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REVIEW

Detecting and attributing climate change effects on vegetation: Australia as a test case

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Societal Impact Statement

Climate change is contributing to vegetation changes that threaten life support systems. Yet, inherent climatic variability and past and present human actions—such as clearing, burning and grazing regimes—also alter vegetation and complicate understanding of vegetation change. Australian ecosystems exemplify such complexity. To predict future vegetation changes, proactively guide management and ensure persistent drivers do not disrupt intended outcomes, we need to untangle the effects of these various change drivers on vegetation. Such attribution of change, which is rarely done, requires historical context, long-term datasets of vegetation and environmental drivers and integrating data with process-based understanding.

Summary

Climate change is expected to affect vegetation: associated rising atmospheric CO_2, higher temperatures and more variable and extreme rainfall regimes can all cause major shifts in vegetation composition, structure and function. Such effects need to be detected to confirm understanding and to inform models that can predict future vegetation change and guide management efforts. However, many change drivers—some related to, and others distinct from, climate change—simultaneously affect vegetation. These drivers include altered land management practices and shifts in fire and grazing regimes. Untangling the signals of climate-change-induced vegetation change from these other drivers of variation poses significant challenges. These challenges are amplified in regions with high interdecadal climate variability and enduring legacies of shifting human activities. Here, we assess attempts to detect and attribute vegetation change across Australia, a continent that exemplifies such complexities.

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We develop a scheme to classify attribution efforts according to whether they consider (1) qualitative or quantitative evidence, (2) mechanistic explanations and (3) alternative plausible change drivers. While a significant body of evidence demonstrates vegetation change in Australia, we find that it is difficult to confidently attribute changes to recent climate shifts—noting that few studies have attempted to do so. Several recommendations emerge that may improve attribution worldwide, including explicitly considering attribution strength, committing to long-term monitoring of vegetation and change drivers and recognising multiple drivers of change, especially past and present human influences. Finally, achieving the strongest level of attribution requires linking observations and mechanistic models.

KEYWORDS
anthropogenic climate change, attribution, change detection, disturbance regimes, historical legacies, land use change, process-based models, vegetation monitoring

1 | INTRODUCTION

Terrestrial vegetation is a fundamental part of the Earth system, driving primary production and shaping the fluxes of energy and materials that underpin the benefits people derive from nature. Vegetation composition, structure and function influence biodiversity, carbon sequestration, surface water runoff, soil erosion, land surface temperatures and wildfire frequency (Ahlström et al., 2015; Poulter et al., 2014; Wilcox et al., 2022). Current and ongoing rapid climate change, driven by anthropogenic greenhouse gas emissions, will ultimately drive significant vegetation change and have major consequences for dependent organisms as well as the functioning of ecosystems. To maintain ecosystem services, we need to predict and proactively manage for climate-driven vegetation change.

However, there are still major uncertainties about the nature of this change. One critical question is the relative importance of the fertilising effect of rising atmospheric CO_2 concentration, which is thought to drive large-scale greening (Walker et al., 2021), compared to the effect of increasing extremes of heat and drought, which may drive large-scale mortality events and increasingly severe fires (Hammond et al., 2022; Higuera & Abatzoglou, 2021; Pederson et al., 2014; Turco et al., 2023). Another open question is the degree to which species' current distributions reflect their climatic tolerances, and what might happen to populations that are increasingly exposed to climatic conditions beyond the range of their historical climate (Sexton et al., 2009). Attempts to study these processes and their interactions using mechanistic models confirm these uncertainties and the complexity of their dynamics (e.g., Abatzoglou et al., 2021; Hudiburg et al., 2013; McDowell et al., 2022), highlighting the need for further empirical research.

One important way in which we can increase our understanding and predictive capacity is by measuring the climate-change-driven effects that have already taken place. Climate drivers have already changed substantially due to human activity. In 2024, atmospheric CO_2 averaged 422 ppm, an increase of 50% above the pre-industrial concentration of 280 ppm, while global surface air temperature was 1.6°C warmer than the pre-industrial baseline (1850–1900) (climate.copernicus.eu). Other dimensions of anthropogenic climate change include more frequent and intense heatwaves, increased droughts and more frequent and intense precipitation events, which have all been observed since the 1950s (IPCC, 2023). These recent climatic changes are highly likely to have already affected vegetation (Harris et al., 2018; Hoffmann et al., 2019; Rosenzweig et al., 2008). Identifying the nature of these effects would help to reduce uncertainty about potential changes in the future.

Monitoring to detect vegetation change is therefore a priority. However, detecting the signal of anthropogenic climate change in vegetation change is not straightforward for several reasons (Figure 1). First, the climate is inherently variable. Thus, detecting directional changes against background variability is challenging and requires long-term, high-resolution datasets, particularly in regions with high inter- and intra-annual climatic variability. Biological systems are also inherently variable, with successional dynamics following disturbance that can unfold over decades or centuries (Davis, 1983; Davis & Shaw, 2001). Moreover, climate change is not the only driver of vegetation change: a wide range of other human activities shape vegetation and have done so for millennia. Many regions have been subject to major transitions in land care and management practices due to waves of human colonisation. These impacts may vary across local to continental scales and variously reinforce or counteract the dynamics and systematic changes in vegetation that would hypothetically occur in the absence of humans (Fletcher et al., 2024). These impacts are also cumulative, and the outcomes are path-dependent: current vegetation reflects unique historical pathways that are the result of interactions between vegetation and drivers in the past. Additional complications include confounding variables and the potential for interactions among drivers and the responses of vegetation to be complex and nonlinear (Byrnes & Dee, 2025; Dudney et al., 2024; Oliver & Morecroft, 2014).

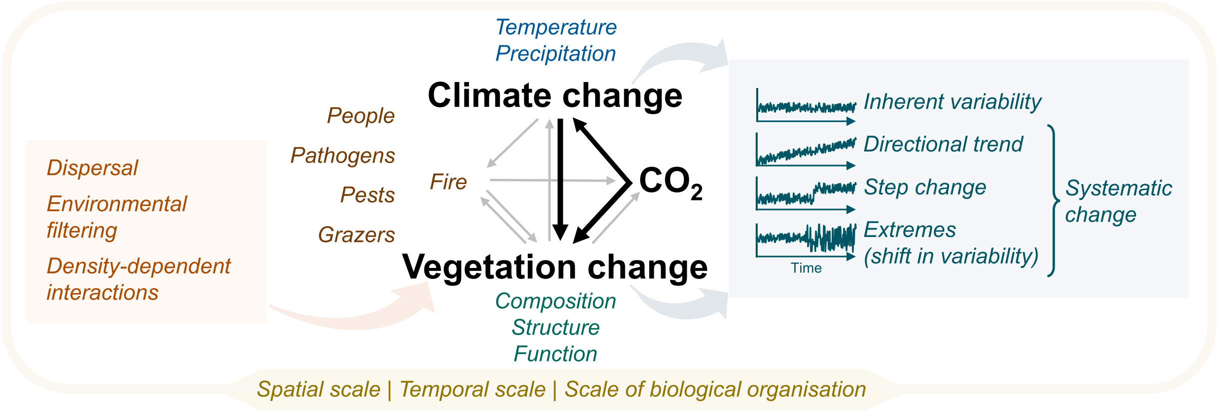

FIGURE 1 The quest to understand how anthropogenic climate change, driven by rising atmospheric CO_2 is affecting vegetation appears simple (shown in black). However, it is underpinned by complexity (shown in colour): climate and vegetation can each be characterised in different ways; change can encompass several dimensions; a suite of biological processes shape vegetation; current and historical change drivers other than climate, including disturbance agents (such as fire, grazers), also shape vegetation in ways that may interact with each other and climate; and perceptions of vegetation change depend on scale.

We argue that these complexities make it important to pay careful attention to attribution because understanding the full complement of vegetation change drivers is needed to predict how and where vegetation will change and to manage these changes. Process-based models—key tools for predicting change—work by representing biological and ecological processes. Thus, these models rely on identifying the right processes and understanding their influence on vegetation from first principles (Gustafson, 2013); empirical examples with strong attribution are needed to assess model performance and ensure predictions emerge via the correct pathways. Effective management also relies on identifying the drivers of vegetation change. There may be scope to take strategic action to shape the rate or direction of vegetation change where, for example, current management regimes are driving change (Prober et al., 2017). On the other hand, failure to recognise and address ongoing change drivers may thwart management outcomes. Emerging markets in nature repair and biodiversity recovery are a case in point and further underscore the need to understand drivers of vegetation change lest markets incentivise actions that are ineffective or fail to achieve benefits that would not otherwise occur (i.e., fail to meet standards of additionality and integrity) (Bryan et al., 2016; Macintosh et al., 2024; West et al., 2023; zu Ermgassen et al., 2023).

In this review, we aim to address current capacity to detect and attribute climate-change-driven vegetation change, drawing on data sources ranging from palaeoecological approaches to remote sensing, and focussing on the composition, structure and function of vegetation in Australia. The Australian continent is a useful test case because it highlights some of the complexities in understanding and attributing vegetation change, including high climate variability (Nicholls et al., 1997; Peel et al., 2004) and diverse anthropogenic drivers of vegetation dynamics over tens of thousands of years (reviewed in e.g., Bergstrom et al., 2021; Bowman et al., 2013; Bradshaw, 2012; Fensham & Fairfax, 2002; Harris et al., 2018; Hoffmann et al., 2019; Hovenden & Williams, 2010; Hughes, 2003; Lunt, 2002). Of particular concern, several Australian ecosystems are thought to be especially vulnerable to change (Laurance et al., 2011), highlighting the need to accurately assess the drivers of change in these ecosystems.

Here we (1) give an overview of the drivers of vegetation change in Australia; (2) summarise the empirical data sources available to detect change and (3) present a new scheme that classifies efforts to attribute change, and illustrate this scheme with examples of vegetation change from across Australia. In doing so, we evaluate the strength of recent attribution attempts, particularly in demonstrating whether signals of elevated atmospheric CO_2 or climate change are evident. By using Australia as a test case, we pinpoint key difficulties and challenges that may limit attribution worldwide and identify steps needed for improvement.

2 | A BRIEF OVERVIEW OF DRIVERS OF VEGETATION CHANGE IN AUSTRALIA

The Australian continent has faced many drivers of vegetation change that have shifted from deep time to the present (Figure 2). Along with the rest of the globe, climate across Australia has been changing over recent decades (CSIRO & Bureau of Meteorology, 2024). From 1910 to 2024, Australia's climate has warmed on average by 1.5°C and the number of extreme heat events has increased. Changes in rainfall have differed across the continent: the highest declines have been observed in the south-west and south-east (16% and 9%, respectively, in the cool season since 1970) while rainfall has increased in the north (20% in the wet season since 1994). There has also been an increase in extreme fire weather, and the fire season has lengthened since the 1950s. These changes in climate means and extremes, combined with the underlying rise in global atmospheric CO_2, are forcing a dynamic system: Australia is subject to inherent high inter-decadal climatic variability, especially in

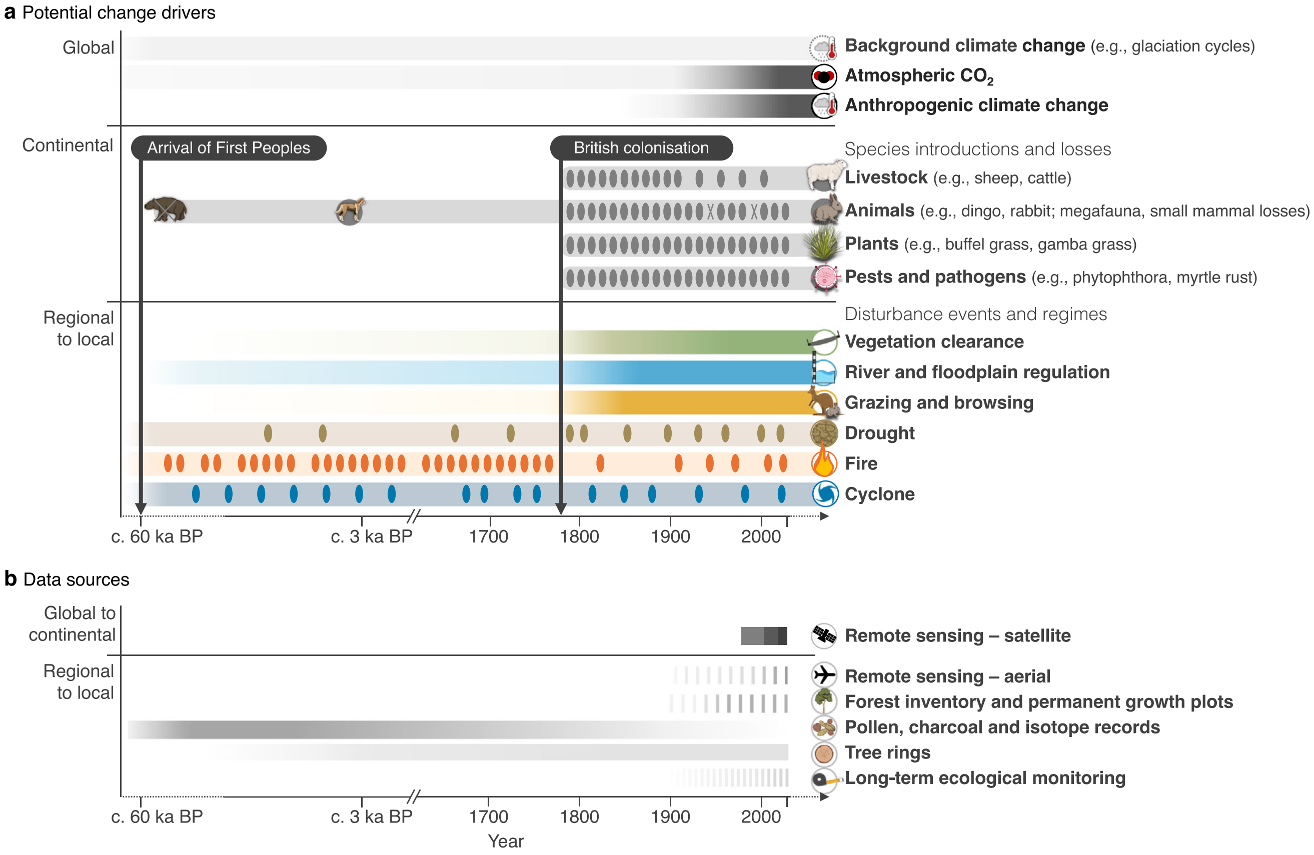

FIGURE 2 In Australia, (a) many potential drivers of vegetation change have operated at various spatial scales from the past to the present. (b) Several approaches collect the time series data needed to detect change; these data sources vary in their spatial and temporal coverage. In (a), shading indicates the hypothesised influence, and ovals indicate the relative timing and frequency of events (under species introductions and losses, filled ovals indicate introductions and crosses indicate losses); these are intended to be broadly indicative. In (b), shading indicates the amount of data (darker = more), and dashed bars indicate the temporal resolution of data.

rainfall (Nicholls et al., 1997; Peel et al., 2004) and hydroclimatic conditions (Palmer et al., 2015).

Since the late Pleistocene, there have been notably acute transitions in change drivers linked to the activities of humans. Indigenous people have shaped vegetation across the Australian continent over tens of millennia through the use of fire, producing landscapes and biodiversity that depend on human agency (Bliege Bird et al., 2008, 2018; Bowman, 1998; Fletcher, Hall, & Alexandra, 2021; Mariani et al., 2022; Russell-Smith et al., 2013). From 1788, British invasion and subsequent colonisation caused rapid shifts in land management: large swaths of the country were denied the care and management they had received from Indigenous people (Fletcher, Romano, et al., 2021), and clearing of vegetation for settlement, agriculture and mining became a priority. Over time, attitudes to land management have evolved, notably with the emergence of the conservation movement in the 1960s. Woody vegetation nevertheless continues to be cleared to expand agriculture (Fensham et al., 2011; Johansen et al., 2015) and, by 2023, one-fifth of Australia's bioregions (18 of 87), mostly in the southern and higher rainfall areas of Australia, were classified as predominantly cleared (Adams et al., 2023).

Fire regimes are a dominant driver of vegetation structure, composition and function. Since the last interglacial period, they have undergone profound shifts associated with climate change, the first arrival of humans to the continent and subsequent cultural shifts. Pre-human fire regimes were characterised by infrequent lightning ignitions that could cause large fires with a mix of severities. Indigenous people shifted fire regimes to frequent, low-severity and typically small (pedestrian-scale) fires that created mosaics of vegetation types and ages (Bliege Bird et al., 2008; Bowman, 1998; Fletcher, Hall, & Alexandra, 2021; Gott, 2005; Jackson, 2022; Murphy et al., 2013). Following British invasion and colonisation, locally nuanced cultural fire regimes were lost from nearly all Australian landscapes (Bliege Bird et al., 2012; Fletcher, Romano, et al., 2021; Mariani et al., 2022; Price et al., 2012). In their place, fire regimes now include frequent and extensive fires, which have caused the loss of older habitat (Doherty et al., 2024). Modern fuel management regimes (prescribed burns) in forested areas of southern Australia are typically larger, more intense and occur in different seasons than cultural burning regimes (Duff et al., 2019; Howard et al., 2020; Morgan et al., 2020). Now, catastrophic fires are a major contributor to Australia's carbon emissions (van der Velde et al., 2021; Villalobos et al., 2023); these fires are thought to be driven principally by a changing climate, but may be fuelled by increasing fuel loads potentially associated with altered management regimes (Abram et al., 2021; Nolan et al., 2021; van Oldenborgh et al., 2021).

Many animal, plant and pathogen species have been introduced while native species have been lost, with implications for vegetation structure, composition and function. Megafaunal species, which browsed vegetation and dispersed seeds, were lost by ca. 40 ka BP (Adeleye, Andrew, et al., 2023; Johnson, 2009; Lopes Dos Santos et al., 2013). Since British colonisation, >10% of endemic terrestrial mammal species (28 of 273 species) have been lost and many more are threatened—most are small mammals, which acted as seed dispersers, seed predators, pollinators and browsers (Woinarski et al., 2019). Some losses may instigate trophic cascades and affect vegetation structure and ecosystem function (e.g., Gordon et al., 2017; Gordon & Letnic, 2019; Stephenson et al., 2024). Colonisation saw the introduction of livestock such as cattle and sheep, with widespread impacts (reviewed in Lunt et al., 2007), as well as now-feral grazers and browsers including rabbits, goats, pigs, deer, horses, donkeys, buffalo and camels. The population size and influence of these feral species have varied over time, shaped by climate, vegetation and human-induced control measures. For example, rabbit populations reached plague proportions by the mid-19th century, have been periodically suppressed with the introduction and spread of viruses (myxoma in the 1950s and rabbit haemorrhagic disease virus in the mid-1990s) and have partly rebounded with the development of disease resistance (Mutze et al., 2014). Many plant species introduced to enhance agricultural production have become invasive. Some of these plant species have increased the size, intensity and frequency of fires through grass-fire feedback cycles, such as *Cenchrus ciliaris* L. (buffel grass) in arid and semi-arid central and northwest Australia, and *Andropogon gayanus* Kunth (gamba grass) in the tropical savannas of the northern Territory (Miller et al., 2010; Rossiter-Rachor et al., 2008; Schlesinger & Westerhuis, 2021).

In summary, shifts in vegetation observed today may be the product of recently imposed change drivers as well as legacies from the past. Any effects of anthropogenic climate change on Australia's vegetation are occurring within this complex and variable milieu of drivers.

3 | DATA SOURCES FOR DETECTING VEGETATION CHANGE IN AUSTRALIA

A range of methodological approaches produce data that may be used to detect vegetation change (Figure 2b). Each of these data sources gives a different perspective of vegetation change—offering views of different dimensions of vegetation and changes across different scales of space, time and biological organisation (Table 1). Each approach also has notable strengths and limitations—some of which become especially evident in the environments of Australia. Here we give a brief survey of approaches that yield time-series data and thus could potentially support quantitative attribution. Beyond these approaches, there is a notable body of work investigating vegetation change in Australia using ethnohistorical approaches (e.g., Gammage, 2011; Howitt, 1890; Mifsud et al., 2025; Prober et al., 2019; Rolls, 1981, 1999).

3.1 | Pollen, charcoal and stable isotope records

Palaeoecological approaches, such as analyses of fossil plant remains, biomarkers and isotopes, are the only source of quantifiable data demonstrating changes in vegetation composition over centuries to millions of years. However, pollen and charcoal records only form in sedimentary environments. Thus, large regions of Australia lack such records. Palaeoecological records also typically lack the fine temporal resolution through to the present that would be needed to capture signals of anthropogenic climate change (Adeleye, Haberle, et al., 2023; Fletcher, Bowman, et al., 2021; Fletcher, Hall, & Alexandra, 2021). Nevertheless, there are some notable pollen records, particularly from southeastern Australia, which give long-term perspectives of vegetation change as well as insight into the relationship between vegetation change driven by past climate shifts and human interventions (e.g., Adeleye, Haberle, et al., 2023; Fletcher & Thomas, 2010; Hill, 1994; Lisé-Pronovost et al., 2019). Elsewhere, analyses of stable carbon isotopes in soil can reveal dynamics between forest and grassland where these vegetation types differ in their photosynthetic pathway (i.e., C3 versus C4 grasses, e.g., Bowman et al., 2007). Palaeoecological analyses can help quantify effect sizes of different drivers and thus may help in attributing observed changes as well as predicting rates and trajectories of future vegetation change (Adeleye, Haberle, et al., 2023; Beck et al., 2018; Fletcher et al., 2014). However, such approaches have significant limitations where change drivers are creating novel environments.

3.2 | Tree rings

Tree ring analyses can inform understanding of vegetation dynamics and links with disturbance and climatic histories of particular regions over potentially thousands of years and at annual (or even seasonal) resolution. For example, dating of fire scars on conifers across North America has helped reconstruct fire histories that provide context for interpreting drivers of landscape and vegetation change (Margolis et al., 2022 and references therein). However, the angiosperm genera that dominate Australia's forests and woodlands (*Acacia*, *Eucalyptus*, *Melaleuca*, *Allocasuarina*) often have complex wood structures and poor delineation of annual growth rings. These traits can make it difficult to accurately age many species and thus link, for example, changes in growth patterns and stand structures to events or regime shifts (e.g., drought, fire, insect attack). Nevertheless, climate reconstructions from tree ring studies of the widespread conifer *Callitris* as well as other long-lived conifers in Tasmania and Queensland have revealed extended drought and flood periods over several centuries (e.g., Allen et al., 2019, 2017; Haines et al., 2018; O'Donnell

TABLE 1 Summary of some of the major methodological approaches that capture historical time-series data needed to detect vegetation change in Australia.

Method	Temporal extent	Temporal grain	Spatial extent	Spatial grain	Scale of biological organisation	Taxonomic resolution	Vegetation dimension	Applicable systems
Pollen, charcoal and isotope records	100–100,000 + years	Coarse (10–100 + years)	Catchment (regional to local)	Catchment (regional to local)	Plant community	Family to genus (or species) for pollen; low (C_3 vs C_4 pathways) for stable isotopes in soil	Composition, structure	Sedimentary environments (lakes, wetlands) for pollen and charcoal
Tree rings	1–3,000 + years	Annual	Stand to landscape	Individual or stand	Plant community (one or more tree species)	Species	Structure, function	Woody taxa with annual growth rings (mainly seasonal environments)
Forest inventory and permanent growth plots	10–100 years	Variable (1–10 years)	1 to 100 s of ha	0.01–50 ha	Tree community (sometimes limited to commercially valuable species)	Species (sometimes species groups)	Function, structure	Forests
Long-term ecological monitoring	10–100 years	Variable (1–5 years for manual, sub-daily for sensor-based observations)	ha to landscape	Variable (1 m^2 to 1 ha)	Plant community (sometimes selective) to ecosystem	Species	Composition, structure, function	Any
Remote sensing	up to ca. 45 years (satellite) ca. 70 years (aerial photos)	Variable (daily to decades)	Patch (unmanned aerial vehicle) to global (satellite)	Variable (cm to km)	Individual plant to ecosystem	None (sometimes family to genus)	Structure, function, composition	Any

et al., 2021; and references therein). This understanding of long-term variability and tree growth responses are important context for interpreting potential impacts of more recent anthropogenic climate change. Regional-scale fire histories have also been developed by dating fire scars in shrublands and woodlands using both *Callitris* and eucalypt species that, in turn provide a framework for assessing impacts of differing fire regimes on vegetation, especially where there is an absence of long-term monitoring (Gosper et al., 2013; O'Donnell et al., 2010). Increased capabilities for high resolution radiocarbon dating coupled with careful characterisation of growth patterns of species in different settings are now revealing new insights as to the underlying drivers of vegetation change, for example, establishing links between mangrove dynamics and changing hydrology (e.g., Goodwin et al., 2022), and interactions between insect attack and drought occurrence on growth of snow gums in southeast Australia (Brookhouse et al., 2024).

3.3 | Forest inventory and permanent growth plots

In Australia, the longest forest inventory and permanent growth plot (PGP) datasets extend back to the early 20th Century. Strategic inventory data have been collected over a wide area of Australia's public forest estate since the 1930s. While individual plots are not revisited, strategic inventory plots can be analysed collectively to infer population-level changes. Forest management agencies also established PGPs, where individual trees are tagged and re-measured through time, to monitor change at the tree and stand level and thus characterise individual demographic parameters (e.g., growth, mortality) (e.g., Bowman, Williamson, et al., 2014; Prior & Bowman, 2014). Two key limitations of forest inventory plots and PGPs are that they have historically focused on commercial timber species (primarily eucalypts in Australia) and have only sampled trees >10 cm DBH, reducing their utility in detecting changes in species composition. Experimental plots were also established to assess the consequences of silvicultural treatments, such as thinning or spacing. Many of the plots were abandoned in the 1980s and 1990s. However, those that were monitored for long time periods may reveal the influence of management treatments under changing environmental conditions (e.g., Horner et al., 2009; Trouvé et al., 2025, 2017).

3.4 | Long-term ecological monitoring

Long-term ecological monitoring refers to repeated measurements of the same ecosystem, typically for 10 or more years (Strayer, 1986; Youngentob et al., 2013). Different long-term monitoring projects focus on different data types (Lindenmayer et al., 2014; Sparrow et al., 2020). Some projects survey floristics, revealing compositional shifts in vegetation communities at local to regional scales (e.g., Ashton, 2000). Others measure tree growth and mortality, similar to forest PGPs (e.g., Bradford et al., 2014), or track the demography of particular species (e.g., Connell & Green, 2000). Monitoring often targets responses to disturbance, such as fire, grazing and drought (Lindenmayer et al., 2014). High intrinsic variability at the relatively small spatial scales of many monitoring projects, coupled with the large influence of disturbance, can limit the power to detect long-term changes related to climate. Instrument-driven monitoring approaches have emerged over recent decades, such as eddy covariance measurements of fluxes from which near-continuous measures of ecosystem properties related to vegetation function can be derived. In Australia, a network of eddy covariance sites covers many of the continent's ecosystems (the OzFlux network, Beringer et al., 2016) and the longest running sites now have measurements for >20 years.

In contrast to long-term ecological monitoring, one-off observations represent a single snapshot in time and cannot demonstrate directional or persistent vegetation change. For example, reports of large-scale tree mortality worldwide (e.g., Hammond et al., 2022) and in Australia (e.g. Brouwers et al., 2013; Duke et al., 2017; Losso et al., 2022; Wright et al., 2023), while notable and worrisome, may not be historically anomalous (Fensham et al., 2019; Godfree et al., 2019) and, because trees can sometimes recover, may be transient (Losso et al., 2022).

3.5 | Remote sensing

Remote sensing spans myriad sensor technologies that can be ground-based (e.g., photopoints, terrestrial laser scanning) or deployed on platforms ranging from unoccupied aerial vehicles to satellites. In Australia, aerial photographs from as early as the 1930s provide a rudimentary but useful characterisation of historical vegetation cover (e.g., Fensham & Fairfax, 1996; Harrington & Sanderson, 1994). Satellite-derived remote-sensing products give systematically retrieved "wall-to-wall" coverage of multispectral data, with some records extending to the early 1970s and more accessible records from the early 1980s (e.g., Landsat and the Advanced Very High Resolution Radiometer, AVHRR). Multispectral remote sensing has been used to map changes in land cover as well as vegetation indices that can approximate canopy leaf area (e.g., Rifai et al., 2022). Several newer remote-sensing techniques (e.g., solar-induced fluorescence, imaging spectroscopy, LiDAR) can detect properties more closely linked to vegetation structure, composition and function (Cavender-Bares et al., 2020; Jucker et al., 2023; Youngentob et al., 2012). They hold substantial future promise, but their broad-scale implementation is slow, and data are currently too limited in temporal and spatial scope to be of use in long-term detection and attribution of change.

4 | ATTRIBUTING DRIVERS TO VEGETATION CHANGES

Most observed vegetation changes—in Australia and worldwide—could be the result of more than one driver. Attribution involves identifying the relative contribution of these drivers and assigning statistical confidence to their roles. Attribution of changes detected in observational data (in contrast to experiments with known manipulations and controls) is typically probabilistic rather than definitive. However, some principles may help assert causality, including: the cause must occur before the effect; a plausible mechanism links the cause and effect; the magnitude of the effect is consistent with process-based understanding (noting that our understanding may be imperfect and frequently ignores or treats separately the influences of humans); and alternative explanations can be eliminated (Byrnes & Dee, 2025; Hill, 1965; Kimmel et al., 2021).

These principles can be formalised into an attribution workflow for detecting and attributing vegetation change following those outlined for climate, biodiversity change and other ecological responses (e.g., Dudney et al., 2024; Gonzalez et al., 2023; Hansen et al., 2016; Hegerl et al., 2010; Rosenzweig & Neofotis, 2013), as follows:

1. Develop a *quantitative causal model* (which may take any form from hypotheses with quantified effect sizes to a formal process-based model, such as a dynamic vegetation model) that predicts the magnitude of vegetation change from hypothesised drivers using process-based understanding derived from observations, experiments and meta-analyses.
2. Collect *observations* of vegetation through time alongside temporally resolved data for specific hypothesised drivers of change.
3. Statistically analyse the vegetation data to *detect* change against background variability, such as the distribution of historical variability.
4. Compare vegetation data with the hypothesised drivers of change (using logic or quantitative techniques such as statistical or process-based models) to *attribute* drivers to observed changes—or to *refute* model hypotheses.

While it is rare to have sufficient information to apply all steps of this formal workflow (Parmesan et al., 2013), attribution should be attempted. Imperfect attempts can still provide valuable insights. However, it is useful to be explicit about which principles have been applied. We posit that attribution efforts differ along three main axes: (i) whether the form of evidence is quantitative or qualitative, (ii) whether a process-based explanation has been investigated (mechanistic or correlative) and (iii) the extent to which alternative plausible change drivers are considered (strong or partial). Based on these axes, we propose a simple scheme to classify attribution efforts into six classes (Table 2).

In the following, we describe each of these six classes and illustrate them with examples of vegetation change that have been detected and attributed from across Australia (Figure 3, Table 3) and which draw upon various data sources outlined above (Section 3). In doing so, we survey the current strength of attribution in Australia, pinpoint the difficulties and challenges that limit attribution and identify pathways toward improving attribution.

4.1 | Qualitative Correlative

Qualitative Correlative attribution describes cases where changes are hypothesised to be consistent with a given change driver, but there is no direct evidence—qualitative or quantitative—to support or refute the effect of the change driver. For example, analyses of digitised aerial photographs from regions of northern Australia have revealed shifts in vegetation distributions: forest expanded into grasslands over 40 years in the Bunya Mountains of Queensland (Fensham & Fairfax, 1996); rainforest expanded into eucalypt forest over ca. 50 years in far north Queensland (Harrington & Sanderson, 1994; Tng et al., 2012); and rainforest expanded into savanna over ca. 50 years at several sites in the Northern Territory (Banfai & Bowman, 2006; Bowman, Walsh, & Milne, 2001; Brook & Bowman, 2006). The drivers of these observed vegetation shifts were hypothesised to include CO_2 fertilisation, changes in rainfall patterns and/or altered fire regimes. However, none of these studies could formally attribute drivers to the observed vegetation changes because data on change drivers was lacking and/or vegetation data was of insufficient temporal resolution for statistical analysis.

While not offering conclusive attribution, cases of *Qualitative Correlative* attribution can contribute important insights and generate hypotheses for further investigation. For example, a study of stable carbon isotopes in soil indicates boundaries between *Triodia* (C_4 photosynthetic pathway) grassland and *Acacia aneura* (C_3 photosynthetic pathway) shrubland in the Tanami Desert of central Australia have remained stable for the past ca. 1,000 years (Bowman et al., 2007).

TABLE 2 Classification of the degree of attribution in studies of vegetation change.

			Form of evidence	
			Quantitative	***Qualitative***
Mechanistic certainty	***Process-based***	***Strong***	*Quantitative Strong*.—Mechanistic model applied; effect size(s) of given driver(s) able to explain observations, other drivers not able to	*Qualitative Strong*.—Evidence to support role of driver(s) and evidence to exclude role of other plausible drivers
		Partial	*Quantitative Partial*.—Mechanistic model applied; effect size of given driver able to explain observations but other drivers not examined	*Qualitative Partial*.—Evidence to support the role of one driver but other plausible drivers not examined
	Correlative		*Quantitative Correlative*.—No mechanistic model applied (thus no process-based expectation of effect sizes), but correlation between driver and observations	*Qualitative Correlative*.—Hypothesis only

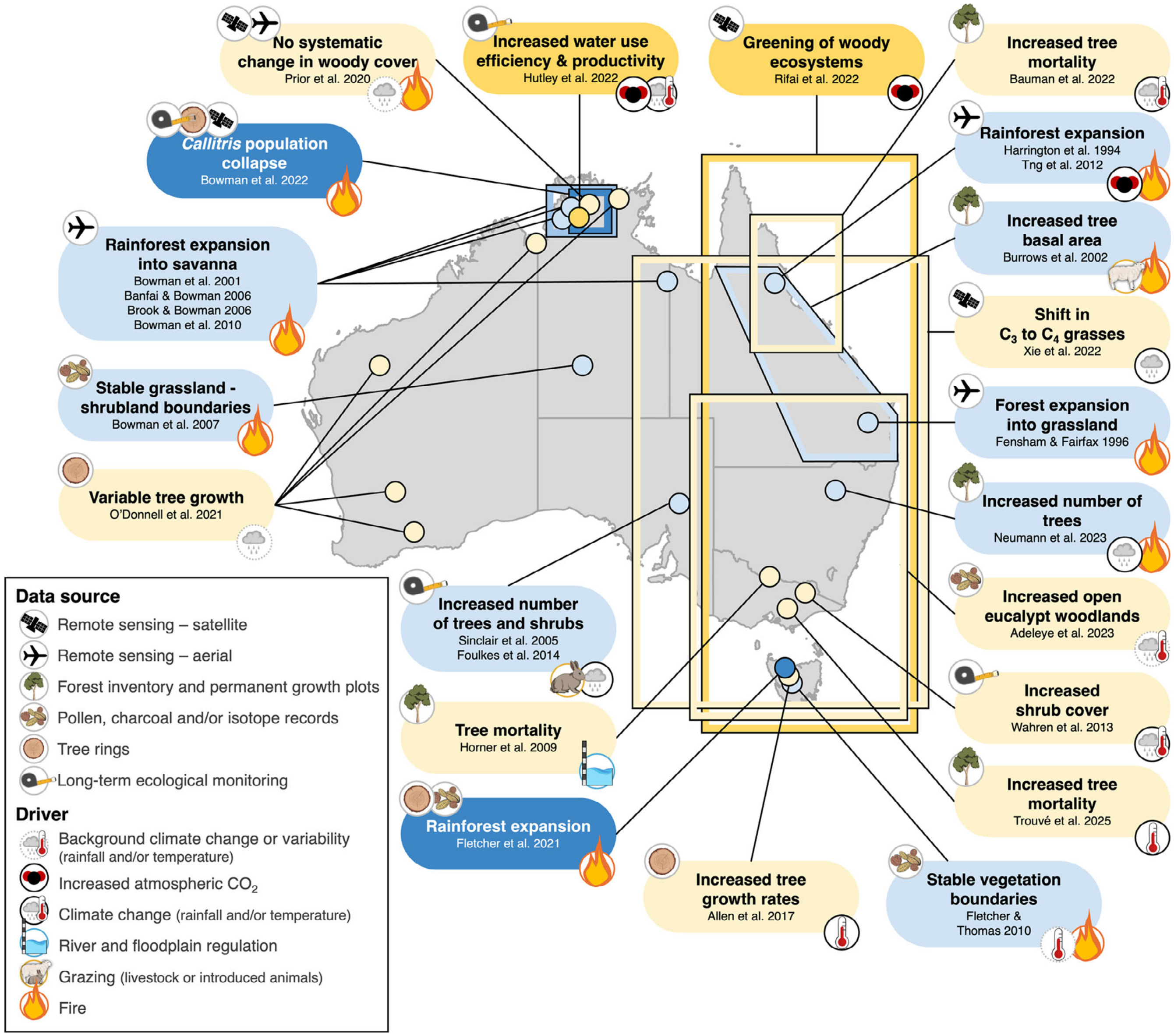

FIGURE 3 Approximate locations of the examples of observed vegetation changes in Australia discussed in Section 4. Examples are colour-coded by their attribution class: blue indicates Qualitative attribution and yellow indicates Quantitative contribution, with darker shades of each colour indicating stronger attribution (Table 2). Symbols indicate the main data sources used in change detection (top left of each example) and the attributed driver(s) (bottom right). See Table 3 for further details.

This is despite the expectation that shifts from Indigenous to modern colonial fire management might have caused the shrubland to retreat. Pollen and charcoal records from western Tasmania indicate vegetation distributions in this region are also stable, but this example reveals how human actions can modify climate-related effects on vegetation (Fletcher & Thomas, 2010). Pollen records show that, over the past 18,000 years, rainforest and moorland boundaries remained static despite warming conditions, and charcoal values during this period are higher than in previous periods of comparable climate. Drawing on these patterns, Fletcher and Thomas (2010) hypothesise that recently arrived humans brought new sources of ignition that were independent of climate, and that vegetation boundaries resisted climate-induced shifts because they were developed and maintained by humans—that is, they argue that this region of western Tasmania is a cultural landscape.

An example from northeastern Australia illustrates how land management may overlay and interact with global changes to complicate change attribution. Burrows et al. (2002) examined tree growth and survival in eucalypt woodlands (savannas) at a network of inventory plots that were repeatedly surveyed for up to 17 years. They found that basal area increased through time, mostly due to tree growth rather than new establishment. The authors acknowledge a potential effect of elevated atmospheric CO_2 and climate change. However, they postulated that elevated atmospheric CO_2 and climate changes that promote plant growth would preferentially enhance grass at the expense of trees. Instead, they draw upon anecdotal observations of

TABLE 3 Summary of some examples of vegetation changes observed in Australia and their attribution.

Attribution class	Data source	Time scale	System and location	Changes observed	Attribution	Reference
Qualitative Correlative	Pollen	Past 18,000 years	Western Tasmania	Increased charcoal; stable vegetation boundaries	Fire regime, climate change (long-term warming)	Fletcher and Thomas (2010)
Qualitative Correlative	Stable isotopes in soil	Past ca. 1,000 years	Tanami Desert, central Australia	Stable boundary between *Triodia* grassland and *Acacia aneura* shrubland	Soil fertility, fire regimes (increased soil fertility leads to more woody biomass, less grass and less fire)	Bowman et al. (2007)
Qualitative Correlative	Forest inventory	1982-ca. 2000	Savanna, Queensland	Stand structure (increased basal area)	Grazing, fire regime	Burrows et al. (2002)
Qualitative Correlative	Long-term monitoring	1926–2002	Chenopod shrubland, Koonamore, South Australia	Increased number of trees and shrubs	Rainfall (increased), grazing (rabbit removal)	Foulkes et al. (2014), Sinclair (2005)
Qualitative Correlative	Long-term monitoring (eddy covariance)	2001–2018	Savanna, Northern Territory and temperate eucalypt forest, southern NSW	Increased water use efficiency	CO_2 fertilisation, recovery from disturbance (insect outbreak), forest development	Beringer et al. (2022)
Qualitative Correlative	Remote sensing (aerial)	1941–1994 1947–1997 1964–2004	Savanna, Northern Territory	Rainforest expansion into savanna	CO_2 fertilisation, rainfall (increased), fire regime	Banfai and Bowman (2006), Bowman, Walsh, and Milne (2001), Brook and Bowman (2006)
Qualitative Correlative	Remote sensing (aerial)	1951–1991	Montane grassland, Queensland	Forest expansion into grasslands	Fire regime	Fensham and Fairfax (1996)
Qualitative Correlative	Remote sensing (aerial)	1943–1992 1949–2008	Wet tropics, Far North Queensland	Rainforest expansion into eucalypt forest	CO_2 fertilisation, fire regime	Harrington and Sanderson (1994), Tng et al. (2012)
Qualitative Partial	Remote sensing (aerial)	1941–2004	Savanna, Northern Territory	Rainforest expansion into savanna	Increased rainfall, CO_2 fertilisation	Bowman et al. (2010)
Qualitative Strong	Multiple (pollen, tree rings, historical records)	Past 250 years	Northwestern Tasmania	Rainforest expansion	Fire regime (cessation of Indigenous fire management)	Fletcher, Hall, and Alexandra (2021)
Qualitative Strong	Multiple (long-term monitoring, tree rings, remote sensing, field experiments, historical records)	20th Century	*Callitris intratropica*, savanna, Northern Territory	Population collapse	Fire regime	Bowman et al. (2022)
Quantitative Correlative	Pollen	Past 12,000 years	Southeastern Australia	Composition shifts including increased dominance of eucalypt woodlands and increasing woodland openness	Climate change (long-term drying)	Adeleye, Haberle, et al. (2023)
Quantitative Correlative	Tree rings	Past ca. 1700 years	*Athrotaxis selaginoides* and *Lagarostrobos franklinii*, northwestern Tasmania	Increasing growth rates since mid-1900s	Climate change (temperature)	Allen et al. (2017)

TABLE 3 (Continued)

Attribution class	Data source	Time scale	System and location	Changes observed	Attribution	Reference
Quantitative Correlative	Tree rings	1908–2018	*Callitris columellaris*, Western Australia and Northern Territory	Highly variable tree growth	Rainfall (amount and interannual variability)	O'Donnell et al. (2021)
Quantitative Correlative	Forest inventory	1947–2000	*Eucalyptus regnans*, Victoria	Increased mortality rates, decreased carrying capacity	Climate change (increased temperature and vapour pressure deficit)	Trouvé et al. (2025)
Quantitative Correlative	Forest inventory	1964–2019	Callitris-eucalypt forest, New South Wales	Stand structure (more but smaller trees)	Fire regime, rainfall	Neumann et al. (2023)
Quantitative Correlative	Forest inventory	1965–2007	Floodplain forest, Victoria	Tree mortality	River regulation (human-induced drought)	Horner et al. (2009)
Quantitative Correlative	Forest inventory	1971–2019	Tropical moist forest, Far North Queensland	Increased mortality rates	Climate change (increased vapour pressure deficit)	Bauman et al. (2022)
Quantitative Correlative	Long-term monitoring	1944–2010	Alpine grassland and heathland, Bogong High Plains, Victoria	Increased shrub cover, species-specific changes in forb cover, recent decreases in graminoid cover	Rainfall (decreased), temperature (increased)	Wahren et al. (2013)
Quantitative Correlative	Remote sensing (aerial and satellite)	1950–2016	Savanna, Northern Territory	Fluctuation in woody cover but no systematic change	Fluctuations attributable to rainfall and fire	Prior et al. (2020)
Quantitative Correlative	Remote sensing (satellite)	2003–2017	Grasslands, southeast Australia	Shift in C_3:C_4 grasses	Rainfall (seasonal timing)	Xie et al. (2022)
Quantitative Partial	Long-term monitoring (eddy covariance)	2001–2018	Savanna, Northern Territory	Increased productivity and water use efficiency	CO_2 fertilisation, rainfall, temperature (increased)	Hutley et al. (2022)
Quantitative Partial	Remote sensing (satellite)	1982–2019	Woody ecosystems, eastern Australia	Greening of woody ecosystems	CO_2 fertilisation	Rifai et al. (2022)

fence lines, where vegetation was subject to different grazing management, to hypothesise that observations of increased tree growth are most likely due to increased grazing intensity and reduced fire frequency.

4.2 | Qualitative Partial

While still lacking quantitative data, other forms of evidence may support or refute a plausible change driver, such as accompanying experiments that demonstrate the effect of a change driver, or evidence for the timing of an event that is hypothesised to be a change driver (i.e., a single data point rather than quantified magnitude). We classify such attribution as *Qualitative Partial*. For example, in synthesising studies of rainforest expansion into tropical savanna in the Northern Territory, Bowman et al. (2010) refute the hypothesis that the changes were the result of fire regime change. They reached this conclusion because demographic studies provided evidence that the population of a dominant rainforest tree was stable in response to altered fire regimes (Prior et al., 2007). By eliminating one plausible change driver, Bowman et al. (2010) were able to attribute rainforest expansion to their remaining hypothesised change drivers: increases in rainfall and elevated atmospheric CO_2. However, additional evidence to distinguish between these two change drivers was lacking.

4.3 | Qualitative Strong

Qualitative attribution may be considered *Strong* where alternative plausible change drivers are considered and evidence is presented to discriminate among them. Such cases often combine data from multiple sources. For example, Fletcher, Hall, and Alexandra (2021) combined pollen and charcoal records, tree ageing from tree rings and a written historical account to examine vegetation change over the past 250 years in the Surrey Hills, northwestern Tasmania. Pollen analysis revealed a shift from grassland to temperate rainforest, consistent with a historical description of vegetation and supported by the timing of tree establishment based on dating of *Nothofagus cunninghamii* and *Phyllocladus aspleniifolius* stands using tree rings. Together, these data sources show that this vegetation change predated human-driven increases in elevated atmospheric CO_2 and climate change. Fletcher, Hall, and Alexandra (2021) attribute the observed vegetation change to altered land management: grasslands were actively maintained by Indigenous people through a regime of burning, which ceased with British colonisation. They concluded that as cultural burning ceased, rainforest tree species were able to successfully recruit and persist. This led to a transition from culturally maintained grasslands to closed rainforest over approximately two centuries. By drawing on multiple lines of evidence, this study builds a case through qualitative reasoning that the observed vegetation changes were driven by altered land management and that their timing is inconsistent with anthropogenic climate change.

Synthesising evidence from multiple sources can reveal insights not evident from a single source alone. For example, the loss of populations of a significant tree species from northern Australia appears consistent with climate change but, taken together, evidence from multiple sources suggests this change is largely attributable to human-altered fire regimes (Box 1).

4.4 | Quantitative Correlative

Quantitative attribution involves comparing data on the magnitudes of change in vegetation and the hypothesised change driver. *Quantitative Correlative* attribution demonstrates a statistical correlation between a plausible change driver and patterns of vegetation change. The sophistication of analyses may vary substantially, with some methods better able to account for confounding variables (see e.g., Byrnes & Dee, 2025).

There are many studies of vegetation change in Australia that could be considered *Quantitative Correlative*. For example, long tree-ring chronologies have been developed for the Tasmanian conifers: *Athrotaxis selaginoides* (King Billy pine) and *Lagarostrobos franklinii* (Huon pine). Each extends over 1,000 years, shows sensitivity to temperature, and shows accelerated growth beginning in the mid-1900s (Allen et al., 2014, 2017; Cook et al., 1991). These growth trends were attributed to increased temperatures based on correlations with instrumental records (Allen et al., 2014, 2017; Cook et al., 1991). However, the role of other potential drivers of growth trends, such as increasing atmospheric CO_2 concentrations, were unclear. Moreover, comparing these two chronologies reveals some intriguing differences: unusually rapid growth was detected from 1965 in the Huon Pine chronology (Cook et al., 1991) but ca. 25 years earlier in King Billy pine (Allen et al., 2017). Why the chronologies indicate that these species began growing faster at different times is unclear, but might relate to differences in sampling intensity, localised climate conditions, physiological differences between species and the effects of climatic drivers of tree growth other than temperature, such as water availability (Allen et al., 2017).

Detecting systematic trends driven by climate change can be complicated by climatic variability, and the consequences of climatic shifts may differ among biomes. This is demonstrated by another tree-ring study: O'Donnell et al. (2021) examined five chronologies of *Callitris columellaris* spanning a climate gradient from southwest Western Australia through to the Northern Territory. They found ring widths were highly variable through time, and they did not document a directional trend in growth over the 100-year study period. Instead, they found growth was strongly correlated with rainfall, with different aspects of rainfall regimes explaining growth in different parts of the species' range: growth at semi-arid sites was strongly and linearly related to annual rainfall, while growth in the wet-dry (monsoon) tropics was sensitive to interannual variability in rainfall. These results suggest the sensitivity of productivity to climate drivers may differ among biomes and show how strong interannual climatic variability may overwhelm the capacity to detect systematic climate-driven trends in growth.

Quantitative-Correlative studies vary in the extent to which alternative plausible change drivers are considered. For example, Horner et al. (2009) examined 42 years of tree inventory data from an experimental spacing trial in floodplain forest in southeastern Australia. They found that tree mortality increased over time in the highest density stands. Using change point analysis, they attributed the increase in mortality to human regulation of stream flow and reduced water table depth. Moreover, they discounted drought as the sole cause of mortality by demonstrating the recurrence of drought periods without concomitant pulses in mortality. This example also demonstrates how other human-related change drivers may mask or be related to climate change in a complex fashion.

Several other examples reveal challenges in strengthening attribution beyond *Qualitative Correlative*. For example, Neumann et al. (2023) examined growth and survival in the Pilliga Forest—semi-arid forest in inland eastern Australia dominated by *Eucalyptus* and *Callitris*—with permanent sample plot data consisting of five repeat censuses between 1964 and 2019. They found subtle changes in median tree basal area and stem density over this period across the plots, with a gradual 26% increase in basal area (24% in stem density) until 2000 and a subsequent small (9% in basal area, 7% in stem density) decrease to 2019. The decline in basal area between 2000 and 2019 was associated with a concomitant decline in rainfall, and thus, this change was attributed largely to drought. However, the relative stability of recent times contrasts with substantial variability during the post-colonisation period. Analyses of historical records and cut stumps (Lunt et al., 2006; Rolls, 1999; Whipp et al., 2012) suggest that the area was likely a widely spaced eucalypt woodland pre-colonisation, but was transformed by extensive clearing, followed by a recruitment pulse of *Callitris*. These stands now have similar basal area but much higher stem densities compared to pre-colonisation. The past disturbance regime may be continuing to shape stand

BOX 1 MULTIPLE LINES OF EVIDENCE: A CASE STUDY OF *CALLITRIS* POPULATION COLLAPSE.

Studies of *Callitris intratropica* R.T.Baker & H.G.Sm. population dynamics reveal a recent population collapse that has been attributed to changing fire regimes, largely independent of climate change.

Evolutionary history, physiology and ecology of *Callitris* explain its current distribution.

Callitris intratropica is a member of an ancient Gondwanan conifer group (Crisp et al., 2019). *Callitris intratropica* trees are slow-growing and live for up to 300 years. The species forms distinct annual tree rings, which enable ageing of trees (Baker et al., 2008; Pearson et al., 2011). Ecophysiological research demonstrates it is an extreme xerophyte (Brodribb et al., 2013). Despite occurring in flammable environments, it is classified as a fire-intolerant obligate seeder (Prior & Bowman, 2020), having few fire resistance and recovery traits, poor dispersal and short-lived seeds that are produced episodically (Bowman et al., 2018; Bowman, MacDermott, et al., 2014; Lawes et al., 2011). The species persists in savannas in localised grass-free groves (Trauernicht et al., 2012).

Climate change and anthropogenic fire regimes in the late-Quaternary appear to have had a negligible effect on *C. intratropica* populations according to genetic analyses (Sakaguchi et al., 2013). In the 20th century, however, there have been widespread population collapses of this species (Bowman & Panton, 1993; Bowman, Price, et al., 2001; Edwards & Russell-Smith, 2009; Haynes, 1985; McVicar, 1922; Sharp & Bowman, 2004; Trauernicht et al., 2013; Yates & Russell-Smith, 2003). Dead *C. intratropica* trees are conspicuous because of their durable termite-resistant timber (Gay & Evans, 1968).

Field research has shown that populations of *C. glaucophylla*, a close relative of *C. intratropica*, rely on episodic wet periods for recruitment in arid environments (Prior et al., 2018). By contrast, climate variation has little effect on demography of *C. intratropica* beyond dryness reducing tree growth (Baker et al., 2008; Bowman et al., 2011).

Lines of evidence combine to show population decline consistent with anthropogenic changes in fire regimes.

A multidisciplinary study was undertaken over two decades to resolve whether changed fire regimes could explain the widespread population collapse of *C. intratropica* (Bowman et al., 2022). This study was based on a comparison of Aboriginal management of a landscape in Arnhem Land and an adjacent landscape in Kakadu National Park that was ecologically comparable but no longer managed by Aboriginal people. The study integrated a range of techniques including demographic surveys, longitudinal growth and survival analysis, field experiments, remote sensing of fire regimes and population modelling. It was found that Aboriginal fire regimes were characterised by frequent, patchy, low-intensity fires. In contrast, the areas sampled in Kakadu were frequently burned by large fires, had very few living *C. intratropica*, and had no regeneration. Dendrochronological analysis, field surveys, field experiments and population modelling explained why a patchy, low intensity Aboriginal fire regime would benefit *C. intratropica*. Such mosaics with long unburned patches enable *C. intratropica* to establish dense stands of regeneration that shade out grasses and develop a deep, fire-excluding litter mat (Trauernicht et al., 2012). Fires can degrade these stands, and continued exposure to fires causes the stand to die-out, thereby leaving clumps and eventually single dead stems. However, if unburned for several decades, a degraded stand can reinitiate another cohort of regeneration. Because contemporary fire regimes involve frequent large fires, there are few long-unburned stands where *C. intratropica* juveniles can establish. Furthermore, such frequent burning builds up grass biomass, making fire more intense and increasing the likelihood of killing juveniles and adults (Bowman et al., 2018; Bowman, MacDermott, et al., 2014). Combined, these processes drive a population collapse and cause a switch from patchy fires that generate unburned elements in the landscape to large frequent fires that produce more homogeneous habitats (Trauernicht et al., 2015, 2016) (Figure B1). There is emerging evidence that increasing temperatures are drying fuels earlier in the dry season, resulting in more intense fires than would have occurred in the late 20th Century (Bowman et al., 2024). This may be accelerating the loss of this fire sensitive savanna species.

dynamics. Given the long time periods between inventory measurements, which limit statistical analysis, it is difficult to attribute changes observed in this ecosystem to a unique driver.

Long and temporally resolved data sequences are needed to identify systematic change. For example, studies of aerial photographs suggest woody cover has increased within the tropical savanna (Lehmann et al., 2009), but this inference is based on a few time points. A recent study (Prior et al., 2020) combined photographic records with satellite data to increase the number of data points from four to ten across the time period 1950 to 2016 and expand the spatial extent of the study area. The improved temporal resolution and extent allowed the authors to conduct statistical analyses that revealed woody cover fluctuated through time following patterns of recent rainfall and fire but—in contrast to earlier conclusions—showed no long-term, directional change.

A related challenge is to distinguish internal vegetation dynamics from externally driven vegetation change. For instance, tree mortality

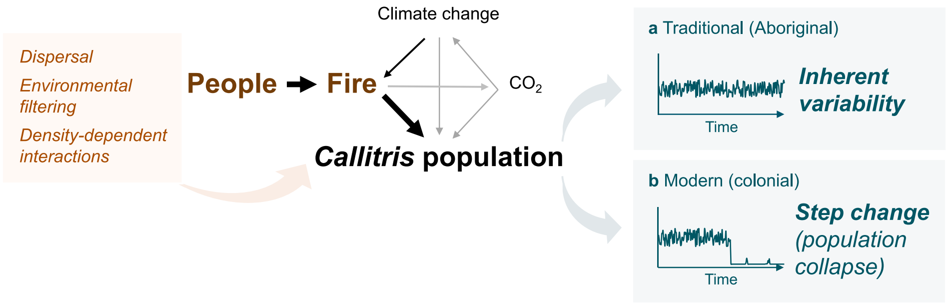

FIGURE B1 *Callitris intratropica* population dynamics on sand sheets of the Arnhem Plateau are influenced by many drivers. Fire regimes shaped by human actions currently have a dominant role in leading to alternative population outcomes. Under traditional Aboriginal fire regimes (a), frequent patchy, low-intensity fires in the landscape maintain a mosaic of groves and individual trees that fluctuate over time. Under modern colonial fire regimes (b), frequent large, higher-intensity fires abet the establishment of flammable grasses, which promote fires and lead to degraded groves, increased mortality, and, eventually, population collapse (following synthesis in Bowman et al., 2022).

naturally varies during stand development due to self-thinning, which can pose a challenge when interpreting changes in mortality rates over time. Trouvé et al. (2025) accounted for these internal dynamics when analysing mortality trends in *Eucalyptus regnans* forests in southeastern Australia. Using 63 years of inventory data from silvicultural experiments, they modelled both spatial and temporal variation in the self-thinning line. They found that mortality rates increased and carrying capacity decreased over time, and showed that these changes statistically correlated with rising temperatures.

Case studies with sufficient data to statistically evaluate relationships can be especially powerful. Bauman et al. (2022) analysed tree mortality across a climate gradient in tropical forests, using an especially rich forest inventory dataset of 20 0.5 ha plots established in the 1970s (Bradford et al., 2014). Across plots and species, they found that tree mortality risk had, on average, doubled over the past 35 years. Bauman et al. (2022) used gridded climate data to quantitatively attribute increasing mortality risk to trends in atmospheric drying (vapour pressure deficit, VPD). They also discounted some plausible alternative change drivers. For example, cyclones were ruled out as the sole explanation of the observed mortality patterns, and mortality risk did not increase with growth rate. However, they did not assess whether the effect size matched process-based understanding—and relevant processes remain uncertain. These tropical forest inventory data are a rare case of having sufficient temporal extent and resolution to quantitatively evaluate a signal of climate change.

Satellite records have revealed some nuanced changes in Australia's vegetation. For example, Xie et al. (2022) analysed a 15-year satellite record of enhanced vegetation index (EVI) across grasslands in southeastern Australia to detect change in C_4 and C_3 grasses by leveraging differences in their seasonal growth patterns. They found the total area covered by grasses has remained relatively constant, but the cover of C_3 grasses had decreased and C_4 grasses had increased over time—a trend corroborated by field observations. This observation is notable because modelling studies disagree on whether rising CO_2 concentrations (Collatz et al., 1998; Luo et al., 2024) or temperature and water availability (Havrilla et al., 2023; Murphy & Bowman, 2007; Winslow et al., 2003) are the main drivers of C_3-C_4 distributions. Xie et al. (2022) also found these trends to be most strongly correlated with a shift in the seasonal timing of rainfall (i.e., more rain in summer). Their study provides a good example of how attempts at attribution can lead to insights into the mechanisms of vegetation change. Nonetheless, process-based estimates of the magnitude of the effect size were absent from this study.

4.5 | Quantitative Partial

Correlations between vegetation change and plausible mechanisms—as demonstrated in cases of *Quantitative Correlative* attribution—can give powerful indications of potential change drivers. However, even where data is sufficient for formal statistical analysis, the presence of statistical significance (or lack thereof) does not necessarily imply biological importance. Incorporating process-based understanding is crucial in moving toward stronger attribution. This may be achieved by using models to delimit the expected magnitude and/or timing of effects based upon an understanding of the biological processes that shape an ecosystem. *Quantitative Partial* attribution describes cases where this is done; that is, where there is explicit consideration of the effect that would be anticipated from process-based understanding.

Broad-scale (i.e., global, continental or large regional) remote-sensing studies often include quantitative attribution (Burrell et al., 2020; Zhu et al., 2016), but only occasionally do they evaluate whether observed effects match the magnitude anticipated from process-based understanding. For example, global studies of long-term increases (greening) and decreases (browning) in vegetation greenness indices derived from satellite remote sensing data (De Jong et al., 2011; Winkler et al., 2021) have revealed signals of vegetation change, but they have reached conflicting conclusions regarding the extent, magnitude and location of greening and browning trends over Australia (Burrell et al., 2020; Cortés et al., 2021; Higgins et al., 2023; Wang et al., 2020; Winkler et al., 2021; Yang et al., 2023; Zhu et al., 2016). This largely stems from differences in time periods of analysis, oversights in data quality processing and statistical analysis (Cortés et al., 2021) and underlying differences in (model) attribution assumptions. For instance, the remote sensing record is short enough that patterns may be affected by a multi-year period of drying or wetting (e.g., the Millennium Drought, a decade-long drought that affected much of southern Australia from the late 1990s through 2010, the 2010–2011 La Niña and the 2017–2019 drought). Rifai et al. (2022) sought to address this by harmonising different NDVI records to analyse the change in NDVI over 38 years across the woody ecosystems of eastern Australia. They found patterns of greening and browning were highly variable at the decadal scale. But, after removing areas affected by disturbance (i.e., fire, deforestation), they detected a widespread greening trend—and the magnitude of this trend matched the CO_2 fertilisation effect predicted from a process-based model. Thus, this is a good example of *Quantitative Partial* attribution. However, this and many other remote sensing studies (e.g., Xie et al., 2022) focus solely on global change drivers represented in gridded datasets (e.g., precipitation, temperature and evapotranspiration) and do not consider the effects of other potential drivers (e.g., grazing).

Ground-based monitoring reveals trends and presents opportunities for detailed attribution, but faces similar challenges in accounting for the full range of potential drivers. For example, Hutley et al. (2022) used 18 years of eddy covariance data to show that gross primary productivity and water-use efficiency increased over time at a savanna in the Northern Territory. A detailed process-based model was used to explore which climate drivers could potentially explain this trend, and found that changes in atmospheric CO_2, temperature and rainfall over the period could all have contributed. However, they also noted that the site is recovering from historic cyclone damage, providing a potential alternative explanation for the trend. The fine temporal resolution and accumulating time series of the eddy covariance data facilitate attribution to climate drivers. Indeed, comparable data are also available for other sites, including an eucalypt forest in southern NSW for which formal attribution has not yet been attempted (Beringer et al., 2022). However, data to assess the effects of land management or historical legacies is typically limited at these monitoring sites.

4.6 | Quantitative Strong

Attribution of the highest level—*Quantitative Strong*—requires a quantitative and mechanistic approach that considers the effects of the range of alternative plausible change drivers. In the example of *Quantitative Partial* attribution (Rifai et al., 2022), an observed vegetation change was shown to be consistent with the effect size of a plausible change driver (elevated CO_2) anticipated from process-based understanding, but the study did not formally evaluate other plausible explanations of the observed changes. Studies rarely (if ever) evaluate the influences of both global change drivers (e.g., CO_2, elevated temperature, altered precipitation) and regional conditions and contexts, such as the influences of fire, livestock grazing, feral browsers and grazers and/or water management. Yet, this is exactly what is needed for the highest level of attribution.

Quantitative Strong attribution quantifies the timing and magnitude of the effects of plausible alternative change drivers, including interactions among them, so as to parse their independent and combined influences. Mechanistic models are central to achieving this standard of attribution because they are the main tool for quantifying process-based understanding of the functioning of plants and their interactions with the environment (Box 2). However, it is important to note that misattribution can still occur within any attribution class. For instance, plausible drivers may be missed because the process-based understanding of a system is incomplete (Grimm et al., 2020).

There are no examples from our collective knowledge of studies of vegetation change in Australia that achieve this 'gold standard' of attribution. However, in the following, we outline two examples in Australia that may have the ingredients required: they have long-term data on vegetation and plausible change drivers as well as process-based expectations that could be formally combined with a process-based model.

The first example comes from the longest-running monitoring site in Australia, Koonamore Reserve, which is an arid chenopod shrubland in South Australia that has been monitored using photo-points and permanent quadrats since 1926. The reserve has experienced pronounced shifts in grazing and browsing intensity over the past century—it was heavily overgrazed by sheep before being fenced in 1925, and populations of rabbits within the reserve have fluctuated with several periods of very heavy rabbit browsing up until the 1980s (Foulkes et al., 2014). The region also experiences highly variable rainfall at both annual and interdecadal timescales, with the period 1970–2010 being considerably wetter than 1920–1970 (Foulkes et al., 2014). Counts of tree and shrub numbers in permanent quadrats within the reserve have revealed changes in the number of plants through time (Crisp, 1978; Crisp & Lange, 1976); in particular, large increases in several shrub species have been observed over the last 30 years (Foulkes et al., 2014; Sinclair, 2005). Previous studies classified as *Qualitative Correlative* attribution reported that reduced intensity of rabbit grazing alongside increasing rainfall may explain these changes, but found the influence of these two factors was difficult to separate (Foulkes et al., 2014). The temporal observations of vegetation and hypothesised dominant change drivers, as well as studies of grazing manipulations (Sinclair & Facelli, 2019), combine to form a rich, long-term dataset that could potentially support a detailed attribution study of vegetation change.

A set of long-term monitoring plots located in alpine grassland and heathland offers a similar opportunity (Williams et al., 2014). The alpine region was used for summer cattle pasturing from the 1820s, and heavy grazing had caused significant degradation by the 1930s. Fenced and unfenced plots were established in the mid-1940s in the Bogong High Plains (Carr & Turner, 1959a, 1959b) and demonstrated that cattle grazing increased bare soil and prevented regeneration of palatable forbs and shrubs, while exclusion of cattle allowed gradual recovery of vegetation (Wahren et al., 1994). This evidence

BOX 2 GETTING TO QUANTITATIVE STRONG: ATTRIBUTION WITH MECHANISTIC MODELS.

The key feature of *Quantitative Strong* attribution is that the magnitude of the observed change can be partitioned, on mechanistic grounds, into potential change drivers. Mechanistic models—that is, quantitative models that include representations of the main processes driving change—are an important tool to achieve attribution. For example, climate models are the main tool used to attribute observed variability in global temperatures to natural or anthropogenic causes (IPCC AR6). Similarly, for vegetation, Dynamic Global Vegetation Models (DGVMs) have been applied at a global scale to attribute spatio-temporal variation in terrestrial carbon storage among three primary drivers, namely changes in atmospheric CO_2, climate change and variability and changes in land use and land cover (Sitch et al., 2024). Coupled fire-vegetation models have also been applied to attribute drivers to variation in fire activity, untangling the interactive and sometimes compensatory effects of human activity and climate drivers on how much area is burned in different regions of the globe (Burton et al., 2024). Mechanistic models are important for Quantitative Strong attribution because (i) they can be used to estimate the relative contributions of drivers, including those that are confounded and their interactions, by conducting idealised simulations with and without the influence of individual drivers (see, e.g., Bond et al., 2005), and (ii) they can draw on a wide range of evidence—not just the dataset to be attributed—to verify that the magnitude of observed change is consistent with expectations based on current scientific understanding.

There are several requirements to apply mechanistic models to the attribution of vegetation change. First, time-series data documenting temporal trends in vegetation properties and the main potential drivers are needed. Some of the relevant driver datasets, such as time series of climate and atmospheric CO_2, are readily available, but others, such as grazing pressure and fire management history, are often less readily available (or in some cases not available at all). One advantage of a model-based attribution approach is that it can help to identify these critical data needs. Second, we need a quantitative bio-physical understanding of how the main drivers affect vegetation processes and properties. Manipulative experiments that study the effects of individual drivers are key to developing this understanding: for example, free-air CO_2 enrichment experiments (Jiang et al., 2020), warming experiments (Wahren et al., 2013) and grazing exclusion experiments (Forrester et al., 2025) can be used to develop the mechanistic understanding required to represent these processes in a model. Natural experiments, when carefully leveraged, can be valuable for understanding phenomena that cannot be experimentally manipulated, such as extreme events or processes that are slow or episodic.

Model predictions also need to be evaluated against observations, to build confidence that processes are sufficiently well represented to support attribution. Applying models for attribution, therefore, involves an iterative process of calibration, validation and updating (Figure B2). Although mechanistic models have not yet been used for attribution of vegetation change in Australia, most of the requirements to do so are in place, including suitable vegetation models (e.g., Stephens et al., 2023; Wang et al., 2024), and should enable the adoption of model-based frameworks for attribution in the near future.

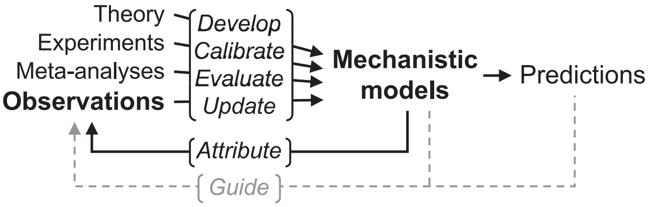

FIGURE B2 The iterative process required for attribution with mechanistic models. Data from manipulative experiments, meta-analyses and observations can be used alongside theory to develop, calibrate and evaluate process-based models to ensure they sufficiently represent vegetation change. Limits in process-based understanding may be identified by insufficient observations to validate model outputs or mismatches between observations and model outputs, and can be used to guide the collection of new data to update models. Once model outputs are consistent with observations, models can be applied to estimate the contribution of individual drivers to the overall change.

contributed to the eventual banning of cattle grazing in the high country in 2004. The major change drivers of concern in this region now include rising temperature and increasing fire frequency. Over time, monitoring has extended to plots in grassland, wetlands and snow-patch vegetation, as well as field experiments manipulating temperature and fire (Camac et al., 2017; Jarrad et al., 2008; Wahren et al., 2013). Long-term, unburnt plots showed ongoing shrub encroachment, a decline in grass cover and variability in forb cover, over the period 1980–2010 (Wahren et al., 2013, 1994). These trends were mirrored in a warming experiment that commenced in 2004, with 1°C warming causing additional shrub expansion (Wahren et al., 2013). The observed vegetation changes were attributed to decreased annual rainfall and increased temperature on the grounds of significant statistical correlations (Wahren et al., 2013). However, the availability of long-term monitoring data in conjunction with experimental manipulation of grazing intensity, fire and temperature could allow for a formal attribution analysis to quantify the contribution of individual drivers to vegetation change.

5 | SYNTHESIS: GLOBAL IMPLICATIONS AND RECOMMENDATIONS

Australia presents a test case for attributing vegetation change to a changing climate across large geographic scales and across a range of climate zones. Globally, attempts to forecast and manage future vegetation change should be informed by observations of past and ongoing change. Across the Australian continent, numerous studies report vegetation changes (Figure 3, Table 3), including forest expansion, vegetation thickening and greening, as well as tree mortality and forest loss. The overall trend could be interpreted as one of increasing vegetation biomass with some pockets of loss that are often abrupt. However, it remains challenging to identify trends from the available data—and even more so to determine the role of climate in driving these trends.

Drivers that have been attributed to the observed vegetation changes in Australia include land management, fire and grazing, in addition to climate drivers such as rainfall seasonality, drought and elevated atmospheric CO_2 (Figure 3, Table 3). Over time, there has been a trend toward quantitative and stronger attribution, likely driven by accumulating data as well as advances in methods of data collection (see e.g., Section 3) and analysis. Yet, to date, few studies approach the upper left of the attribution classification scheme (Table 2), having both quantitative evidence and strong mechanistic certainty while also considering alternative plausible change drivers. This reflects the fact that attributing drivers to vegetation change—particularly attribution that approaches Quantitative Strong—is extremely difficult both theoretically and practically. Nevertheless, we advocate for explicitly considering the strength of attribution and striving for improved attribution because such understanding is needed to develop accurate predictions that, in turn, can support management and environmental markets.

Several of the challenges that limit attribution in Australia certainly exist elsewhere in the world, including a complex history of changing land use, short and patchy instrumental records and environmental conditions that limit the availability of palaeoecological records (e.g., pollen, tree rings). Similarly, some key recommendations from our review of Australia are likely applicable to improve detection and attribution in other parts of the world.

A stronger commitment to long-term monitoring is needed if we are to detect trends against high background variability. For example, in regions with high levels of background variability, such as the high inter-decadal variability in rainfall across Australia, datasets stretching back several decades are particularly valuable. However, long intervals between observations (>10 years) significantly reduce the utility of data for detecting and attributing change. Different approaches to gathering observations (including those outlined in Section 3 and Table 2) have clear strengths and limitations relative to the steps needed for detection and attribution (Section 4). As long recognised (e.g., Delcourt et al., 1982), studies focused at different spatio-temporal scales may be best placed to detect vegetation changes in response to different change drivers. For example, regional to local scale studies might be able to fingerprint interactions among drivers of change that cannot be assessed with global datasets. Combining approaches can also lead to greater insight (Box 1).

In addition to the observations of vegetation that are needed to detect changes, observations of the range of plausible change drivers (such as grazing and fire) are needed to attribute drivers to change. Moving toward stronger attribution requires consideration of plausible change drivers beyond those that may be derived from the current suite of gridded datasets. Further, attempts to understand past and ongoing vegetation change must consider the influences of human activities. This includes recognising the underpinning purpose and practice of Indigenous care and management structures that, in the case of Australia, created and maintained environments for millennia (Section 2).

Finally, a recurring thread that weaves throughout this review is the integral partnership between mechanistic models and observations (Box 2). Moving toward more robust attribution of vegetation change and identifying the influence of climate requires the development of quantitative causal models whereby observations of change can be compared to predicted effects (Section 4). Ultimately, long-term observations of vegetation and change drivers in partnership with mechanistic models are needed to predict vegetation change, inform proactive management and give the best chance of sustaining the ecosystem services upon which humans rely.

AUTHOR CONTRIBUTIONS

B.E.M. initially conceived the idea for the symposium and subsequent paper. B.E.M., D.M.J.B., J.R.E., L.J.W., M.A.A., P.F.G., P.J.B., R.T. and S.W.R. contributed text to the initial draft. L.J.W. led manuscript development and writing, and all authors contributed to revisions and further manuscript development.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

No new data were generated by this study.

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