated rapidly, depleting oxygen levels and causing hundreds of thousands of fish to die. Mannus Creek near the Snowy Mountains was home to the endangered Macquarie perch (*Macquaria australasica*), a freshwater fish native to the Murray-Darling river system. Ten fish were rescued before a deluge of sludge filled the creek. Since recovery of their natural habitat is likely to take decades (provided no further adverse impacts occur), on-ground interventions are urgently required[25] (Conversation 13 July 2020).
Pressures	**Global climate change presses**	Reductions in cool-season rainfall and river flow across the system and drought; long-term drying and warming conditions, with extreme fluctuations in river temperatures; sea level rise combined with low flows leading to seawater incursion at river mouth affecting Coorong wetlands and Lower Lakes[19,26,27].
	Global climate change pulses	Heatwaves, flooding.
	Human presses	Fragmentation of river habitat through canalisation and long-term alteration in riverine hydrology; modification and degradation of habitat; snag removal to enable vessel traffic; riverbank erosion, and increased salinity. Threats to fish include recreational and commercial fishing pressure on depleted stocks, illegal fishing and the loss of fish stocks from irrigation pumps, increased suspended sediment loads, introduction of non-native fish. Alteration and loss of water flow due to agricultural and urban water diversion; modified seasonal timing of water release; overall reduction of water flow. Increasing water extraction in conjunction with reductions in rainfall are leading to low or no flows in part of the river system; prioritisation of human water uses (agriculture and urban livelihoods) over environmental requirements during drought events
	Human pulses	Agricultural runoff of nutrients. Pulsed cold water releases impact fish and other species, leading to poor recruitment and persistence. Water diversion and reduction in environmental water during drought conditions contribute to sharp pulses such as mass deaths of species.
Ecological impacts and trajectory		The Murray Darling river ecosystem is increasingly non-functional with decreasing freshwater biodiversity (fish and invertebrates), decreased recruitment and loss of ecosystem services and cultural values[26]. The Proposed Basin Plan released in 2011 set a target of 2,750 Gl of environmental surface water recovery. The diversion of the water from irrigation back into the environment was estimated to cost $542 million annually; however, the additional water added $3–8 billion worth of ecosystem services to the entire basin[28]. Fish kills incur costs of tens or hundreds of thousands of dollars in clean-up, losses in fisheries income, and restocking costs. To replace lost fish stocks, such as Murray Cod in the Goldburn river, would cost $1.2–1.7 million dollars with an 80% chance that the population would be replaced in 29–34 years and no adult fish were taken (i.e. fishery closure), as the recovery time would increase[17]. Restocking the Darling river with fingerlings (50,000 per year for up to 40 years) would have a recovery period of up to 52

	years at a cost of $1.2 million per year[17]. The Macquarie perch will be lost if the rescued fish do not survive in captivity or their natural habitat is not/ cannot be restored.
Time to detection of impact	Realised impacts are apparent each year and season, especially during drought cycles. There have been rapid responses by food webs to the loss or gain in environmental water.
Collapse profile	SMOOTH — regional, e.g., long-term warming, drought and reduced rainfall[11] STEPPED — regional, e.g., construction of locks and weirs[7] ABRUPT — local, e.g., from heatwaves FLUCTUATING — local, e.g., massfish deaths (e.g., Menindee Lakes)[16]
Social and economic consequences	At a cost of $13 billion, the Murray Darling Basin Plan (2012) was to balance extractive and environmental water requirements[29]. In 2017–18, ~$2.7 billion was spent on water buy-backs for the environment (~1,200 Gl of the committed 2,750 Gl) and $3.9 billion was spent on improvements to the water infrastructure[28]. Other social and economic consequences include the loss of ecosystem functions of rivers and wetlands (e.g., hydrological regulation and nutrient cycling), reduced aesthetic value, diminished water quality and decreases in endemic fish species (including culturally significant and recreationally valued fish)[30]. In February to July 2019, shortages of potable water occurred in some MDRB towns while dams at the upper reaches of the system contained water used for the irrigation of water-intensive crops[1] Recreational fishing in the Murray-Darling river system is worth ~1.35 billion per year[31].
Current mitigation and challenges	*Current mitigation:* in 2006/07, the MDRB Salinity Management scheme removed 470,000t of salt from the water[32]. Other mitigation strategies include the breeding and release of native fish, eradication projects targeting non-native fish and the regulation of weir water release to maintain O_2 levels above critical levels for fish and the installation of aerators[1,27]. To restore vital fish habitat, parts of the Murray river have been resnagged (reintroducing dead tree trunks), for example, between the Hume Dam and Yarrawonga Weir (~237 km distance)[33]. The NSW Rivers Environment Restoration Program[33], established in 2007 and ending in 2011, received $181.12 million from the NSW and Federal governments. For $147.2 million (80% of budget), water access licenses were bought equivalent to 108,000 Ml for wetlands application. Four properties covering 14,000 ha with wetlands of high conservation value were also purchased. Community engagement, restoration of fish passages, remediation of water pollution and many other activities were also undertaken[34]. In August 2019, State and Federal governments committed to an independent Inspector-General to oversee the Murray Darling Basin plan, including examination for water theft[35]. *Challenges:* there are considerable jurisdictional tensions in the management of the MDRB as responsibility for management covers four state legislatures but is also the subject of federal policy[6]. Other challenges include delays in the implementation of water resource plans, inadequate water distribution for environmental and extractive purposes and ineffective enforcement and compliance. Water levels in the Darling system have been insufficient to avoid a catastrophic decline of condition through dry periods. Balancing environmental needs of river flow with demands for water for human consumption, especially in times of drought, and ensuring substantial increases and consistency in water flow is critical[27]. Preparation for the potential impacts of a megadrought should be considered. Commitment for water buy-backs for the environment was scaled back from 2,750 Gl to 2,075 Gl in 2018[29]. There is no clear responsibility or coordinated funding for managing the introduced carp. Improved management of riparian vegetation is needed to avoid costly and labour intensive resnagging activities[33].
Potential actions	AVOID: reduce regional permanent plantings of highly water dependant crops (e.g., almonds); global climate action. RECOVER: increase environmental water flow and restoration of rocky rubble and snags (dead tree trunks) in waterways for fish habitat[33]. RESTORE: restock fish populations (needs to occur for many years while fisheries remain closed)[17]; maintain free-flowing freshwater ecosystems to ensure continuation of ecological processes and enhance ecological resilience; fully implement the *2003 Native Fish Strategy*[14,36], including the installation of fish ways to allow fish migration, installation of carp separation cages to support native fish communities[17], and the installation of fish hotels for spawning habitats and declaration of strategically located

	protected areas[27]. Provide independent oversight of basin management, insure sufficient environmental water flow, and restore the Menindee Lakes.
Global context	In arid and semi-arid regions, substantial ecosystem losses and reduction in water quality can occur when >50% of the mean annual river flow is extracted[37]. Globally, 64–71% of wetlands have been lost or degraded and there is a continuing decline in the quantity and quality of wetlands and rivers. Many examples of water management issues with dammed rivers exist, including the shrinking of the Aral Sea, impact on Indigenous peoples (e.g., Amazon), and biodiversity (e.g., Mekong River)[38,39].

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Images: Healthy river red gum, Murray River, Calperum Station. (Images: S. M. Prober)

Images L–R: Weir with logs laid onto the channel, Perricoota. (Images: S. M. Prober). Dry riverbed with dead sheep, 2018/19 summer, Darling River near Louth, South Australia. (Image: A. Dielenberg - Flickr)

Ecosystem	**10. Murray-Darling River Basin — riverine**, New South Wales, Victoria and South Australia (24–37°S)
Biome	Riverine: temperate forests and woodlands
Action	**Avoid, Restore, Renovate, Adapt**
Baseline state	The large and diverse system of the Murray Darling River Basin covers 1.07 million km^2 or ~14% of Australia's land area[1]. The complex basin comprises low-lying undulating areas, extensive plains and parts of the Great Dividing Range. There are 40,000 km of major rivers plus ~400,000 of small rivers and tributaries that carry on average 35,000 Gl each year, 30,000 wetlands (of which 16 are Ramsar-listed), and floodplains with riparian open forests and woodlands. The basin is one of the flattest water catchment regions globally[2]. It is also Australia's most important water catchment; ~55% of Australia's water use occurs here mainly in agriculture, and 86% of water used in the basin comes from surface water[3]. The long-term (1900–2016) average rainfall in the basin is 469 mm p.a. but varies from <200 mm in certain south-western areas to >1,200 mm in the south-east[4]. Forests cover 106 million ha of the basin[5]. Australia's largest forest of river red gums (*Eucalyptus camaldulensis*) occurs on the floodplains of the Murray River and covers 166,000 ha. Trees grow up to 45 m tall and live up to 1,000 years, and dominate floodplain forests[2]. River red gums are keystone species associated with the health of wetlands. Gums have deep sinker roots with high rates of water uptake and are dependent on frequent flooding (approximately once every three years) for growth, germination and sapling survival[6]. Floodplain and riparian vegetation provides corridors and habitat for millions of mammals, birds, fish and other animals; 120 species of waterbird and 46 species of native fish inhabit the region[2]. The basin is also home to 46 aboriginal nations and has at least 10,000 culturally significant places[2,3]. More than 2.25 million people occupy the Murray-Darling Basin[7].
Current state and nature of collapse or shift	Over the last 200 years, much of the Murray-Darling Basin has been substantially altered at various scales through human activities. Major transformations include the construction of weirs, irrigation channels, farm dams and municipal water reservoirs, all of which affected the natural water flow of streams and rivers as well as the region's hydrology. The federation drought (1895–1902) accelerated the construction of large water storages[8]. The highly diverse ecosystems of the floodplains of the Murray-Darling Basin have been intensely modified for agricultural use. More than 85% of the 90 million ha of agricultural land is used for grazing (both native and modified pastures). A further 15% of land supports dryland cropping and horticulture, and ~3% are used for irrigated agriculture; the latter has the highest water use[9]. Cereal crops and fodder have largely replaced native vegetation[8]. Agriculture extracts ~1.8 million Ml of groundwater from a number of large aquifers[3]. Across three of the four states responsible for the management of the Basin, new horticultural irrigation projects are developing while, in some regions the irrigated areas are reducing. However, this reduction is at least in part due to changes in water trade and recovery and not due to official retirement of irrigation permissions[10]. Increasing irrigated agriculture led to a rise in soil salinity, affecting crop yields[11]. The combination of widespread clearing of native vegetation and the installation of irrigation systems allowed the highly saline groundwater to reach the land surface and rivers. Once considered the most environmentally and economically challenging issue for the Murray-Darling Basin, soil and water salinity has been actively managed since the mid-1980s. The basin state and the Commonwealth governments cooperatively tackled the issue by implementing three salinity management strategies, and currently the problem appears to be largely under control. However, as conditions in the basin are becoming hotter and drier, it is yet unclear how salinity may be affected[9]. The remaining floodplains in the Murray-Darling Basin are patchy and vary in size; collectively they cover about 1000 km^2. They naturally flooded for up to two months per year; now floods typically only last a few days and occur in late summer rather than in spring. Large floods are expected to become less frequent as the climate changes[12]. While parts of the plant communities appear to be relatively resilient to drought[13], the consequences for waterbirds and other biota are expected to be catastrophic if water usage for agriculture and human consumption does not change[14]. The region experienced a mega-drought ('millennium drought') from 1997 to 2010, the

Current state and nature of collapse or shift (cont.)		longest drought on record. The most extreme period lasted from 2006 to 2009; the lowest ever flows were recorded in 2006[15]. The extent of woodlands and forests has been greatly reduced through agricultural clearing and native forest logging; in Victoria and New South Wales about 60% and 68% of the historical extent of floodplain forests remained in ~2010. However, in some areas of Victoria sawlog extractions were 43% above the estimated productivity after tree growth slowed by up to 40% post-1996[16]. Changed water regimes from unregulated to regulated flows have affected riparian river red gum forests through the reduction of flooding in late winter and spring. By the 1990s, hydrological changes had caused major deterioration in riparian communities, reduced tree growth rate, reduced flowering, accelerated mortality, inhibited regeneration and increased susceptibility to herbivory (e.g., by the leaf-skeletonising moth)[6]. By 2008, mapping of the river red gum stands on the Murray River over 1,600 km indicated only 30% of stands were in good condition[17]. In the Macquarie Marshes, 44% of river red gums were lost from 1993 to 2011. Severe droughts occurred in 2003–2009 and 2017–2019[18]. Willows (*Salix* spp.) were introduced to Australia in the 1800s for a variety of purposes. They are now abundant along creeks and river systems, in floodplains and stream banks and beds where they compete with red river gums. Due to the extensive spread of willow trees water availability is reduced[19]. Willows are listed as a 'weed of national significance' in Australia[20]. Deterioration of riparian vegetation has led to flow–on impacts on dependent fauna and changes to understorey composition. From 1995 to 2008, the populations of woodland birds had collapsed; 84 of 128 (66%) woodland bird species declined in occurrence and abundance in reserves and agricultural landscapes along the Murray River (Victoria)[21]. The degradation of wetlands (including Ramsar sites) and alterations of flow and flood regimes reduce habitat and hamper the breeding ability of water birds such as the straw-necked ibis (*Threskiornis spinicollis*)[22]. Damage from wave action of recreational boats has eroded banks[23]. Additional impacts have resulted from changed fire regimes, and non-native vertebrates.
Pressures	**Global climate change presses**	Extension and shift in timing of dry season; increasing air temperatures. Droughts
	Global climate change pulses	Heatwaves, fire.
	Human presses	Land use change for agriculture; clearing of riparian woodland and forests; timber harvesting. Diversion of water, lack of environmental watering in some seasons. Excessive water extraction for agriculture and human consumption (see #9) has led to long-term changes in riverine hydrology and dryland salinisation; grazing in riparian areas; introduced species (willow)[14].
	Human pulses	Unknown.
Ecological impacts and trajectory		Reduction in forest canopy, tree mortality; reduced river flow and groundwater levels (extraction) in combination with declining rainfall and increasing temperatures; loss and degradation of habitat; decreased bird and mammal abundance; lack of tree recruitment. Ecological stratification (red gums replaced by other spp.) as regular flooding levels recede. Reduced water flow shifts wetlands to woodland and forest communities resulting in loss of wetland flora and fauna wetlands, including 16 Ramsar sites. Many waterbirds commence breeding when river flows reach a certain volume as the availability of food and nesting materials depend on it. For example, the Narran Lakes in NSW, a Ramsar wetland, support 46 breeding species of waterbirds, including the largest population of straw-necked ibises (*Threskiornis spinicollis*) in Australia[22]. These ibises only breed after large river flows (>154 Gl in 90 days). Since water resources have been developed for commercial purposes and reduction of large river flows, the frequency of breeding events decreased by 170%, i.e. the birds bred only in 1 of 11.4 years compared to 1 in 4.2 years prior to water development. Despite restoration efforts, the breeding frequency is still only about 59% of the predevelopment frequency[22].
Time to detection of impact		Decades
Collapse profile		SMOOTH — regional, e.g., soil salinisation[15] STEPPED — regional, e.g., logging and clearing[16] ABRUPT — local, e.g., drought[18]

Social and economic consequences	Some 9,200 irrigated agricultural businesses are located in the Murray Darling Basin. This is a highly productive agricultural area where food worth \$22 billion is produced annually. Tourism contributes some \$8 billion each year[2]. Towards the end of the longest drought on record (1997–2010), the Australian Government launched a \$10 billion plan to invest in water efficient infrastructure and to ensure sustainable water use[13]. Since early 2017, ongoing rainfall deficiencies have affected large areas in south-eastern Australia, and are particularly severe in the northern and western Murray-Darling Basin[24]. Due to the long running dry period, farm production has continue to decline. It decreased ~12% from 2016/17 to 2018/19, and a further 5% drop was expected in 2019/20. Rural exports declined about 18% since early 2017, and for the first time since 2007, Australia had to import certain grains. Farm profits fell by about 30%, and the cost of bread and other cereal products, and milk has increased[25]. In addition to the effects of drought, bushfires claimed many homes, business assets and infrastructure. Rural exports, tourism and consumer spending are reduced. Meat exports have increased but due to higher slaughter rates, the size of herds has declined significantly[25]. Reduced aesthetic value, loss of pollination services, water quality and timber resources and reduced erosion control and carbon storage are occurring.
Current mitigation and challenges	*Current mitigation:* More than 100 parks and reserves covering >2,550 km^2; willow control and strategic release of water to key waterways and wetlands. Monitoring program for water quality and salinity, and salt interception schemes[2]. Riverine Recovery Project (\$98 million State Priority Project, South Australia) to restore wetlands[26]. Murray-Darling Basin Salinity Management Strategy[27]. The artificial Lake Mokoan (fifth largest water storage in Victoria) with a 365,000 Ml holding capacity was decommissioned and parts of the dam embankment were removed[28]. In its place is now an 8,750 ha wetland, Winton Wetlands Reserve, on its way to recover its former wetland condition[29]. A number of riverbank restoration projects are underway with the goal to improve resilience of the riparian habitats to disruptions, and increase biodiversity. Activities include removal of weeds (e.g., willows) and planting of native shrubs such as river sheoaks (*Casuarina cunninghamiana*)[30]. *Challenges:* same as in case study #9. Areas risk becoming functionally extinct due to continued clearing and landscape modification for agricultural cultivation. The long-term trend of drying and increased fire risk raises the challenge of rural communities to recover[25].
Potential actions	AVOID: avoid loss of remaining values, identify and protect areas relatively resilient to climate change; plan at landscape level[31]. Global climate action. RESTORE: restore natural flows by increasing allocation of environmental water; maintain appropriate fire regimes; reduce grazing pressure — destocking of rural properties (may lead to ecological recovery with time)[8]; implement weed and predator control. Restore habitat, e.g., by removing hard engineering structures[31]. RENOVATE: introduce suitable new species more resilient to climate change (e.g., river coobar (*Acacia stenophylla*)[2]; introduce genetically modified species ADAPT: shade stream habitats; translocate species (e.g., red river gum) to areas with suitable soil and hydrology[32].
Global context	Floodplains extend over >2 million km^2 globally. They are highly productive and diverse ecosystems. For these reasons, they are used extensively for human purposes. Consequently, they have become one of the most threatened ecosystems on Earth due to habitat alteration, control of flood and flow, introduction of invasive species and pollution. Their freshwater biodiversity is declining quickly. Up to 90% of floodplains in North America and Europe are already functionally extinct due to agricultural cultivation. As the human population increases, further degradation of riparian areas is expected due to changes in their hydrology, increased pollution and increased non-native species invasions[10].

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Image: Dead river red gums (*Eucalyptus camaldulensis*), Murray River, Berri, South Australia. (Image: denisbin_Flikr)

Images clockwise from left top: Healthy river red gum (*Eucalyptus camaldulensis*) floodplain forest during a flood event (Perricoota State Forest, NSW), black box (*E. largiflorens*) floodplain woodland with lignum (*Duma florulenta*) understorey (Jerilderie, NSW), dieback affected floodplain eucalypt woodland (Koondrook State Forest, NSW), logging affected *E. camaldulensis* forest (Koondrook State Forest, NSW). (Images: S. M. Prober)

Ecosystem	**11. Montane and Sub-alpine Forests,** New South Wales and the Victorian highlands (27–38°S)
Biome	Temperate broadleaf forests
Action	**Avoid, Restore, Renovate**
Baseline state	The montane zone (900–1,500 m a.s.l.) of the Australian Alps experiences relatively high precipitation (>1,200 mm), and Eucalypt forests tend to be tall, dense and wet; ferns, herbs and small trees make up the understorey. Deep soils are the result of high rates of organic breakdown. Many *Eucalyptus* trees have evolved a range of strategies that enable them to regenerate after fires, storms, drought and extensive defoliation by insects. These include resprouting from buds or lignotubers, or from seed if the whole tree died, or a combination of regenerative strategies[1]. In south-eastern Australia, the tall montane forests are dominated by the alpine ash (*Eucalyptus delegatensis*), the tallest eucalypt in the Australian Alps that can grow up to 80 m. The species is an obligate re-seeder and a large proportion of the population requires 15–20 years to mature to flowering stage and fruit without fire[2]. Alpine ash is very sensitive to fires and relies on the seed banks of mature trees to regenerate. At an elevation of >1,400 m a.s.l., the tall forests are replaced by low-growing, open sub-alpine broadleaf forests with moist understoreys comprising grasses and herbs or low-growing shrubs. These extend to about to about 1,900 m a.s.l. Temperatures are low throughout the year and precipitation often falls as snow and ice. The snow gum (*E. pauciflora sensu lato*) is the dominant species, the only tree at these altitudes, although growing as a krummholz or shrub-like form at the highest altitudes[3]. Snow gums grow lignotubers from which they regenerate after fires; they can also regenerate from seed[4]. In Victoria, alpine ash covers a total of 459,391 ha of which 121,228 ha occur in nature reserves; this comprises about one third of the state's nature conservation reserves[5,6].
Current state and nature of collapse or shift	Since the early to mid-1890s, four major droughts affected south-eastern Australia: the Federation Drought (~1895–1902), drought from ~1937–1945, the 'Big Dry' (1997–2010)[7], and the drought from 2017–2020 when conditions changed rapidly from wet (December 2017) to dry (January 2018) despite above average rainfall in November 2017[8]. Cumulative effects of warming (air temperature increase of 0.2° C per decade)[9], and drying conditions[10] are increasing stress in ecosystem elements. The drier landscape allows for larger fires[11], and the increased incidence of dry lightning[12] results in more widespread ignitions[13]. The alpine ash requires fire to form even-aged stands. Fire frequency has increased. Intense fires kill many mature trees, but they also release seed stored in the canopy from where it is released after the canopy burns[14]. Thus, after a fire regrowth can be abundant provided the seedlings are not exposed to further fires. If a fire burns the before the seedlings are mature, the seed bank is not replenished. In an area of post-fire regrowth, the density of young trees was 97% lower after a second fire[15]. Thus, increased fire frequency has outpaced maturation in some areas. From 2000 to 2019, ~84% of the entire alpine ash forests in NSW and Victoria were burned[15]. Some areas were burned three times (2003, 2006/07 and 2009) in less than a decade[16]. Unprecedented lightning-ignited fires in 2003, and 2007, followed by human ignitions in 2009 burned >87% of alpine ash forests in Victoria alone[14]; some of the areas burned again in 2013. Thus, large areas of the Australian Alps were burned two or three times in a decade[15]. The 2019/20 fire season again saw another 20% of alpine ash burned[17]. These multiple fires in quick succession resulted in the population collapse of these keystone species due to insufficient recovery time between events[14]. In some areas, shrub-land has replaced the ecosystem[15,16]. The combination of increases in air temperatures, extreme fire weather and fire frequency is preventing saplings from maturing. A positive feedback to fire has developed where regenerating alpine ash stands are eight times more likely to burn than mature stands and patches, and regenerating snow gums more than twice as likely to burn as mature stands[18]. In addition, high temperatures have reduced the growth rate of mature trees[19], and recent and current drought curtails seed production in alpine ash forests. Alpine ash that has been burned within the preceding 20 years is therefore vulnerable at two levels — trees regrowing from seed have not reached maturity, and the forest is far more likely to burn[17]. Analysis of NSW and Victorian National Parks departmental fire records[20,21] shows that from 1980–2000, 21–29% of alpine ash distribution consisted of immature trees. From 2000–2020, this area has increased lineally to 70%.

Current state and nature of collapse or shift (cont.)		For snow gums, increasing fire frequency (e.g., three fires in a decade) has probably led to the depletion of buds of the lignotubers[4]. Consecutive high intensity fires in ~ a decade prevent snow gum trunks from resprouting and can also change the vegetation composition of understorey species (from shrubs to grasses)[4]. In February 2009, one of the most severe bushfire on record in Australia occurred due to an extreme heatwave and >100 km h^{-1} winds. The average intensity at the fire line was up to 88,000 kW m^{-1} and 0.5 million km^2 were burned[22]. Altered fire management has increased the frequency of planned burns as part of forest management in subalpine and surrounding forests[13], and thereby changed the landscape flammability[18]. Increased fire frequency has changed the canopy structure and understorey[23]. Analyses of NSW and Victorian National Parks departmental fire records[20,21] show that from 1980–2000, 39–45% of snow gum communities were in their most flammable age range. From 2000–2020, this area has this has doubled to 75–83%. Impacts on humic soils include the loss of organic soil horizons due to more frequent erosion following high-intensity fires[24]. Vegetation communities and montane to subalpine fauna already under threat face added pressures from overgrazing, non-native plant invasions, trampling, wallowing and erosion, through the combined impacts of non-native grazers (e.g., horses)[25,26]. For >100 years, management of some sub-alpine areas included clear felling and burning of stands for sheep and cattle grazing[13]. Deliberate, regular burning of natural grasses eliminated plant species unpalatable to livestock. Managed burns occurred across the warmer months, but lightning strikes caused natural fires in summer[13]. Clear-fell logging has removed many old trees resulting in over- and understorey of similar age[27]. Grazing sheep limited the regeneration of snow gums from seed, and areas where sheep grazing ceased showed high rates of germination and seedling establishment[24].
Pressures	**Global climate change presses**	Increasing temperatures particularly in winter[10]; decreased snow depth and duration, and earlier snowmelt[30]. Drought[7,8]; increase in extreme fire weather[28,29];
	Global climate change pulses	Increased fire frequencies, increased lightning storms[12] and more intense heatwaves.
	Human presses	Fragmentation of ecosystem, salvage logging after fires[31]; erosion. Introduction of hard-hoofed animals (e.g., horses and deer)[25,26].
	Human pulses	Escaped forestry silviculture fires, fires from campers and bushwalkers, management fires.
Ecological impacts and trajectory		Further ecosystem collapse with transition to shrub-land is expected[15]. Warmer climate may reduce tree growth[19]. The rate of climatic change is faster than the ecosystem's capacity to move to higher altitudes[9].
Time to detection of impact		Less than a decade
Collapse profile		SMOOTH — regional, e.g., grazing[13] STEPPED — regional, e.g., clearing ABRUPT — local, e.g., multiple fire recurrences[31]
Social and economic consequences		Loss of forest resources and ecosystem services (carbon storage), decrease in tourism.
Current mitigation and challenges		*Current mitigation:* currently there are 11 alpine and subalpine reserves covering 16,532 km^2, and include most of the remaining alpine and subalpine ecosystems in the Australian Capital Territory, New South Wales and Victoria. In addition, the Alpine National Park (Victoria) covers 6,460 km^2. In 2008, this park was added to the Australian National Heritage List. Active restoration and renovation measures include aerial sowing of seed over small areas, thinning of new stands and using *Eucalyptus* species from lower elevations[14]. *Challenges:* droughts affect seedling survival; need to exclude severe fires from alpine ash areas for 20+ years to allow seedlings to reach reproductive maturity. However, germination success rates and seedling establishment remain unknown. Replacement with sprouting eucalypts may be a lesser impact than collapse to shrub-land or grassland, but it

	could still constitute a major form of ecosystem change and result in increased fire likelihood, and consequent increased impact on forest remnants[18].
Potential actions	AVOID: improve protection of remaining unburned mature forest, and targeted burning to protect old growth elements. Eliminate harvesting activities to improve forest ecosystem services, such as habitat provision, carbon sequestration and water yield. Manage fire risk and ant populations. Global climate action. RESTORE: distribute seeds from aircraft, re-sow and thin out burned areas[14]. Control/ eradicate large non-native herbivore populations. RENOVATE: introduce climate-ready provenancing propagation and planting of hybrids with other fire adaptive traits. Early seed-setting population (with six years to maturity) in the northern area[32] has the potential to buffer short-interval fire events.
Global context	Mixed broad-leaf temperate forests are under pressure in western parts of the Indian Himalayas due to the increasing degradation of stands. Canopy disturbance affects recruitment levels and leads to the establishment of non-native herbaceous species[33]. Temperate broadleaf forests in the United States National Park system are highly vulnerable to invasive species, biome shifts, habitat fragmentation and increasing wildfire frequency. Positive fire feedbacks occur in forests globally and there is growing concern that increases in fire frequency are pushing forests into "fire traps", ultimately leading to ecosystem collapse. A particular concern has been that feedbacks are commonly assumed to be negative. However, in cases such as this, feedbacks are positive, and the planned use of more fire as a tool for fire mitigation is likely to increase the fire risk in these ecosystems[4].

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Images clockwise L-R: Healthy alpine ash (*Eucalyptus delegatensis*), Falls Creek, Victoria, May 2019. (Image: D. M. Bergstrom). Fire-killed alpine ash ecosystem from summer fires in 2000, with a regenerated shrub understory. Falls Creek, Victoria, May 2019. (Image: D. M. Bergstrom). Bottom: Burned, dead snowgums (*Eucalyptus pauciflora*) in sub-alpine zone. (Image: P. J. Zylstra).

Ecosystem	**12. Great Southern Reef Kelp Forests**, southern Australia (27–44°S)
Biome	Coastal marine: kelp forests
Action	**Avoid, Recover, Restore, Renovate, Adapt**
Baseline state	The Great Southern Reef comprises a large number of rocky temperate reefs that support kelp forests and extend from Moreton Island near Brisbane (Queensland) around the south coast of Australia and Tasmania, and to ~600 km north of Perth (Kalbarri, Western Australia), covering ~71,000 km^2 along 8,100 km of coast[1]. *Eklonia radiata* is the dominant kelp species of the Great Southern Reef occurring mainly in <30 m water depth, but in some areas it grows at >60 m[1,2]. Giant kelp (*Macrocystis pyrifera*) forests occur in the cool temperate zone of the Great Southern Reef in SE Australia, where individuals can exceed 20–30 m in length[3,4]. Kelp forests thrive in cold, nutrient rich water; they are ecosystem engineers as they influence water flow, light penetration[5], and sedimentation and growth and development of juvenile kelp[6]. Kelp forests also offer structural habitat and support high levels of biodiversity for other seaweeds, sponges, crustaceans, chordates, bryozoans, echinoderms, including abalone (*Haliotis rubra*) and rock-lobster (*Jasus edwardsii*), with many endemic species[1]. Up to 80% of kelp forest can eventually become 'drift' kelp affecting habitats distant from the forest location delivering nutrients to the ocean floor and increasing secondary production elsewhere. Kelp forests also offer important ecosystem services, e.g., they act as carbon sinks, support valuable fisheries, and ameliorate effects of wave energy on the shoreline[1].
Current state and nature of collapse or shift	Overall the range of habitat-forming kelps has contracted with widespread region-specific declines in biomass and cover. Giant kelp forests are currently listed as endangered under the *Environmental Protection Biodiversity and Conservation Act 1999.* In eastern Tasmania, the ocean is warming at ~4 times the global average because of increased influence of warm and nutrient-depleted water of the East Australian Current. Increased frequency and size of eddies of the current propagate southwards, transporting heat and larvae[7,8]. These warm nutrient-poor waters have been associated with major losses (>95%) of giant kelp (*Macrocystis pyrifera*) in eastern Tasmania[8], and incursion of the long-spined sea urchin (*Centrostephanus rodgersii*) from New South Wales[9]. The urchin overgrazes kelp forests (mostly *Ecklonia* beds), resulting in bare seafloor or 'urchin barrens' largely devoid of kelps and other seaweed, leading to local collapse of production, fisheries, and biodiversity[8,10,11]. Overfishing of large lobsters, the primary predators of this urchin in Tasmania, permitted urchin populations to expand to the point of destructive grazing[12]. *Centrostephanus* barrens are now a feature of ~9% of eastern Tasmanian reefs (between Eddystone Point and Tasman Island)[8]. Approximately 50% of inshore reefs of southern NSW, eastern Victoria, and several of the Bass Straight islands area characterised as *Centrostephanus* barrens devoid of kelp[8,13]. Overfishing of urchin predators again is likely to have contributed to this situation[8,9]. Around Sydney, NSW, intense coastal development and localised pollution have caused the total loss of some kelp species[14,15], while at the offshore Solitary Islands southerly range shifts of tropical herbivorous fish have devastated kelps and caused a shift to dominance by seaweed turfs[16]. In Melbourne's Port Phillip Bay, Victoria, *Ecklonia* beds have largely been lost from the northern and north-eastern reefs and replaced by algal turfs or sea urchin (*Heliocidaris erythrogramma*) barrens; urchins and nutrient loading are key drivers of the transition[17]. Off Adelaide, South Australia, declining water quality and increasing nutrient levels have led to replacement of kelp beds with algal turfs[18]. Western Australian waters temperate kelp bed experienced 40 years of background warming. Then in 2011, an extreme heat wave driven by a strong La Niña event, delivered summer temperatures 2–4° C above average. The temperatures exceeded the thermal tolerance of kelp and caused a dramatic loss (43% or ~960 km^2) of *Ecklonia radiata* over ~500 km of coastline[19]. Additional positive sea-surface anomalies occurred in 2012, 2013 and 2019. On northern reefs from Perth to Kalbarri (~100 km of coastline), virtually 100% of kelps was lost and replaced by algal turfs, *Sargassum* spp. and corals. Post-heatwave, a simultaneous expansion of rabbitfish (*Siganus fuscescens*) populations and incursion of tropical and subtropical fish and invertebrate grazers and scrappers increased grazing rates 400-fold preventing recovery of the kelp[19,20]. Even south of the heatwave impact zone, tropical fish established themselves and reduced the cover of the kelp canopy by nearly

		70% in <5 years. Nine years post-heatwave, there has been minimal recovery[20].
Pressures	**Global climate change presses**	Increasing sea-surface temperatures, ocean acidification, sea urchin expansion, tropicalisation of the fish fauna, decrease of nutrients on the south Australian coast with the southern extension of the East Australian Current.
	Global climate change pulses	Extended large-scale marine heatwaves. Increased storm severity and frequency.
	Human presses	Tourism, commercial and recreational lobster fishing, local nutrient pollution, eutrophication.
	Human pulses	Contamination in stormwater runoff; local damage from anchor chains.
Ecological impacts and trajectory		Extensive mortality of kelp and associated species including fish, lobsters, abalone and coral[8,19]; range extension of grazing tropical fish prevents kelp recovery[21]; warming in south-eastern and western reefs occurring at two to four times the rate of increase in the global average. Two years after the heatwave in 2011, canopy loss on the Western Australian coast was greatest at lower latitudes (up to 100%), with little or no recovery at heavily impacted sites by 2018. Communities now have low genetic diversity[22].
Time to detection of impact		Declines due to local pressures are gradual and occur over many years, but the impacts of marine heatwaves (e.g., in Western Australia in 2011) become apparent within months.
Collapse profile		SMOOTH — regional, e.g., increasing sea temperature leads to regional decrease of areas of dense kelp beds, incursion of warm water species, and changes in community structure[8]. SMOOTH — local, e.g., fishing removes urchin predators leading to urchin overgrazing[8]. ABRUPT — local, e.g., marine heatwaves kill kelp when temperature tolerance is exceeded[16,19].
Social and economic consequences		The Great Southern Reef kelp forests in past have generated at least $10 billion per year in economic and activity[21]. Economic and social consequences include the collapse of the rock lobster, abalone and other fisheries, as well as impacts on Indigenous communities and decreases in tourism[8,23].
Current mitigation and challenges		*Current mitigation:* Many areas are included in marine reserves but this does not provide protection against pressures like large scale warming. Giant kelp forests are listed as an 'endangered community' under the *Environmental Protection Biodiversity and Conservation Act 1999*. In Tasmanian, the Government is attempting to rebuild lobster biomass to increase predation rates on sea urchins; an urchin fishery has also been established. Trials of plant patches of self-sustaining, more heat tolerant kelp off southern Tasmania to restore the forests are underway. *Challenges:* Ongoing coastal urbanisation and associated pollution will continue to increase pressure on near-coastal environments. Low public awareness of the Great Southern Reef kelp forests, their value and the threats they face, and low investment in research and management, continue as major challenges[1]. So far, there is no adequate response to rehabilitate kelp on extensive urchin barrens in deeper water (>20 m) where most of the Tasmanian barrens occur.
Potential actions		AVOID: establish further marine reserves and protected areas. Limit pollution. Global climate action. RECOVER: manage catchment to improve water quality (reduce sediment and nutrient runoff); improve the design of Marine Protected Areas to enhance connectivity; restrict fishing (reduce over-harvesting of lobsters)[24] to increase the resistance of kelp ecosystems by limiting their exposure to multiple stressors, e.g., eutrophication and pollution[12,20,25]. RESTORE: rehabilitate kelp habitat and restore through translocation (assisted migration of warm adapted genotypes[20, 25]. Use robotic control of kelp grazers such as urchins[26]. Harness host-associated microbial defences against pathogens/disease[25]. Harness host-associated microbial defences against pathogens/disease; RENOVATE: implement assisted evolution of strong genotypes and gene editing[23, 25]. Replace species (functional redundancy), e.g., *Sargassum* spp.[20,23,]. ADAPT: develop new fisheries to reduce pressures on kelp, e.g., rabbitfish, urchins[23].

	Encourage tropicalisation, e.g., coral instead of turfing algae[23]. Technologize reforestation in barren areas.
Global context	Worldwide, similar declines have occurred over the last five decades in 38% of ecoregions, while possible increases were observed in 27% of regions[15,27]. However, at many of the sites where increases are indicated, the temporal series of observations are quite short. Large regional differences occur due to the action of multiple pressures, including urchins (and, by inference, fishing of urchin predators), warming, heatwaves, and nutrient loading[27]. Where kelp forests collapse into meadows of turf algal beds or barrens, simple ecosystems replace structurally complex ones leading to a shift in ecosystem services (e.g., decline in production, magnitude of carbon sink, fisheries, damping of wave energy)[1,5,8,9].

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Image clockwise L–R: Healthy *Macrocystis pyrifera* kelp forest, southern Tasmania (Image N. Barrett). Two images of healthy *Eklonia radiata* kelp forests, east coast Tasmania (Images: M. Doggett). Widespread urchin barren, southern Tasmania (see urchin lower foreground). (Image: E. Flukes)

Ecosystem		13. Mediterranean-type Forests and Woodlands, south-western Western Australia (31–35°S)
Biome		Mediterranean region: forests and woodlands
Action		**Avoid, Restore, Renovate**
Baseline state		Mediterranean-type forests and woodlands cover >10,000 km^2. Extensive forests and woodlands experience wet winters and dry summers, and rainfall ranges from 700 mm to 1,100 mm per year. Vegetation comprises a mix of *Eucalyptus*-dominated forests comprising mainly northern jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*), but also tuart (*E. gomphocephala*), and banksia-dominated (*Banksia attenuata* and *B. menziesii*) woodlands of the Swan Coastal Plain. The forests and woodlands are part of the Southwest Australian Floristic Region (SWAFR) biodiversity hotspot[1] with >8,370 native vascular plant taxa. This area has a very high diversity of endemic species, particularly Proteaceae[2]. Ecosystems occur on plateau uplands of Archaean granite outcrops, on some of the oldest soils on Earth, and on sandy, very low fertility soils of the Swan Coastal Plain.
Current state and nature of collapse or shift		The vegetation is now highly fragmented due to clearing for agriculture, mining, and urban development. Since the 1970s, rainfall has greatly reduced as winter-dominant rainfall areas have contracted to the south-west[3,4]. Since the 1970s, rising air temperatures and decreased rainfall[4] have led to increases in very high and extreme forest fire weather, increased areas burned, increased fire frequency[5], and lengthened fire season[6]. For example, the Perth Airport weather station has shown a significant positive trend in the annual cumulative Forest Fire Danger Index over 37 years (1973/74–2009/10)[6]. Regional projections include a continued, consistent reduction in winter rainfall and overall warming over the coming decades[7]. In February 2011, prolonged drought stress from an acute drought in 2010 was followed by a record heatwave (9 days >35° C) driven by a strong La Niña event [8]. In a range of forest and woodland types covering ~165 km^2, the impact of the drought combined with the heatwave resulted in rapid die-off in forest canopies and tree mortality[9]. Within six months, distinct patches with up to 74% crown death led to 26% stem death in key species in the northern jarrah forest (jarrah, marri, and *B. grandis*). Some banksias died within five days[10]. In a *Banksia* woodland on the Swan Coastal Plain, 13–58% of Menzies' banksia *(B. menziesii*) died[11,12]. In addition, 500 ha of tuart woodlands ~90% of trees >20 cm diameter at breast height were affected. Die-off and mortality was associated with sites with lower water holding capacity and rocky outcrops, and xeric areas in the landscape[13]. In January 2010, after a day of extremely high temperatures, 145 endemic and endangered Carnaby's black cockatoos (*Calyptorhynchus latirostris*) succumbed to heat stress and died[14]. In March 2010, a severe hailstorm killed or severely injured other birds as well as vegetation[14,15]. Long-term decrease in rainfall and increase in temperature appear to have intensified pressures from pathogens, such as the fungus *Phytophthora cinnamomi*, canker (*Quambalaria coyrecup*)[16–18], and leaf blight (*Q. pitereka*)[19]. Outbreaks of an endemic wood-boring Eucalyptus longhorn beetles (*Phoracantha semipunctata*)[20,21] and the gum-leaf skeletoniser *Uraba lugens* also occurred in drought-stressed trees following drought/heatwave conditions[22].
Pressures	Global climate change presses	Increased air temperatures and chronic decrease in rainfall since the 1970s[4].
	Global climate change pulses	Heatwaves[9], increasing fire frequency[23]; increased storm frequency and intensity; fires.
	Human presses	Land clearing for agriculture, urban development, and forestry activities. Management fires.
	Human pulses	Unknown.
Ecological impacts and trajectory		Following die-off and tree mortality, some forest and woodlands systems are characterised by an altered structure via the decrease in tree height and prolific resprouting[24]. Changes affect remaining mid-storey trees, regeneration rates, understorey plant species[25], fuel dynamics and potential fire behaviour[23], fauna communities[9], microbial communities[26], and carbon dynamics[27]. Climate shifts are changing host-pest interactions in the region[9,20]. A

	legacy of chronic drought has exacerbated tree mortality and crown dieback during a heatwave-compounded drought[28]. Altered fire seasonality could affect the persistence of plant populations and community composition[29]. Modelling has predicted that Mediterranean-type ecosystems in the northern part of south-western Australia will contract, while areas to the south are expected to remain stable or expand[30].
Time to detection of impact	Days to months
Collapse profile	SMOOTH — regional, e.g., decreased precipitation[31] STEPPED — regional, e.g., clearing destroys habitat and communities[32] ABRUPT — local, e.g., drought/heatwave[10,12, 31]
Social and economic consequences	Loss of forest resources and ecosystem services (carbon storage), tourism and increasing fire risk.
Current mitigation and challenges	*Current mitigation:* reserves, management for plant pathogens, e.g., *Phytophthora* spp. The Banksia woodland of the Swan Coastal Plain, and tuart forests and woodlands of the Swan Coastal Plain are both listed nationally as Threatened Ecological Communities. Experimentation with climate-ready provenancing is another mitigation strategy being explored[19], and a proposed focus for mining rehabilitation on understorey[33]. *Challenges:* long-term climate change, the loss of water availability and consequential loss of ecosystems, the size of the region, the speed of change and the loss of keystone species. Dead plants can increase fuel load with potential positive feedbacks that may change fire behaviour, followed by non-native plant species expansions, including invasive grasses and African bulbs on the Swan Coastal Plain[23, 34]. Determine response of thinning on forest health[35].
Potential actions	AVOID: expand protected areas for key woodlands. Protect vegetation patches adjacent to water-gaining sites as forest and woodland relicts of a former climate. Continue extension and management of conservation reserves as a point of reference informing targets for restoration of degraded lands (carbon storage). Global climate action. RESTORE: active restoration in banksia woodlands on the Swan Coastal Plain[36,37], and tuart woodlands of the Swan Coastal Plain[38,39] including plantings of native taxa. Focus on understorey rehabilitation to sustain vegetation cover and promote diversity of native species characteristic of the region, and to sustain and connect faunal populations[40,41]. Control/ manage overabundant herbivore populations[41]. Remove non-native species. RENOVATE: investigate genotypes resistant to warmer and drier conditions, and pathogens[19,41]. Assisted gene flow and migration of widespread foundation/ keystone species.
Global context	Mediterranean forests and woodlands are a global conservation priority because of their high plant diversity. Droughts and heatwaves are having greater impacts and fire frequency and intensity will continue to increase under climate change in Mediterranean biomes[29,41].

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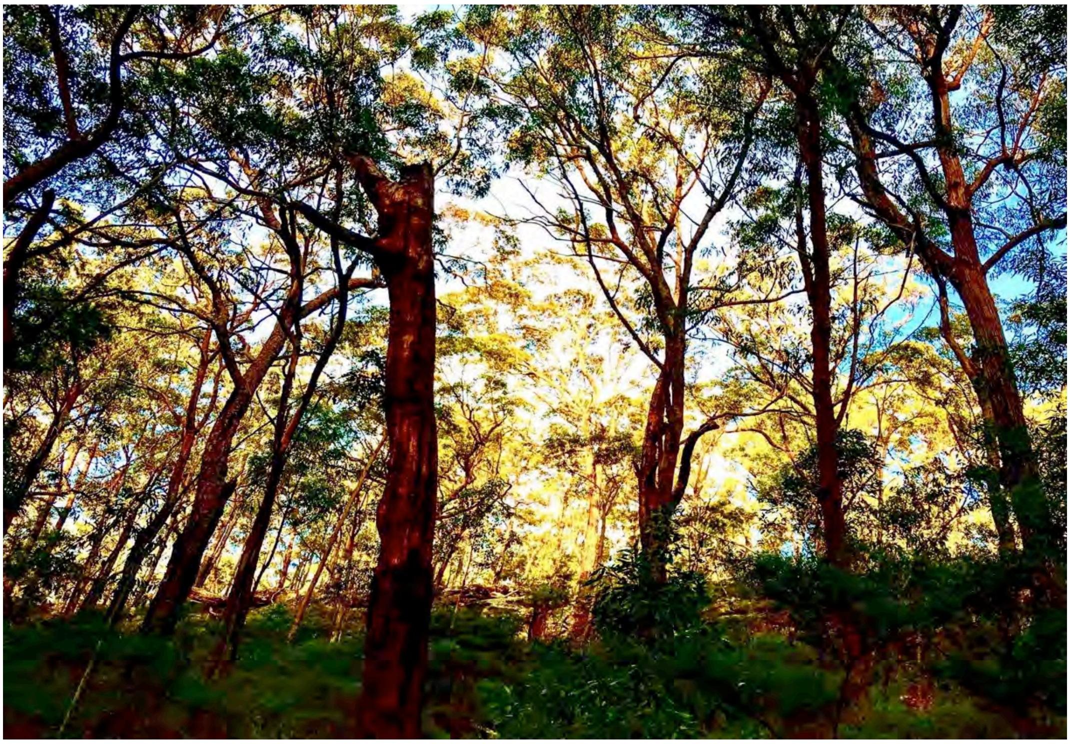
Image top: Intact forest dominated by jarrah (*Eucalyptus marginata*) (Image: Carl Freedman). Bottom: Stand of jarrah and marri (*Corymbia calophylla*) that experienced drought and heatwave-induced die-off in 2011. Stands still have altered structure eight years after the collapse (photo taken January 2019). (Image: Katinka Ruthrof)



Ecosystem	**14. Monaro Tablelands, South Eastern Highlands,** New South Wales (32–38°S)
Biome	Temperate woodlands and forests
Action	**Avoid, Restore, Renovate**
Baseline state	The Monaro Tablelands are located mainly in the southern parts of New South Wales, east of the Snowy Mountains. They lie about 1,000 m a.s.l. with plant communities spread across the cold and dry plateau of the southern highlands. Low rainfall (<600 mm per year makes fire possible during most of the year. Mean monthly temperatures range from -2° C in June to 28° C in January[1]. The ecosystem comprises a mosaic of grasslands, grassy woodlands and forests dominated by ribbon gum (*Eucalyptus viminalis*) and brown barrel (*E. fastigata*) [2,3]. These two species provide up to 40% of tree canopy cover in some areas[4]; snow gum (*E. pauciflora*) and southern blue gum (*E. globulus*) also occur. The understorey comprises kangaroo grass (*Themeda triandra*), shrubs and *Lepidosperma* spp. sedges[3]. Cold winters and lack of water in summer generally limit plant growth[1]. Eucalypts play a major ecosystem-engineering role in nutrient redispersal[5]. Trees up to 30 m tall provide important habitat for koalas (*Phascolarctos cinereus*), 15 other smaller marsupial species, 95 bird species — including two threatened species, the diamond firetail (*Stagonopleura guttata*) and the dusky woodswallow (*Artamus cyanopterus*) — 14 species of reptiles, 9 species of frogs, 7 species of bats[6], and many insects.
Current state and nature of collapse or shift	Australia-wide woodlands and eucalypt forests have been declining continuously since traditional Indigenous burning regimes were supressed[7]. In June 2016, the NSW Threatened Species Scientific Committee listed the cool temperate grassy woodland in the Monaro Tableland region as a 'critically endangered ecological community'[8]. Until July 2019, landholders were not permitted to clear land where critically endangered communities exist unless special permission was given to clear small areas, for example for the construction of fence lines[9]. However, amendments to state legislation now allows landholders to clear large areas of grassy woodlands should the quality of the grassy woodland be deemed not viable in the long term[9]. In areas with increased grazing frequency, non-native invading annual plants become dominant while native perennials decline steeply. Furthermore, application of fertilizers and cultivation of land reduce the abundance of native species[1]. Pre-1750, cool temperate grassy woodlands covered ~295,500 ha. Currently, only 15,600 ha (5%)[8] remain due to extensive clearing for urban development, infrastructure and agriculture[10]. The Monaro woodlands and forests are already a highly fragmented, modified tableland landscape. Since the 1820s, pastoral activities caused widespread clearing and grazing by domestic stock resulting in structural and compositional degradation[8]. Trees were removed to facilitate pastoral activities, and grazing by non-native, invasive herbivores (rabbits) and domestic stock hampered regeneration. The remnant areas are habitats to 16 threatened plant species (vulnerable to threatened) and 21 threatened animal species, for example the endangered spotted-tail quoll (*Dasyurus maculatus*), the largest marsupial predator on mainland Australia[11].Wherever land is cleared, all resident wildlife is exterminated[12]. In the last two decades, wide spread dieback affected mainly the once dominant ribbon gum. Ribbon gums are more prominent in areas wetter than the tablelands. Continuing climate related temperature change and the drought of 1994–2010 likely created conditions in the Monaro region that exceeded the tolerance of the trees. However, the immediate cause of this dieback that affected all age classes was an unusual outbreak of an endemic weevil (*Gonipterus* sp.) whose preferred host is the ribbon gum[13]. Since about 2005, ribbon gums started to die and by 2013 almost all (100,000s of trees) had died in an area of 2,000 km^2, including those in relatively undisturbed areas. The few remaining healthy ribbon gums appear to have dieback in the early stages[13]. In the past, various pressures contributed to dieback including changes in fire history, land management. Declining complexity of structural ecosystem components has added to tree stress. Unlike in previous dieback events, grazing and land management appear not to have been a factor. So far, there is no evidence that as proposed a lack of fire promoted the

Current state and nature of collapse or shift (cont.)		weevil outbreak[14]. The direct causes are still unknown. Since 2015, the dieback appears to be spreading north with ongoing dieback observed in the Australian Capital Territory (ACT). In the ACT, dieback affects mainly Box Gum Grassy Woodlands dominated by Blakley's red gum (*E. blakelyi*)[15]. Non-native, invasive transformational plant species (weeds), including sweet briar (*Rosa rubiginosa*), gorse (*Ulex europaeus*) and African boxthorn (*Lycium ferocissimum*), have altered many areas of grassy forest ecosystems[8]. Drought (2017–2019) and an extensive heatwave in January 2019 were the preconditions to one of Australia's worst bushfire season. Soaring temperatures and catastrophic fires destroyed bushland, killed people and wildlife, and annihilated whole towns. The fires burned tens of thousands of hectares; one fire east of Cooma burned 64,000 ha[16].
Pressures	**Global climate change presses**	Increasing temperatures, drought.
	Global climate change pulses	More frequent and sever forest fires; heatwaves; increased temperatures weaken tree resistance to native invertebrates.
	Human presses	Extensive land clearing and land use changes; introduced herbivores (grazing livestock, rabbits, deer)[17]. Removal of woody debris may affect tree hollow dwelling species, invasions by non-native grass species.
	Human pulses	Unknown.
Ecological impacts and trajectory		Loss of biodiversity, high likelihood of localised extinction with resulting effects on microclimates and dependent faunal populations.
Time to detection of impact		Months, years
Collapse profile		SMOOTH — regional, e.g., increasing temperatures STEPPED — regional, e.g., clearing[12] ABRUPT — local, e.g., dieback[14]
Social and economic consequences		Loss of carbon storage, stock shelter, and aesthetic values.
Current mitigation and challenges		*Current mitigation:* multiple reserves, the listing of the assemblage as an endangered ecological community at the State level, restoration projects, resilience testing of plantings from other provenances and tests of the effectiveness of Indigenous fire-management strategies. Box Gum Grassy Woodlands, a critically endangered vegetation type under the *Environment Protection and Biodiversity Conservation Act 1999* and in the ACT *Nature Conservation Act 2014*. *Challenges:* remnants of grassy woodlands and forests are poorly represented in the formal reserve network, and unreserved areas are subject to the threat of vegetation clearing associated with pastoral activities. The direct cause of dieback remains unknown.
Potential amelioration and adaptation actions		AVOID: increase size of existing reserves, nominate new reserves, and improve connectivity among reserve areas. Currently there are seven small reserves with a combined area of 3,935 ha[5]. Global climate action. Stop clearing. RESTORE: remove non-native plants and animals and improve grazing strategies[1]; retain dead trees and fallen timber for arboreal and ground habitat; revegetate degraded areas[18]. RENOVATE: continue search for more resistant local provenances[19] to replant with more resistant ecotypes. Replant with alternate tree species not susceptible to dieback.
Global context		Dieback is a multifaceted problem affecting many of the world's forests and woodlands. Water stress induced by climate change, outbreaks of insects, increased susceptibility to fungal pathogens often act together. Drought associated forest mortality has been reported from every wooded continent[20].

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Images clockwise L–R: Healthy ribbon gum (*Eucalyptus viminalis*) woodland, near Bombala, New South Wales, September 2014. Ribbon gum with dieback, Berridale NSW, January 2017. (Image: S. M. Prober)

Ecosystem		15. Snowpatch Herbfields, Australian Alps, south-eastern Australia (35–37°S)
Biome		Mountains: alpine herbfield
Action		**Avoid, Restore**
Baseline state		Alpine snowpatch herbfields (>1,850 m a.s.l.) occur in the Australian Alps Bioregion that include the Snowy Mountains, New South Wales, and Victorian Alps, Victoria. With an area of only 793,818 ha, it is one of Australia's smallest bioregions[1]. Mean annual temperatures are 3 to 12° C ranging from -7 to 29.5° C. Annual precipitation ranges from 606–2,344 mm[1]. The ecological, hydrological and climatological characteristics of this region are unique to Australia and susceptible to changes in temperature and precipitation[2]. The snowpatch herbfields are one of the rarest and most restricted ecosystems in Australia, occurring only on steep, south-east-facing slopes of alpine and high treeless subalpine zones where snow persists into the spring and summer growing seasons[3,4]. Snow patches occur in area with low insolation and can reach depths of up to 30 m[5]. Dwarf grasses and alpine herbs dominate the ecosystem; occasional dwarf shrubs occur. The herbfields are floristically variable between and within patches. There are many endemic species, such as the white purslane (*Neopaxia australasica*), the alpine marsh-marigold (*Caltha introloba*) that starts flowering while still covered by snow, and the spreading daisy (*Brachyscome stolonifera*)[3]. The range of these species is highly restricted[1]. Snowpatches commonly persist for >240 days and some have frequently persisted throughout summer[5]. They may reduce the growing season of the plants they cover. In late summer, they can be a source of water for flora and fauna. The Australian Alps are an important catchment area and source of freshwater[2]. In particular they generate the headwaters of the Murray River (see #9 Murray Darling River Basin).
Current state and nature of collapse or shift		Over the past 35 years, southeast Australian alpine areas have warmed by 0.7º C[5]. Since the 1960s, the maximum snow depth in the region has decreased by up to 15%[6]; snow cover and persistence have also decreased[7]. The snow free period used to last about 153 d but increased to 193 d in the 2006/07 season[5]. Snow depth has decreased about 23 cm (15%) per decade over the past 25 years. Similarly, snow accumulation has declined 21 cm (9%) per decade. The frequency of light snowfall events (1–10 cm) has decreased significantly[2]. Shortening of the snow season and reductions in snow depth are leading to a collapse where taller, novel species are outcompeting snowpatch herbfield taxa[8,9]. Rising land air temperatures increase fire frequency and extreme fire weather[10] with unprecedented lightning — ignited fire events occurring in 2003, 2006[11] and 2020 (P. Zylstra, pers. obs.) — consistent with an increase in dry lightning storms[12]. Fire spread is greatly enhanced by positive fire feedback in all surrounding alpine, subalpine, montane and foothill ecosystems[13–15], and drier vegetation enables larger fires[16]. Fire is furthering the replacement of dwarf plants (herbs and graminoids) by larger shrubs and grasses[15]. By 2050, a 24% decrease in precipitation is expected in the Snowy Mountains[7]. Reductions in snow cover and increases in snow free days already resulted in the encroachment of taller species in some areas[5]. Ongoing destruction of vegetation and erosion of soil due to non-native species, especially feral horses[19]. Plant deaths recorded in the alpine and sub-alpine areas were probably due to various species of *Phytophthora* fungi. The recent identification of several new *Phytophthora* species, apparently well adapted to the low temperature environment, suggests potential for developing risk[17,18].
Pressures	**Global climate change presses**	Declining snowfall; shortening of the snow season[7]; increasing temperature and increasing extreme fire weather[10].
	Global climate change pulses	Increased ignition of dry lightning storms leading to increased fire frequency[12].
	Human presses	Legacy of past livestock grazing; ongoing damage by non-native horses and deer[19];

		tourism (including skiing, and bushwalking), resort infrastructure[20]. Increased flammability of surrounding landscapes[13] due to management burning and other fire increases[11].
	Human pulses	Fires from campers and bushwalkers.
Ecological impacts and trajectory		Loss of biodiversity. Loss of snowpatch herbfields due to changing abiotic and biotic conditions has consequences for individual alpine species for which these plant communities are refugia.
Collapse profile		SMOOTH — regional, e.g., novel species establishment in response to increasing temperatures and loss of snow[5,7] ABRUPT — local destruction, e.g., fire[13]
Time to detection of impact		Decades
Social and economic consequences		Importance to tourism and visual amenity. Visitors to the Australian Alps generate around $812 million and $505 million gross state product annually in Victoria and New South Wales, respectively. Some 10,459 and 6, 571 annual equivalent employment opportunities are generated annually in NSW and Victoria, respectively[21]. Greater fire contagion through the alpine region.
Current mitigation and challenges		*Current mitigation:* the Australian Alps National Parks and reserves are currently on the National Heritage list, and the community is listed as critically endangered under the NSW Biodiversity Conservation Act (2016)[22,23]. Cooperation of managers and scientists to anticipate and manage change is ongoing. *Ex situ* seed harvest and storage (global seed bank networks) is occurring[24]. *Challenges:* the restricted nature and rarity of the ecosystem; difficulty of access for fire suppression; increased exposure to fire resulting from positive flammability feedbacks in the alpine area and surrounding forests; political tensions regarding non-native animal control and other management issues.
Potential actions		AVOID: recognize rarity and threat by listing as an endangered ecological community under the *Environmental Protection and Biodiversity Conservation Act 1999* and associated protective actions, local fire suppression, fire exclusion in upwind/down-slope (fire-source) forests where positive flammability feedbacks operate, to minimise direct damage from trampling that facilitates shrub invasion. Close roads and implement other hygiene measures to limit the spread of fungal pathogens. Global climate action. RESTORE: reseed after fire, repair soil damage from horses, management of non-native plant species and non-native herbivore control; remove invading novel native species.
Global context		Alpine communities are highly threatened by climate change due to the limited scope for upward redistribution. Existing climatic changes may have already triggered a level of ecosystem change that has not yet been realised. Global extinctions are anticipated and *ex situ* seed bank networks are gathering genetic material for preservation[25].

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Images clockwise L–R: Healthy snow patch ecosystem. Damaged snow patch ecosystem with evidence of trampling by non-native horses (see dung in foreground), Kosciuszko National Park, New South Wales. (Images: C. M. Pickering)

Below: Burned show patch ecosystem, Kosciuszko National Park, New South Wales. (Images: C. M. Pickering)

Ecosystem	**16. Mountain Ash Forests, Victorian Central Highlands,** south-east Australia (36–37°S)
Biome	Temperate: broadleaf forests
Action	**Avoid, Recover, Restore, Adapt**
Baseline state	In Victoria's cool, moist Central Highlands region, a tall forest dominated by the mountain ash (*Eucalyptus regnans*) covers ~157,000 ha. Mean annual temperatures range from 7.2–14.1° C, and rainfall varies from 815–1775 mm per year[1]. At high elevations, mountain ash tends to occur in monotypic sands, while at lower elevations, it is mixed with other species, such as mountain grey gum (*E. cypellocarpa*), messmate (*E. obliqua*) and red stringybark (*E. macrorhyncha*)[2]. The mid-storey comprises trees usually 15–40 m tall and includes myrtle beech (*Nothofagus cunninghamii*), southern sassafras (*Atherosperma moschatum*) and various acacias. The understorey is made up of broad-leaved shrubs, such as blanket leaf (*Bedfordia arborescens*), mountain pepper (*Tasmannia lanceolata*), the hard tree fern (*Cyathea australis*), and soft tree fern (*Dicksonia antarctica*). The forests comprise several hundred plant species[3]. Many of the plants occurring here can be found in other Australian forests but the dominance of the mountain ash overstory is unique. The mountain ash is the tallest flowering plant on Earth, approaching 100 m in height[1]. Old-growth mountain ash forests contain the world's highest known carbon density (1,867 tC ha^{-1})[4]. The ecosystem provides habitat for diverse animal and plant communities and old-growth trees (>120 years) provide food resources and hollows for cavity-dependent marsupials, including the critically endangered Leadbeater's possum (*Gymnobelideus leadbeateri*). The forest supports >100 bird and >30 mammal species[3].
Current state and nature of collapse or shift	The IUCN lists the mountain ash forests in the Central Highlands of Victoria as a critically endangered ecosystem (https://iucnrle.org/assessments/). The requirements of mountain ash forests for cool, moist conditions make these forests vulnerable to climate change (higher temperatures, less rain)[1,5]. Ash-type eucalypts in tall, wet montane forests are particularly sensitive to increased fire frequency. Here, fires occurred 8.3 times more frequently in younger, post-disturbance stands than in mature forest[5]. Habitat fragmentation due to natural disturbance (fire) and human activities (logging) is putting the mountain ash forests increasingly at risk. One of the worst fires in the last two decades burned 78,300 ha (nearly 50%) of mountain ash forests in 2009[6]. High intensity fires devastated 21,132 ha (16%). By 2019, 48,095 ha (35%) of mountain ash forest had either been burned in 2009 or clear-felled. Some 70% of mountain ash has been either disturbed or is located within 200 m of disturbed habitat[7]. Hidden collapse has occurred. The ecosystem is superficially intact, but nearly 99% of the ecosystem has been burned or logged and is dominated by trees <80 years old. In 1997–2011, ~50% of large cavity-bearing trees have been lost, and there has been a 50–80% decline in site occupancy by cavity-dependent arboreal marsupials and significant declines in mountain ash-associated bird species. The loss of large trees and reduced recruitment of mountain ash is resulting in further drivers of collapse[8]. Multiple interacting pressures include natural and human pressures. The primary human disturbance is clear-fell logging (>70% of the ecosystem). Coups of up to 120 ha are clearcut over about 5 years. High intensity burns are used to regenerate clear-felled forest but those kill many old-growth trees[3]. Key ecosystem components continue to decline long after pressures of collapse have been removed due to long lag times. Logging and fire produce positive feedback with regrowth more flammable than mature forest[9]. Logging depletes or destroys fire-resistant understory plants. Clear felling changes the landscape composition, reduces nesting sites for birds and habitat for tree-dwelling marsupials, and reduces their abundance[3]. After large fires (especially in 1939 and 2009), burned areas are exploited for decades through post-fire salvage logging. Fire damaged trees are removed with large mechanical plant with effects similar to clear felling[3]. The populations of arboreal marsupials were severely affected by the 2009 fires as the tree canopies were destroyed in 30 of 180 (16.6%) study sites; another 30 sites experienced less damage in moderate to low severity burns. Existing reserves are not large enough to provide sufficient habitat for arboreal marsupials and need to be

Current state and nature of collapse or shift (cont.)		expanded urgently[10]. Populations of ground-dwelling marsupials appeared to have largely recovered from the 2009 fires. Bush rats (*Rattus fuscipes*) and agile antechinus (*Antechinus agilis*) — abundant pre-fire — persisted even in severely burned areas[10]. The responses of forest birds to habitat changes induced by bushfire and/or logging varied among species Forest birds were largely negatively affected by the bushfires and many populations decreased both in burned and unburned areas; the populations of 24 of 49 modelled species have not yet recovered, and some continue to decline. When sites are clearcut, the birds are forced into new, unlogged areas[10]. The 2009 fires destroyed >40% of potential habitat of the critically endangered Leadbeater's possum[6]. To protect Leadbeater's possum and other mammal species (e.g., gliders and other possum species) and birds, the rate of loss of hollow-bearing trees needs to dramatically slow and recruitment of new trees encouraged[10]. In addition, logging and commercial use of the mountain ash forests needs to cease[11,12]. Thus, industrial clear felling has become unsustainable, especially in the 1939 regrowth forest (which is the next nearest cohort of trees to old growth forest). If extensive logging continues, there is a 92% chance that the current ecosystem will no longer exist by 2067[1]. The extreme bushfires on the east coast of Australia in the summer of 2019/20 penetrated the mountain ash forest of north-eastern Victoria. Some forests have now been burned four times in 25 years, when in the past fires occurred at intervals of 75 to 150 years (D. Lindenmayer, pers. obs. 2020).
Pressures	**Global climate change presses**	Reductions in rainfall, increases in temperatures.
	Global climate change pulses	Increases in extreme fire weather and length of fire season.
	Human presses	Habitat fragmentation due to land tenure and clear-cut logging; forestry; post-fire salvage logging. Invasive non-native herbivores (e.g., deer).
	Human pulses	Tourism.
Ecological impacts and trajectory		Trees <80 years old dominate nearly 99% of the ecosystem. Trees have to be at least 120 years old before they start to develop cavities that provide habitat for tree-dwelling species. The population of old-growth trees is estimated to be <10% of 1997 levels; based on a number of logging and fire scenarios (including a scenario of no fire and no logging), projections indicate that by 2067 only 0.3–0.8 old trees ha^{-1} will be left compared to 3.8 trees ha^{-1} in 2011[8]. Mountain ash forests belong to the Wet Ecological Vegetation Class in Victoria that has suffered an 85% reduction in old growth cover in the past 25 years, and 35% has experienced two or more major stand-replacing disturbances in that time[7]. The Mountain ash ecosystem is now highly fragmented, and the average distance to a disturbance boundary within wood production forests is 71 m compared to 1,700 m in protected areas[13]. Separate climate modelling indicates warming combined with drying could reduce the climatically suitable area by 80% by 2080. Acacia-dominated shrub-land might replace the mountain ash forest[1]. Industrial clear felling logging operations use only about 40% of the forest biomass for commercial use; 60% are left in situ where it decomposes or is burned off contributing significantly to greenhouse gas emissions[13].
Time to detection of impact		Decades (logging since the 1860s)
Collapse profile		SMOOTH — regional, e.g., increasing temperatures[1,5] STEPPED — regional, e.g., clear-cut logging[13] ABRUPT — local and regional, e.g., fire[5]
Social and economic consequences		Sawlogs and residual logs from mountain ash forests generated an income of $11 million and $4 million per year, respectively, for the Victorian Government[14]. However, only ~35% of logs cut from native forests ultimately end up as timber products and of those <40% are used to build houses or make furniture. The use of 84% of cut logs is short-lived (e.g., copy paper)[13].

	Mountain ash forests sequester carbon at the rate of 1.87 tC per hectare per year. This equates to \$134 ha^{-1} yr^{-1}. As this potential no longer exists in logged areas, it has cost Australia \$15.5 million per year. Also, had the forest been left to grow, another 0.344 MtC would have been sequestered each year[15]. If revegetated, Victorian parks could sequester 21,000 tC per year. Carbon storage resulting from two revegetation programs is worth >\$1 million per year (at \$15 per tCO_2); the cost to offset emissions of all carbon stored in Victoria's parks if released would be ~ \$15 billion[16]. The ecosystem also supports timber, pulpwood and tourism industries[8]. Habitat in the catchment provides water for 4.5 million people in Melbourne and for agriculture[8].
Current mitigation and challenges	*Current mitigation:* some areas are protected from logging and some areas are managed reserves. Long term monitoring of mountain ash forests to determine effect of fragmentation of native forests on their biodiversity[17]. *Challenges:* rotation times for logging are insufficient for new recruitment of hollow-bearing trees. Large trees are more susceptible to decay, mortality and collapse in logged areas. Fire risk and fire severity are higher in logged regrowth areas. Inefficient logging methods. Lack of suitable conservation strategies for endangered species. In effective zoning strategies. Determination of susceptibilities of forest ecosystems and communities to climate change. Improved utilisation of forest resources and reduction waste[13] can reduce pressures from logging.
Potential actions	AVOID: cease clear felling and introduce the Variable Retention Harvest System to maintain critical structural elements of the forest ecosystem in logged areas to ensure conservation of biodiversity[14]. Expand protected area network (including non-logged buffer zones around old-growth stands) in appropriate areas, i.e. comprehensive, adequate and representative[18,19]. Protection of all hollow-bearing trees (individuals and those in old growth areas)[20]. Cease logging in 1939-regrowth forests to restore carbon sequestration potential[21]. Global climate action. RECOVER: manage forests to improve forest recovery after fire and logging. RESTORE: plant better suited genotypes and /or new species[22.] Artificial re-seeding after clear-felling and fire. ADAPT: establish nest boxes for cavity-dependent fauna in younger forest stands to support cavity-dependent species (artificial re-seeding after clear felling aids regeneration of new stands of mountain ash[1] but does not support re-establishment of the understorey vegetation critical for possums and gliders).
Global context	Approximately 18% of global carbon emissions come from deforestation[4]. The conservation of intact old-growth mountain ash forests results in substantial reduction of net emissions relative to commercial harvesting[15].

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Images clockwise L–R: Old growth mountain ash (*Eucalyptus regnans*) (see person for scale), February 2015. Only 1.16% of remaining forest is old growth and is spread across 147 patches. Immature stand of mountain ash (*Eucalyptus regnans*) killed by fire — collapse due to loss of regenerative capacity. (Images: D. Lindenmayer). Clear felled mountain ash forest. (Image: Chris Taylor)

Ecosystem		17. Gondwanan Conifer forests, Tasmania (41–43°S)
Biome		Subalpine temperate: broadleaf and mixed forests
Action		**Avoid, Restore, Adapt**
Baseline state		The core range of Gondwanan conifer rainforests, woodlands and subalpine scrubs are located on the temperate montane Central Plateau of Tasmania. This is a global hotspot for fire-sensitive remnant Gondwanan woody plant species that date back >180 million years, and is conserved within the Tasmanian Wilderness World Heritage Area (TWWHA). Two species the pencil pine (*Athrotaxis cupressoides*) and the closely related King Billy pine (*A. selaginoides*) are Tasmanian endemic ancestral gymnosperms. Both are foundation species of these forests that occur in high rainfall, lower elevation areas[1]. Both are extremely slow growing, long lived (some stems are >1,000 years old) plants restricted to areas that are rarely burned (fire refugia), and often grow on deep organic soils. The pencil pine is a mast seeder but also regenerates clonally. The thick bark of adult trees has some capacity to tolerate low severity fires, and infrequent ground fires, but repeated fires result in tree death[2]. Historically, large and intense fires were rare reflecting infrequent droughts and limited ignitions during periods of peak fuel dryness, and possible because of a legacy of skilful patch fire use by Indigenous people[3]. Records reveal increasing occurrence of lightning ignited fires probably reflecting increased fuel dryness rather than more frequent convection storms[4]. Thus, given the absence of fire resistance and post-fire recovery traits of most plant taxa that co-occur with *A. cupressoides,* this ecosystem is vulnerable to intense fires and lacks resilience[1,4,5]. Other species in the forests, woodlands and subalpine scrub include *Nothfagus gunnii* (Australia's only deciduous species) and *N. cunninghamii*, the monotypic coniferous shrub *Diselma archeri,* the podocarp *Pherosphaera hookeriana,* the shrubs *Orites revoluta*, *Richea scoparia*, *Ozothamnus rodway, Leptospermum lanigerum,* various Eucalypts including *Eucalyptus coccifera*, as well as bryophytes and ferns[6].
Current state and nature of collapse or shift		In 1960 (then the driest recorded spring-summer), deliberately lit fires set by pastoralists became uncontrolled and destroyed 10% of the pencil pine population. Pencil pine trees and seedlings are still largely absent from the areas burned in 1960[3]. Several subsequent small high-severity fires have further lead to range contraction of the species[7]. In 2015/16, Tasmania experienced its then driest spring and warmest summer. In January and February 2016, thousands of dry lightning strikes caused most of the 145 vegetation fires including several on the Central Plateau. These fires burned 85 ha in fire-sensitive alpine and sub-alpine areas affecting ~1% of the pencil pine population. The 2018/19 summer was the second warmest and driest summer on record for Tasmania. In January 2019, two large dry lightning storms caused 70+ fires and 200 km^2 (3% of the state) to burn including some small areas of Gondwanan refugia. Overall, in 2016 and 2018/19 lightning ignited fires burned ~5% of the state. Frequent fires adversely affect the Gondwanan refugia by causing population collapse of foundation species such as the pencil pine [8], increasing the abundance of flammable species[3] and, hence, fire risk. Fires also destroy organic soils (peat)[5] which prevent the re-establishment of the long-lived Gondwanan plant species[3,4,5]. The drought in 2015/16 was associated with an intense negative Indian Ocean Dipole event. Furthermore, a more positive Southern Annual Mode is also associated with more dangerous fire weather and lightning ignitions[9]. Climate change attribution studies suggest that the warmth, and to a lesser degree the dryness associated with the fires, can be attributed to the forcing of anthropogenic climate change[10,11].
Pressures	**Global climate change presses**	Changes in rainfall, increasing temperatures.
	Global climate change pulses	Since the 1990s, there has been a steady increase in the number and area burned by lightning fires reflecting the increasing dryness of fuels in western Tasmania[4].
	Human presses	Tourism; road constructions; ongoing damage by invasive vertebrate herbivores (e.g., fallow deer (*Dama dama*))[12].
	Human pulses	Anthropogenic ignitions have sharply declined since the proclamation and expansion of the World Heritage Area in the late 1980s that prohibited campfires. Prior to this, fires were set deliberately by Indigenous people, hunters, pastoralists[7].

Ecological impacts and trajectory	Species distributional modelling suggests climate change will see the shrinking of the range of palaeoendemics because of the loss of cool, moist, fire-free refugia critical to their survival[13,14]. Fire weather in this region is predicted to worsen[15].
Collapse profile	SMOOTH — regional, e.g., increasing temperatures[1] STEPPED — regional, e.g., legacy clearing[1,16] ABRUPT — local, e.g., fire[1,5]
Time to detection of impact	Days to decades
Social and economic consequences	Gondwanan communities are a core feature of the Tasmanian Wilderness World Heritage Area, natural, touristic and cultural values, and contribute to contemporary Tasmanian cultural identity[6].
Current mitigation and challenges	*Current mitigation:* fire management involves (a) reduction of other potential sources of fire[4], (b) target prescribed burning to reduce fuel loads in flammable plant communities in adjacent areas, and (c) active fire fighting practices involving use of fire fighting chemicals and irrigated fire breaks[7]. Fine-scale mapping of vulnerable plant communities, improved fire weather prediction and behaviour models, enable identification of at-risk areas for greater protection during fire seasons[7] (also S. Brooks, pers. obs. 2016). See case study for 3As below. *Challenges:* potential increase in fire season duration and fire intensity. The wilderness area is very difficult to access for ground-based fire fighting.
Potential amelioration and adaptation actions	AVOID: increase resourcing of fire protection including rapid detection of lightening strikes; install rapid remote area fire suppression for key Gondwanan refugia; reduce fuel loads around ecosystem refugia; potentially introduce Indigenous patch burning[4]. Global climate action. RESTORE: seed banks of key plant taxa have been established, and restoration plant trials of pencil pine and sphagnum bogs are underway[17]. ADAPT: consider the possibility of establishment of *ex situ* populations (possibly excavating whole trees) to fire-free moist environments both within and outside Tasmania.
Global context	Fire seasons are lengthening, and higher frequency of dangerous fire weather activity is predicted to increase in temperate forests under projected future climate scenarios[15,18].

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Images top: Healthy subalpine, Gondwanan conifer forests, Cradle Mountain, March 2017. (Image: Daniel, Engelbrekt). Bottom: Fire killed pencil pine (*Athrotaxis cupressoides*), Lake Mackenzie Tasmania, February 2017. (Image: Amiee Bliss)

Ecosystem	**18. Subantarctic Tundra, Macquarie Island,** south-west Pacific (54°S)
Biome	Polar region
Action	**Avoid, Recover, Restore, Renovate, Adapt**
Baseline state	The ecosystem is a World Heritage-listed patterned, alpine tundra dominated by cushion plants and bryophytes with minor impacts from historical rabbit grazing. Endemic cushion plants are the most extensive vegetation type[1], covering most of the island's uplands in one of the rarest ecosystems on the planet (one of only eight subantarctic island groups)[2,3]. The mean maximum temperature is 6.6° C (range 5–9° C) and the average annual rainfall is ~970 mm. The sky is usually covered by cloud. Mean annual daily sunshine is 2.4 h. Snowfalls occur generally from June to October[4].
Current state and nature of collapse or sift	Extensive change in the alpine tundra (fellfield) ecosystem has occurred with the collapse of endemic keystone species, such as the Macquarie cushion plant (*Azorella macquariensis*) and associated bryophytes[5]. The speed of collapse was very rapid. Due to substantial death, the status of the cushion plant changed from healthy to critically endangered in three years with >30% of loss in cover[5,6]. Almost one decade after it was first observed, dieback remained present island-wide, affecting 98.7% of populations (90 randomly stratified sites, island-wide)[7]. Cushion dieback increased along a north-south gradient, with the most extensive and advanced dieback occurring in the north of the island[7]. Death in Macquarie cushions and many bryophyte species is still occurring. The loss of vegetation and peat (soil carbon) is leaving only bare gravel in high elevation, exposed areas of the tundra[3,8], while the slightly lower and warmer elevations are favouring invasion by opportunistic native grasses[9]. Storm frequency and intensity have increased since the 1970s[10]. In January 2015, 106 mm of rain in 36 h (more than the monthly average) contributed to the removal of exposed peat. Since the start of 2015, eight of the eleven highest daily rainfall totals were recorded on the island[11]. Greenhouse gas increases and ozone loss have led to a southwards shift in low pressure systems and the westerly jet stream resulting in altered wind and precipitation patterns, as well as other changes to the regional climate[12]. Complex climatic changes include increases in mean wind speed, sunshine hours, and evapotranspiration[5]. Winter rainfall has increased by about 55% since 1970. However, increased cyclonic activity, higher mean wind speeds and a generally drier atmosphere[10] appear to have increased surface drying and raised surface evaporation in summer. Cushions are adapted to constant cold and wet conditions but now they, and associated bryophytes, experience conditions fluctuating between wet and extended dry periods[5,13]. In 17 consecutive summers of water stress (1992–2008), the water available to plants in summer (growing season) was greatly reduced[5]. Initially, this water stress appeared to be the primary pressure causing dieback, but a secondary pressure appeared with the emergence of a putative pathogen. More than 10 species of potential pathogenic bacterial, fungal and oomycete populations have been identified[5]. However, over the last decade, there has been a shift in fundamental ecosystem processes with the pathogenic system now appearing to be the predominant cause of dieback rather than a combination of drought and disease. Cushion dieback appears to be positively related to sites with less freezing days and very high humidity[9]. The healthiest cushions occur in the south of the island, where the temperatures are significantly colder and there are more freezing events[9]. It appears that cushions are protected from disease by extreme cold temperatures[14]; consequently, the south of the island may provide a temporary refugium[9]. However, there is also evidence that bands of pathogens are moving through the landscape multiple times, eroding cushions cover over time[3,7]. A threshold appears to have been crossed into a new operating state. Ecosystem collapse with two clear new states (grassland and bare ground) appears to be emerging with the loss of the ecosystem engineering species from many areas of tundra[3,8,9]. Under projected climate change, as the maximum temperatures continue to increase over time, it is expected that these changes will continue, and grasslands will continue to expand upslope replacing the open tundra and ecosystem engineer[9]. The megaherb silver-leaf daisy (*Pleurophyllum hookeri*) is now also showing widespread death across the island[3,9]. Adult silver-leaf daisies appear to be susceptible to the same expanding pathogen line seen in the Macquarie cushions.

Pressures	**Global climate change presses**	Increased winter rainfall[5] and increased maximum temperatures[9]. Increased sunshine (fewer clouds), increased wind speed, change in predominant wind directions.
	Global climate change pulses	Extreme storms and flooding[11]; probable emergence of pathogens[3,5,6,8,9].
	Human presses	None. Minor disturbance by non-native rabbits until 2012[5].
	Human pulses	Occasional trampling[5,15].
Ecological impacts and trajectory		Significant loss of cover of the most widespread species on the island, many areas transitioned to bare ground or grassland, altered microclimate, loss of biodiversity and loss of substantial reserves of accumulated soil carbon[3,5,6,8,9]. The trajectory is not reversible under current climate conditions with continued increase in wind speed, summer sunshine and temperature increases[3,9]. Increased winter rain may encourage further emergence of saprophytes and pathogens. However, 15% of the island has been identified as a potential cold climate refugium for cold growing species, such as the slow growing Macquarie cushions.
Collapse profile		ABRUPT — regional, e.g., dieback[3,5,8,9]
Time to detection of impact		First detected in 2008 with evidence of collapse having occurred for at least two seasons. The status of the Macquarie cushion plant was upgraded from 'not threatened' to 'critically endangered' within three years of detection[5,6].
Social and economic consequences		Loss of World Heritage values including geomorphological features (terraces and patterned ground)[1,9,16].
Current mitigation and challenges		*Current mitigation:* three specially protected areas with restricted access, have low levels of dieback; *ex situ* conservation in place (watered, managed seed orchard of Macquarie cushion growing in pots) and off-island seed bank[5,9]. *Challenges:* climate change is ongoing; lack of funding for research and management; lack of experience, expertise and investment on pathogen issues in environmental agencies concerned with the protection of native biota; and pathogens not identified. Seed dormancy manipulation and tissue culture of Macquarie cushions not successful to date.
Potential amelioration and adaptation actions		AVOID: global climate action. RECOVER: some evidence of minor recovery occurring[7,9]. RESTORE: replanting and pathogen control[3,9]. RENOVATE: selection for more climate change and/ or pathogen resistant genotypes of *A. macquariensis*[9] with aim to replant. ADAPT: potential genetic engineering; potential replacement of endemic species with more robust sister species or closely related South American species[9].
Global context		Extensive collapse of communities in the Arctic where elements of tundra have died (i.e. Arctic browning)[17].

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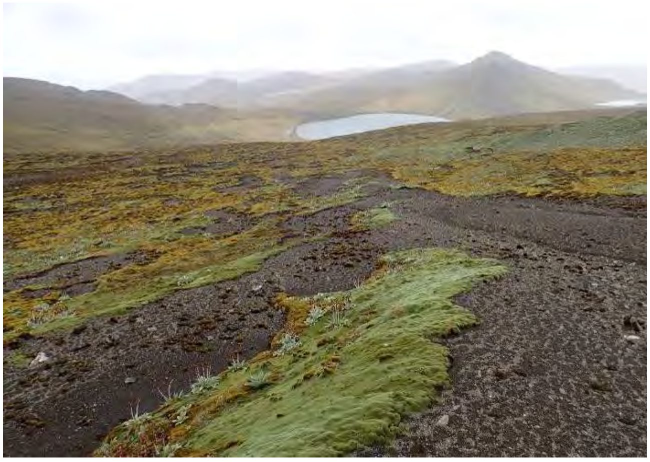
Images L–R: Healthy feldmark. Brown and yellow pathogen line across *Azorella macquariensis* cushion. Extensive dead cushion and moss (pink). All images 2017. (Images: C. R. Dickson)



19. East Antarctica Moss Beds, Windmill Islands (66°S), Vestfold Hills (68°S)		
Biome		Polar region: Antarctic polar desert
Action		**Avoid, Recover, Restore, Renovate, Adapt**
Baseline state		The flora of East Antarctica is limited to the small ice-free areas (<0.4% of land area), and is dominated by algae and cyanobacteria, lichens and mosses. There are no flowering plants. Lichens are relatively well adapted to drier conditions. Moss beds occur only in areas where sufficient moisture is available during the short growing season in summer (2–4 months)[1,2]. Rare old-growth moss banks are some of the most extensive and well-developed vegetation in continental Antarctica. Green, lush moss banks and extensive lichen coverage occurs in coastal ice-free areas. The regional endemic moss *Schistidium antarctici* dominates the Windmill Islands[3,4], whereas *Byum* spp. dominate the Vestfold Hills. Moss banks support the majority of invertebrates in the ecosystem. On drier sites, lichens dominate. These are slow growing, long-lived (hundreds of years) in a stable system. No vegetation occurs in extremely arid areas. Freeze-thaw cycles, precipitation and wind affect the availability of water and determine plant distribution rather than temperature[3,5,6].
New state and nature of collapse or shift		In the Windmill Islands, the species composition of moss beds changed significantly over 13 years (2000–2013); the submergence tolerant *S. antarctici* was at least 30% less abundant in 2013 than in 2008, while desiccation-tolerant species such as the cosmopolitan *Ceratodon purpureus* were 8–16 times more abundant. The increase in more drought-tolerant species is indicative of drying conditions. The health status of the endemic mosses also deteriorated; by 2008, half the mosses that had been green and healthy five years earlier showed signs of physiological stress. Moribund (dying) mosses also increased over the study period providing further evidence for regional drying[7]. The drying is likely due to a combination of climate change and ozone thinning that has intensified the positive phase of the Southern Annular Mode; this shift strengthened the winds and lowered maximum temperatures in much of East Antarctica in summer[8]. Lower temperatures, increased winds and increased evapotranspiration make water biologically less available during the growing season thus limiting moss growth. Furthermore, water availability has decreased through loss of connection to water sources (snow reservoirs)[7]. In 2008, plant health deteriorated unexpectedly, and a partial recovery occurred during the following seasons. Sixteen anomalous freezing rainfall events had occurred in the years from 1989 to 2014; twelve of those took place from 2006 to 2009. Anecdotal evidence indicates that freezing rain (supercooled water that freezes on impact) events in December 2007 added to the stress of endemic mosses and furthered the growth of *C. purpureus*[7]. Loss of some local populations from human activity is associated with research station activity[9]. Drying appears to be more widespread than just the Windmill Islands. A time series of photos from extensive moss banks at Mossel Lake in the Vestfold Hills, ~1400 km to the west, showed prolonged degradation in moss health between 1998 and 2005, and limited recovery since[7]. Although, in the summer of 2019/20 prolonged warm weather, associated with a heat wave that circumnavigated the Antarctic continent melted nearby snow banks and glaciers, resulted in flooding of this lake. Some moribund mosses responded very quickly to this additional water, greening within a month. Mosses that did not receive flood water remained moribund[10,11]. A biodiversity survey of the Vestfold Hill in the 2019/20 austral summer included sites with extensive moss banks; at 51 of 78 (68%) sites, mosses present had dead or moribund moss cover (unpublished data D. M. Bergstrom).
Pressures	**Global climate change presses**	Changes in precipitation (rain events); increased wind speed, loss of water from snow banks, fewer degree-days (until 2020)[7].
	Global climate change pulses	Extreme winter event (rain and positive temperatures) possibly causing some mortality in 2008 (Ball, Bergstrom and Robinson, unpublished data), plus freezing rain events[7]. Heatwave 2020[10,11].
	Human presses	Human activities (e.g., trampling, dust and dumping of gravel and snow piling and extraction of water for station use) affect moss banks adjacent to buildings.

	Human pulses	Drainage altered by station building developments since 1957; the effects of this pulse event are ongoing.
Ecological impacts and trajectory		Change in species composition, reduced abundance and increasing mortality within some of the most extensive, vegetated areas on Antarctic continent. Loss of habitat for associated micro-invertebrates. Carbon from dead moss creates new habitat for lichens, which are therefore expanding. The continued loss of moss banks and associated habitat. Potential building of new infrastructure (aerodrome) could have regional impact from pollutants.
Collapse profile		SMOOTH — regional, e.g., desiccation[7,10] ABRUPT — freezing rain in 2007/08[7]; heatwaves and increased ice melt[10]
Time to detection of impact		Change in Windmill Islands was detected over 5 years[4] but can also occur over months (e.g., Vestfold Hills).
Social and economic consequences		Loss of wilderness values in Antarctica (recognised Antarctic Treaty value).
Current mitigation and challenges		*Current mitigation:* The Antarctic Treaty Parties (including Australia) have committed to comprehensively protecting the Antarctic environment. Its Committee for Environmental Protection (CEP) has a rolling 5 year priority work plan focused on establishing management actions and associated science required for evidence based decision making on issues, including climate change implications, tourism and station management. Reduction in global chlorofluorocarbons resulting in gradual repair of ozone thinning, which will affect the state of the Southern Annular Mode[8,12]. Local human presses minimised through modified management (D. M. Bergstrom, pers. comm.). *Challenges:* climate change is ongoing with little public awareness of Antarctica's terrestrial biota and value and, therefore, a lack of funding for research and management.
Potential actions		AVOID: minimise future station activity footprint[9]; global climate action. RECOVER: leave vegetated areas to recover after extreme events. RESTORE: reduce pressures from station, research and operation activities. RENOVATE: hydro-ecological engineering to replace lost water (e.g., building of strategically placed snow fences); translocation of biota to areas with more secure future water availability. ADAPT: actively create new habitats.
Global context		Extreme events (heatwaves, flooding) have had substantial impacts on ecosystems in other parts of Antarctica including major ecosystems shifts[10,11,13]. Extensive collapse of communities in the Arctic where elements of tundra have died (i.e. Arctic browning)[14,15].

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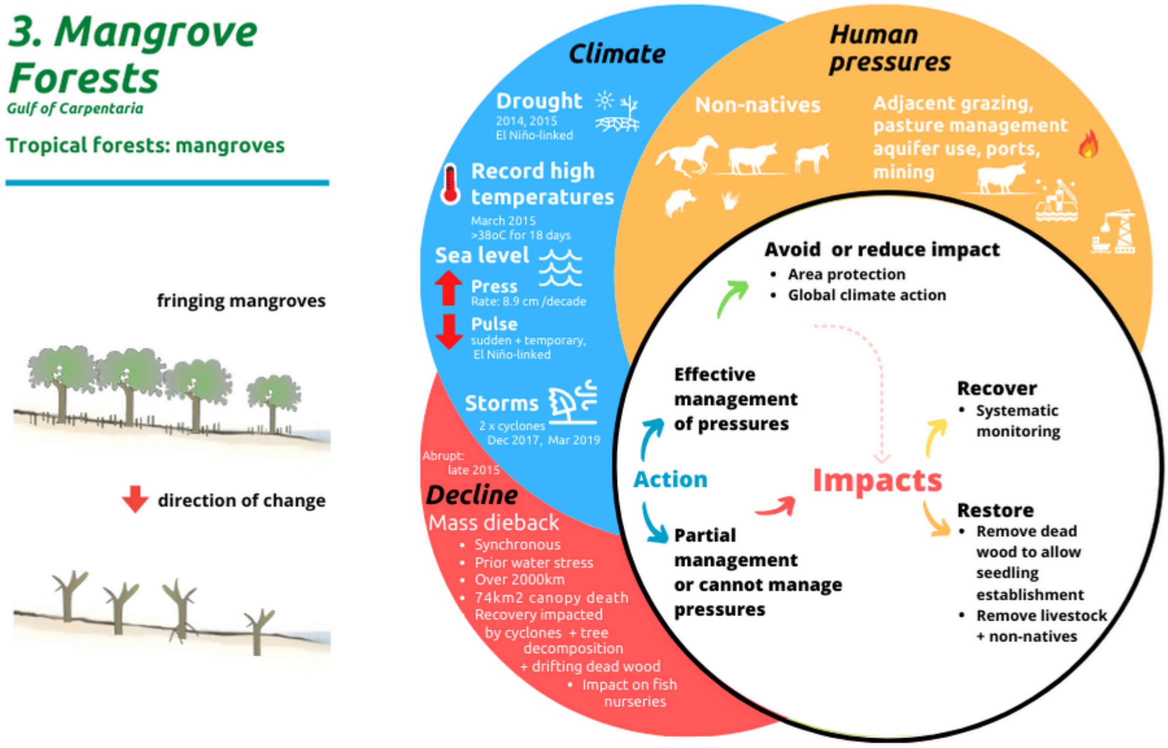
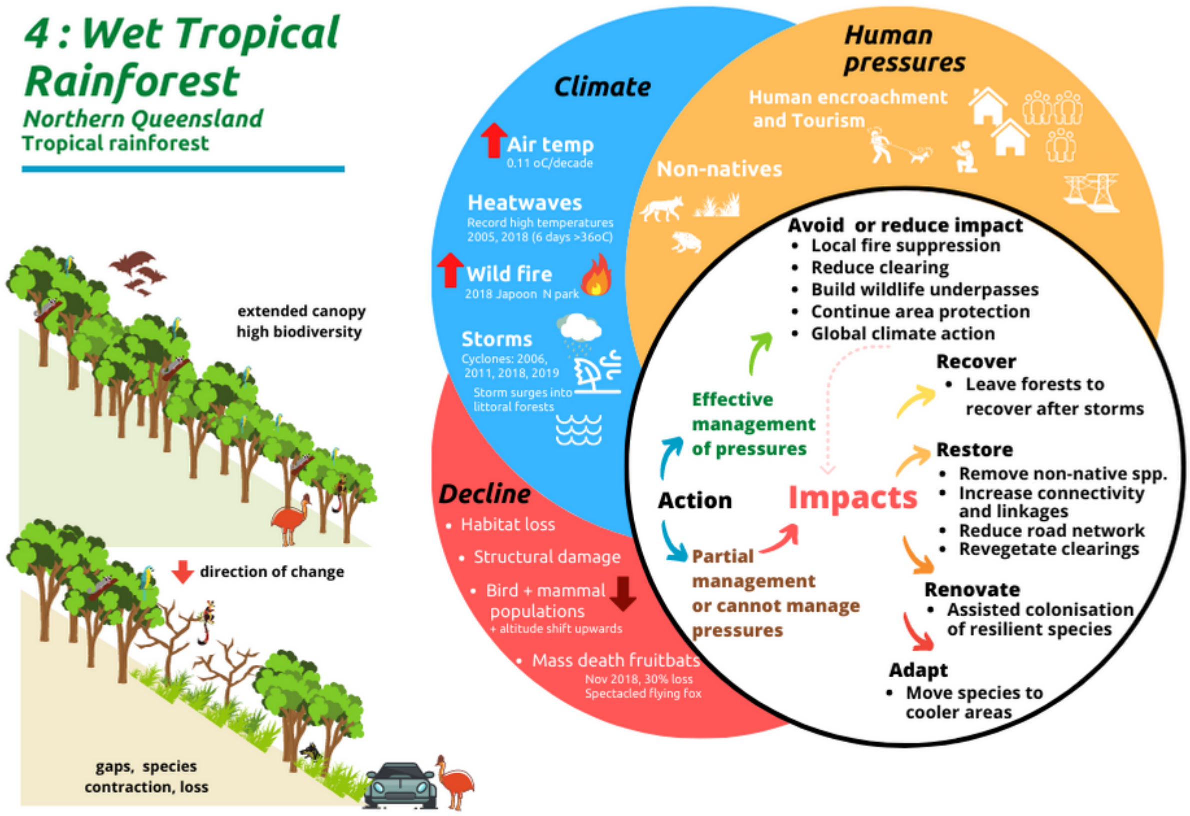
Images L–R: Ecosystem collapse in mosses at Mossel Lake, Vestfold Hills, from healthy (1998) to moribund (2005, 2018) with some repair after heatwave related flood 2020. (Images John French, Marcus Salton, Dana Bergstrom)

Image: Moribund moss bank, Lichen Valley Vestfold Hills (December 2019). (Image Dana Bergstrom)

Infographics for a subset of collapsing ecosystems

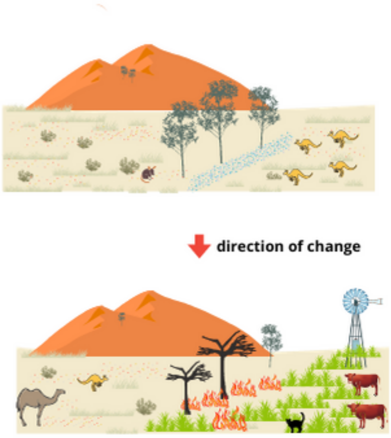
Symbols used from Canva.com and courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

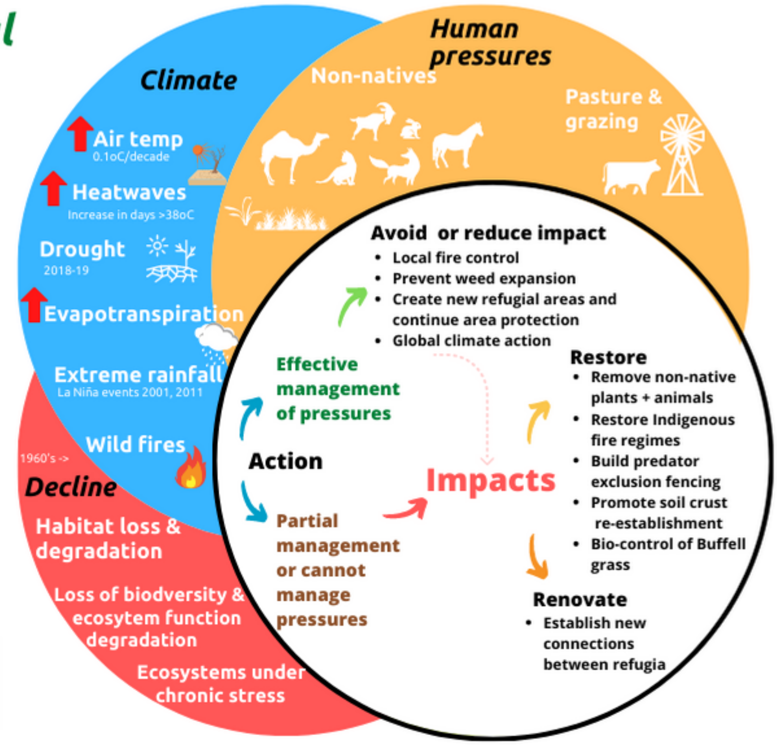




5: Western-central Arid Zone

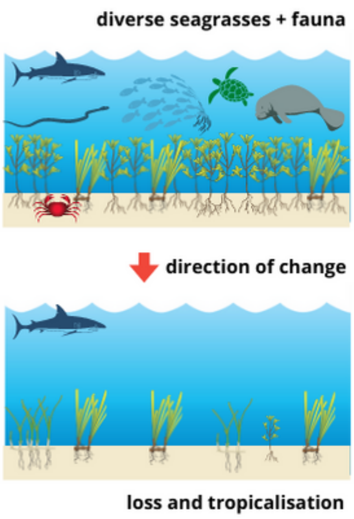
Deserts and xeric shrublands

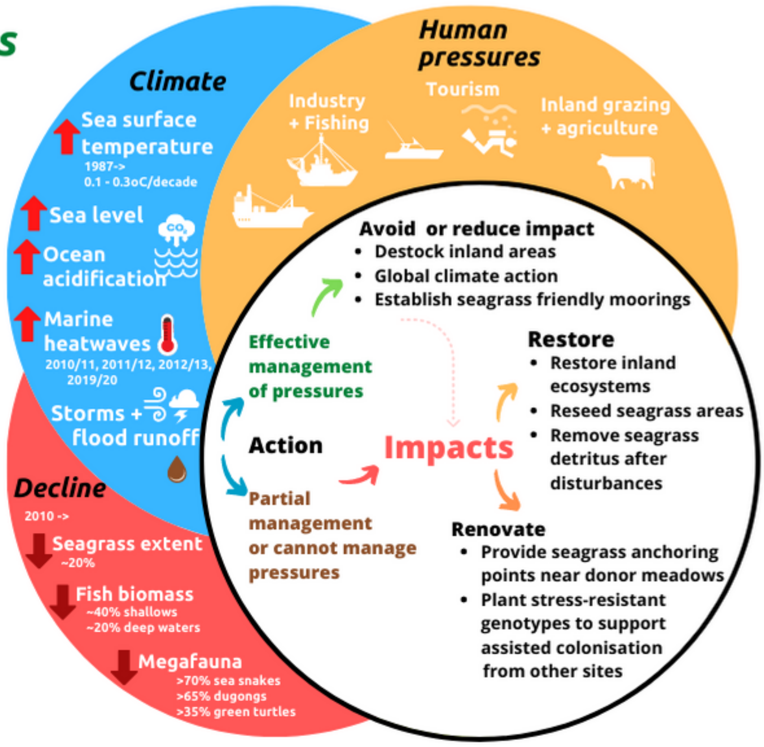




8: Shark Bay Seagrass

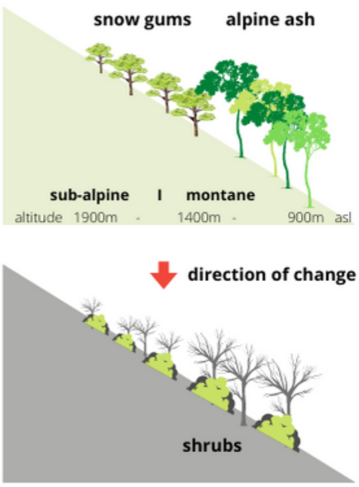
Coastal marine: seagrass

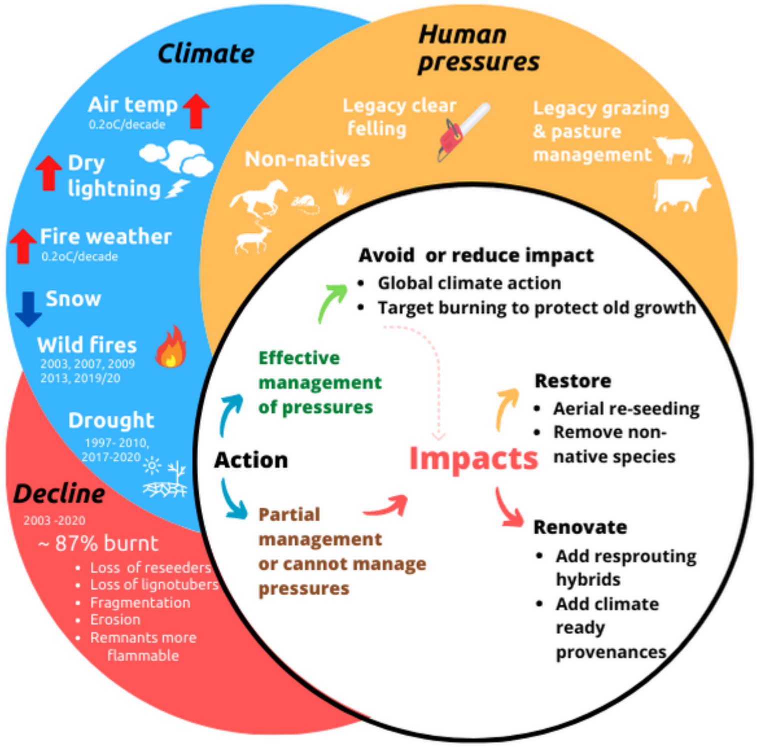




11. Montane and Sub-alpine Forests

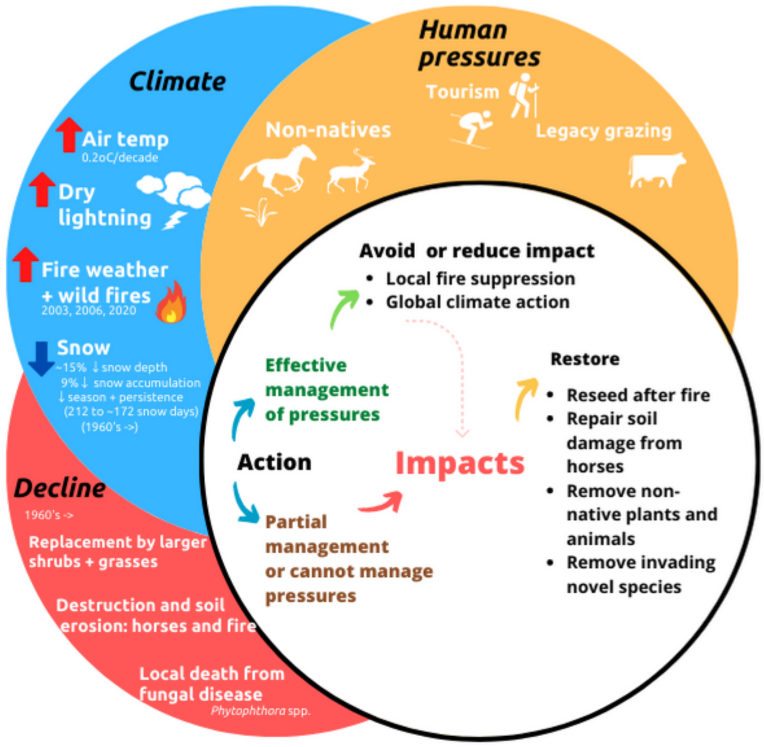
Temperate broadleaf forests





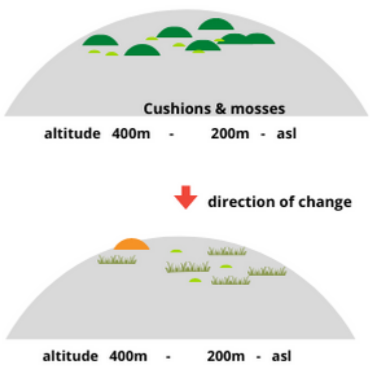
15 : Snowpatch herbfields

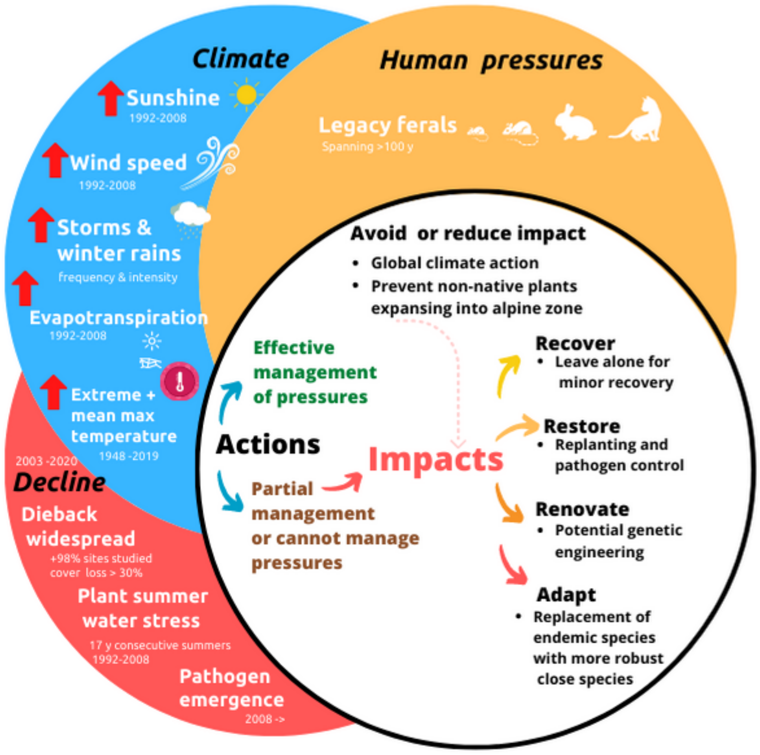
Mountains: alpine herbfield



18. Subantarctic Tundra

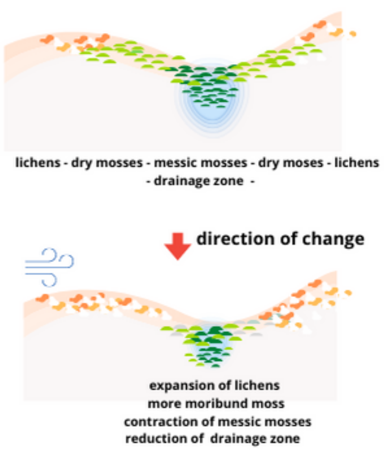
Polar Region

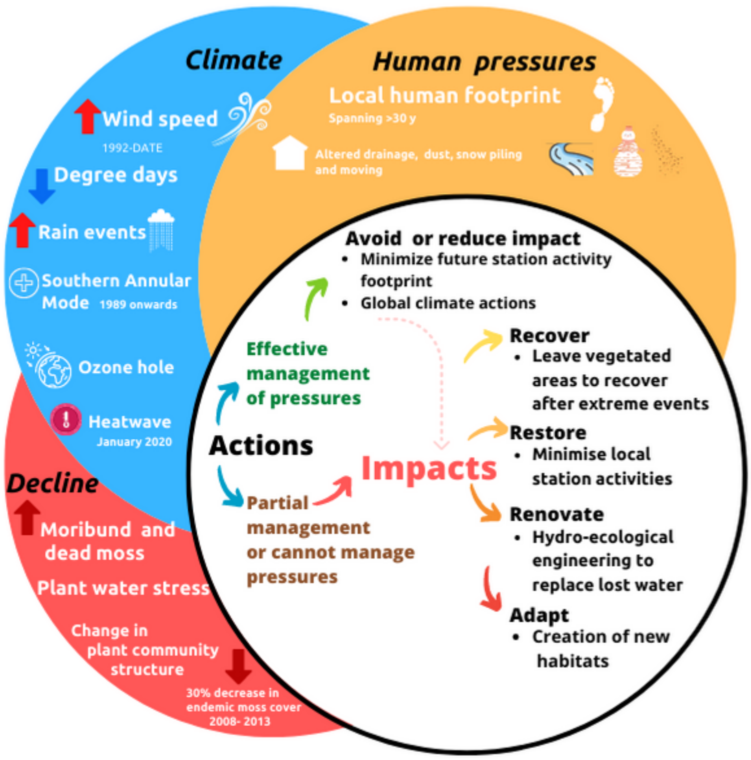




19. East Antarctic moss beds

Antarctic polar desert





Case Study: Practical application of the 3As Pathways

Fire management in the Gondwanan Conifer Forests (Ecosystem 17).

- Tasmania's temperate Gondwanan conifer forests, protected within the Tasmanian Wilderness World Heritage Area, face the ongoing and shifting pressures from bushfires. Bushfire ignition within the Tasmanian Wilderness World Heritage Area has transitioned over the decades from human caused to natural (lightning). The reduction in human caused fires was achieved through regulation of protected areas, community education and application of successful management strategies. However, changes in climate have led to a higher incidence of dry lightning fires[1]. These fires are now the most serious acute pulses in this ecosystem[1]. Dry lightning fires resulted in 19,800 ha of the TWWHA being burned in 2016, and a further 95,000 ha burned during the 2018/19 fire season[2,3].
- *Awareness* and *Anticipation*: After the 2016 fires, adaptive fire management practices led to improved awareness of values. Tasmania Parks & Wildlife Service land managers identified values in the Tasmanian Wilderness World Heritage Area based on fire sensitivity and capacity to recover. Ecosystems dominated by ancestral gymnosperm lineages were identified as highly priority for protection.
- During the summer of 2018/19 bushfire season, managers used an improved Bushfire Risk Assessment Model that compiled at-risk values versus likelihood of fire impact, with overlays of existing spatial data (including vegetation values attributes). Supplementary expert knowledge was also captured in the spatial data. This characterisation of values within a risk assessment matrix and associated maps, plus on-ground feedback, informed daily planning of fire-fighting operations (*Action*).
- Seasonal climate and weather forecasts provided by the Australian Bureau of Meteorology enabled forward planning for and throughout the fire seasons. During the 2018/19 season, daily weather forecasts allowed the pre-positioning of fire response crews in *Anticipation* of new ignitions during high-risk periods.
- *Action*: The anticipatory tools led to the development of new strategies to prepare for fires. When they occurred, novel and innovative actions were deployed to protect high value vegetation threatened by fire. On the ground, these included the use of portable water reservoirs and sprinkler lines (see below) to offer local protection to high value areas. Similarly, anticipatory research into the likely impacts from the use of aerially applied fire fighting chemicals (i.e. retardants and suppressants) enabled managers to make the decision to use these within the Tasmanian Wilderness World Heritage Area.
- Despite the larger overall area burned during the 2018/19 fire season, these mitigation actions proved to be effective, and only 19 ha of high value Gondwanan forests were affected compared to the 85 ha in 2016.
- By mapping vegetation values against fire sensitivity, maintaining an area specific awareness of the shifting causation of bushfires, and developing new action strategies to lessen the pressure of unregulated fire, the managers have established and used *Awareness* and *Anticipation* to formulate positive *Action*.
- Prepare for future change: in the long term, improving regional climate projections will enabling future planning, including changes in the opportunities available for fuel reduction burning. Long-term climate change projections for the Tasmanian Wilderness World Heritage Area are being incorporated into fire simulation models developed specifically for the region. This enables fire managers to devise effective planned reduction-burning programs that could mitigate pressures on natural values.

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Image clockwise L–R: Firefighting at Mount Cullen, Tasmanian Wilderness World Heritage Area, 2016. (Image: S. T. Brooks).

Sprinkler system installed at the Gell River Fire, January 2019. (Image: Chris Emms)

Table S2. Summary of total and median numbers of pressures (presses and pulses) on 19 ecosystems. If the categories contained more than one pressure, the numbers are shown. Salinity occurred as both a press and a pulse. Several human impact activities lead to habitat change/loss including clear felling, urban and agricultural development, erosion and marine infrastructure (See Table S1 for details).

	Global Climate Change Pressures										Regional Human Impacts Pressures												Collapse Profiles			
	Presses					Pulses					Presses				Pulses			Summaries								
Ecosystem #	Precipitation	Temperature	Ocean acidification /CO2	Salinity	Sea level change	Native spp interactions	Heatwave	Flood	Storm	Fire	Habitat change/ loss*	Invasive spp	Livestock/ harvesting	Water extraction	Runoff/ pollution	Human-lit fire	Other	Global climate change presses	Global climate change pulses	Human presses	Human pulses	Total	Abrupt	Smooth	Stepped	Fluctuating
1		1	1	2		1	1	1	1		4				1		1	4	4	4	2	14				
2	1	1	1						1	1	2	1	1	1		1		3	2	5	1	11				
3	1	1		1	1		1	1	1		3	1	1	1	1	1	2	4	3	6	4	17				
4	1	1					1	1	1	1	5	1			1			2	4	6	1	13				
5	1	1					1			1	1	1	1	1				2	2	4	0	8				
6	1	1					1			1	2	1	1	1			1	2	2	5	1	10				
7		1	1		1		1		1		5		1	1	1		1	3	2	7	2	14				
8		1	1				1	1	1		5		1				2	2	3	6	2	13				
9	1	1			1		1	1		1	5	1	1	1	1		1	3	3	8	2	16				
10	1	1					1			1	3	1	1	1				2	2	6	0	10				
11	1	1					1		1	1	3	1	1			1		2	3	5	1	11				
12		1	1			1	1		1		3		1		1		1	2	3	4	2	11				
13	1	1				1	1		1	1	3					1		2	4	3	1	10				
14	1	1				1	1			1	2	1	1					2	3	4	0	9				
15	1	1							1	1	2	1				1		2	2	3	1	8				
16	1	1								1	3	1					1	2	1	4	1	8				
17	1	1							1	1	2	1						2	2	3	0	7				
18	1	1				1		1	1								1	2	3	0	1	6				
19	1	0				1	1		1		3			1			1	1	2	4	1	8				
Total	15	18	5	3	3	6	14	6	13	12	56	12	11	8	6	5	12									
																Mean		2	3	5	1	11				
																Median		2	3	4	1	10				