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OPINION

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

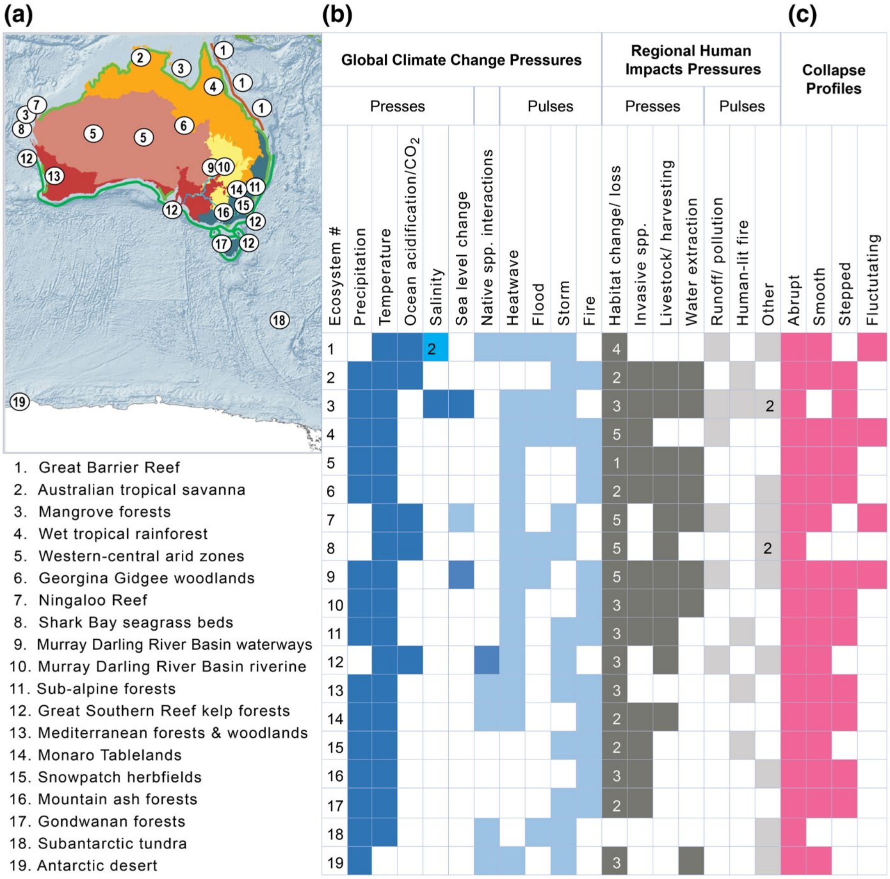

FIGURE 1 Locations and pressures of ecosystem change. (a) Map showing focal ecosystems (westernmost site in Antarctica is not shown) and geographical coverage of broad biomes (coloured areas from Ecoregions, 2017). Coloured lines indicate the extent of the marine ecosystems included in this study. (b) 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 [Colour figure can be viewed at wileyonlinelibrary.com]

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,

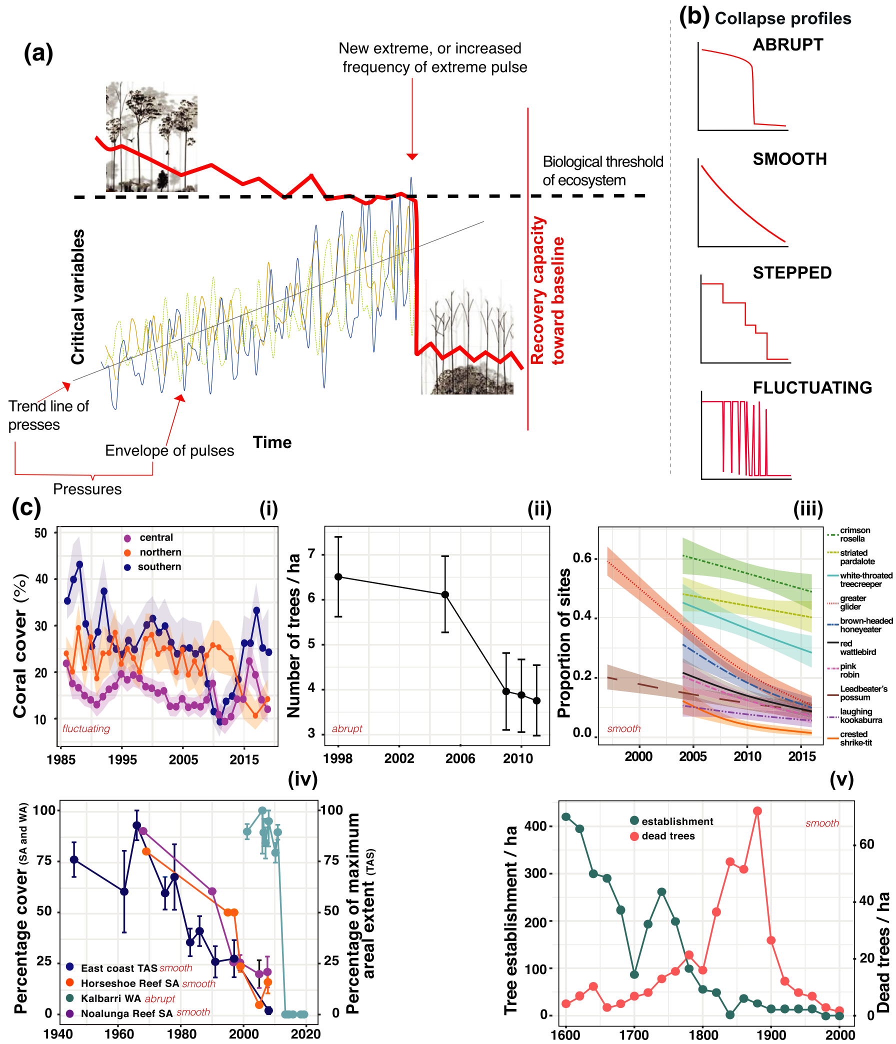

FIGURE 2 Ecosystem collapse trajectories. (a) Hypothetical trajectory for ecosystem collapse. *Y*-axis (left side): change in three hypothetical environmental variables (dotted green, orange and blue). Orange and blue are generally synchronous, and green is antagonistic. The trend line of presses is 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) [Colour figure can be viewed at wileyonlinelibrary.com]

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

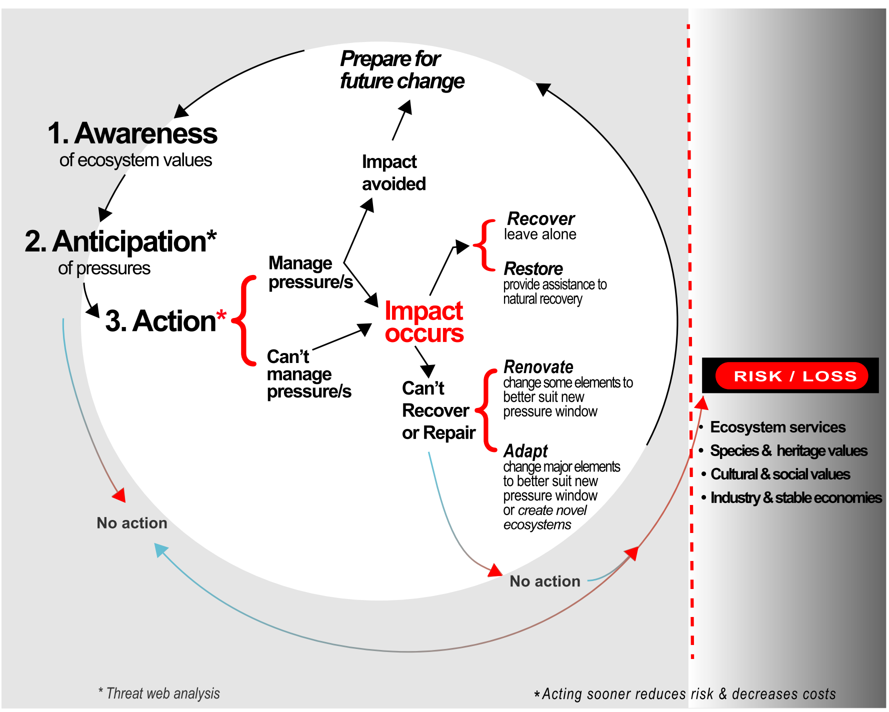

FIGURE 3 The 3As Pathway. *Awareness*, *Anticipation* and *Action* pathway for guiding strategic and effective threat abatement and ecosystem management. Anticipation can be enhanced with early warning tools such as vulnerability assessments and threat web analysis of the network of co-occurring pressures.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

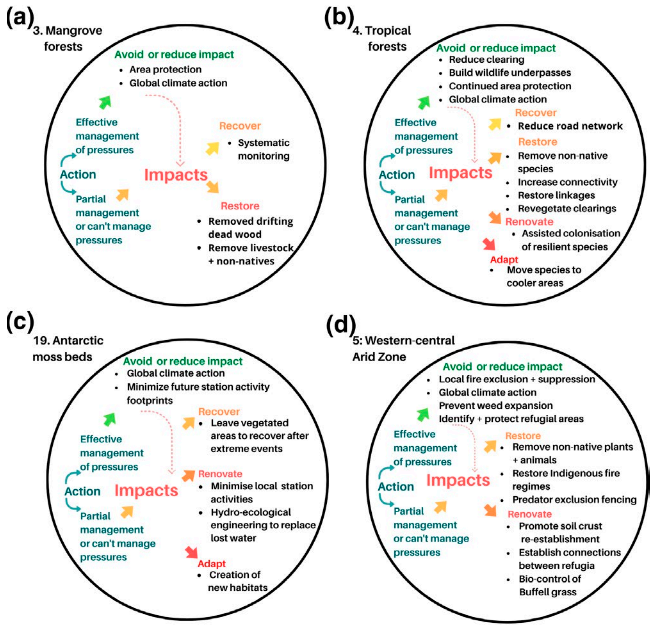

FIGURE 4 Examples of potential *Action* steps from the 3As Pathway for four ecosystems in sequential order from attempting to manage pressures to consequential actions to deal with impacts. Application of the pathways is based on consideration of the collapse profiles combined with ecological knowledge 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 [Colour figure can be viewed at wileyonlinelibrary.com]

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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