A structured approach for building multi-community State and Transition Models to support conservation planning

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Summary

1. Global declines in ecosystem extent and condition mean there is an increasing demand for recovery and conservation plans. Conservation plans for ecological communities require a management framework with measurable, time-bound objectives. Efficient and structured processes that facilitate timely and comparable conservation plans are essential, especially where resources are constrained.
2. We describe a process to streamline the development of conservation plans by combining functionally similar community sub-types into a multi-community State and Transition Model that can be used to guide conservation planning. We demonstrate this approach in a case study using eucalypt dominated woodlands of southern Australia – an ecosystem which occupies a vast geographical range across temperate Australia and includes many distinct vegetation communities, a growing number of which are endangered or threatened.
3. Australian woodland ecologists (grouped according to their knowledge of three broad woodland sub-types) were asked to develop causal-chains to describe all factors associated with transitions among woodland condition states and estimate the likelihoods associated with each transition at two time-scales.
4. The resultant State and Transition model includes a set of eight general condition states that are common to eucalypt dominated woodlands and some 364 unique causal-chains describing the drivers of all plausible transitions. We also include an example of how the

same information can be presented as a series of decision trees aimed at supporting on-ground management decisions.

5. The case-study demonstrates that it is possible to construct a detailed State and Transition Model that synthesizes knowledge across multiple similar vegetation communities. To date, State and Transition Models focused on single communities or a smaller spatial scale, and this is the first attempt to construct a nationally relevant multi-community State and Transition Model via a structured and participatory process.
6. *Synthesis and applications*: This approach can be applied at multiple spatial scales to improve and streamline the development of robust conservation plans to improve how we plan for, implement and measure global biodiversity outcomes.

Introduction

Globally, ecosystems face increasing rates of degradation and collapse, due to a host of threats (Salafsky et al 2007) including habitat destruction, invasive species and climate change (Wilcove et al. 1998; Rouget et al. 2003; Powers & Jetz 2019; Mayfield et al. 2020; Bergstrom et al. 2021). International efforts to classify ecosystems according to their level of risk (i.e. IUCN Red List) can accompany or provide a means to justify national or state listing and legislative protection, triggering mechanisms for protection and recovery (Nicholson et al. 2009; Rodríguez et al. 2011; Keith et al. 2013; Keith et al. 2022). Among these mechanisms is the development of plans to support recovery (e.g. Australian Government Department of Agriculture, Water and the Environment 2007), which provide the information necessary for direct management and threat abatement and improve biodiversity outcomes (Schultz & Gerber 2002; Clark et al. 2002a). However, the complexity of developing recovery plans and the urgent need for better restoration outcomes for threatened communities have led to calls for improved processes to allow for swift and effective interventions (Scheele et al. 2018; Noss et al. 2021).

Best practice recovery planning includes clear goals to guide management efforts, a catalog of threats, the corresponding candidate actions for recovery, costings, measures that enable monitoring of progress toward goals, and the research necessary to resolve uncertainties impeding management decisions (Clark et al., 2002; Roberts & Hamann, 2016; Weiss et al., 2021). However, describing and planning the recovery of a threatened community is challenging (Rodríguez et al. 2011; Keith et al. 2013) and resource intensive (McDonald et al. 2015), often relying on subjective expert advice where empirical data is lacking. Thus, the backlog of threatened species and ecosystems requiring plans is ever-growing (Noss et al. 2021). As threatened species and communities are added to such lists, there is a growing need to make the development of conservation plans more efficient and consistent.

Ecosystems and communities within the same broad type likely share commonalities including their prevailing threats and drivers of change, which suggest there may be opportunities to generalize and transfer understanding from one system to another. Indeed, multi-species and ecosystem planning has been used in the United States since the 1990s, although with mixed results (Clark & Harvey 2002). Key issues with generalization include inadequate identification, review and monitoring of threats (Noss et al. 2021). However, a consistent framework gains time efficiencies, increases the number of threatened communities with relevant recovery plans, and ensures that plans address the stated objectives and that the success of management can be measured (Clark & Harvey 2002; Noss et al. 2021).

Conceptual models that systematically describe threats and drivers of change at higher levels of ecological classification are critical to risk assessments (Keith et al. 2013) and conservation planning more generally (Margoluis et al. 2009; Biggs et al. 2011). State and Transition Models are an intuitive modelling framework (Bestelmeyer et al. 2009) and a popular tool among land managers and government agencies (Knapp et al. 2011), as they define discrete alternative 'states' of vegetation condition based on measurable attributes (Westoby et al. 1989; Stringham et al. 2003; Briske et al. 2005), and describe key drivers of change between states and opportunities to mitigate threats (Yates & Hobbs 1997; Standish et al. 2008; Sinclair et al. 2019; Sato & Lindenmayer 2021). The delineation of 'states' in a management-focused State and Transition Model context, represents a conceptual partitioning between the most common or important expressions of a community or ecosystem that are stable over a management time-frame and can be easily identified at the site level. Transitions between states are generally driven by management activities, in combination with abiotic and/or biotic processes. The State and Transition Model framework, therefore, offers a system to organize management actions and ecological knowledge across multiple similar communities where generalities in states and drivers of transitions are expected. However, whilst there may be growing interest in the development and use of State and Transition Models at various levels of government, there is a need to implement a more structured and standardized approach that improves transparency and allows for review and revision (Knapp et al. 2011). Further, the resultant model should be accessible and relevant to ecosystem managers.

In this study, we developed a method for creating and evaluating multi-community State and Transition Models, to support a more efficient, transparent and consistent system for conservation planning. As proof-of-concept we develop a State and Transition Model for all eucalypt woodland communities of southern Australia. Eucalypt woodland communities provide a useful case-study system, as they were once widespread across southern inland Australia (Yates & Hobbs 1997a), but have declined in proportional area more than any other biome (Mappin et al. 2022) due to extensive historical and ongoing modification by agricultural land uses, changes to climate, flood and fire regimes, as well as soil nutrification and exotic species invasions (ABARES, 2018). As a result, many woodland communities and woodland-dependent species are threatened (Richards et al. 2020), with 28 southern eucalypt woodland communities listed as threatened under Australian federal legislation as of December 2023 (of 106 threatened ecological communities in total). Commonalities in ecological processes, threats and management interventions between these threatened communities may make generalized models of ecological dynamics a useful foundation for management and restoration decisions (Keith et al .2022). Our method is a systematic approach to synthesize disparate data and knowledge from diverse experts into a consistent framework. The resultant model includes descriptions of different states of vegetation condition, the environmental drivers and management activities associated with transitions between states, and the likelihoods of transitions at different time-frames. This approach could enable rapid, consistent and comprehensive development of conservation plans that can be later tailored to individual communities as required.

Methods

We designed an approach to synthesize disparate data and knowledge from diverse experts into a consistent framework, using State and Transition Modelling (Figure 1). The aim of this approach is to provide a systematic process for collating knowledge about groups of similar vegetation communities to capture the key drivers (natural processes, threats and management activities) that are associated with transitions and estimate the likelihood of these transitions when these drivers are present.

We tested and refined (Figure 1) this protocol by applying it to a case study of eucalypt woodlands in southern Australia. We utilized expert knowledge to create a multi-community State and Transition Model for eucalypt woodlands in southern Australia. Here, we describe the process we used to create a State and Transition Model that captures the key drivers of change in condition across multiple woodlands that are dominated by eucalypt trees (including tree species of the closely related genera *Eucalyptus*, *Corymbia* and *Angophora*).

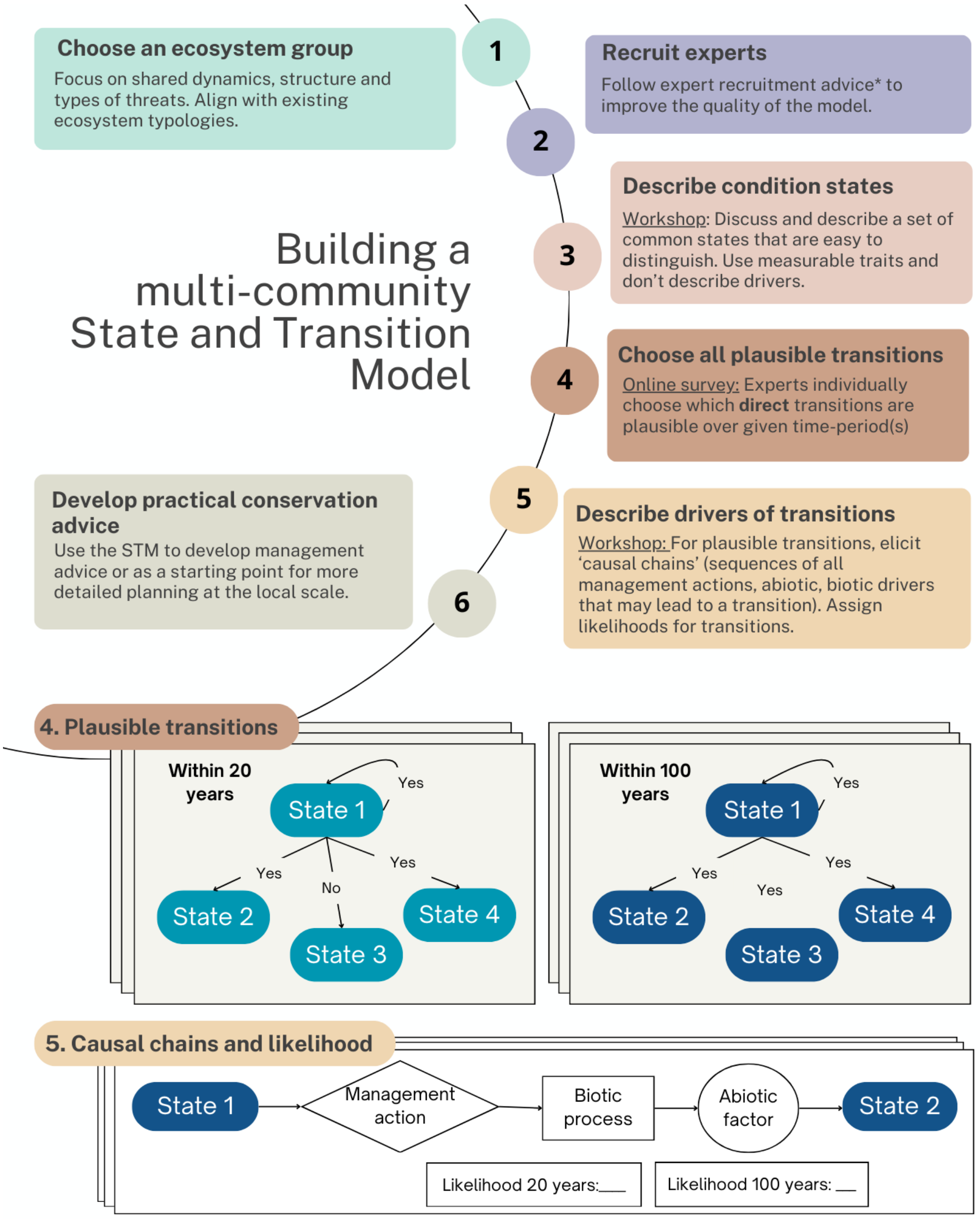


Figure 1. Protocol for synthesizing a multi-community State and Transition Model. More detail on each step can be found in the Methods section and suggested refinements are described in the Discussion. *See Travers *et al*

Step 1: Define the scope of the model and delineate any relevant community sub-types

To clarify the scope of the model, we used the Australian Ecosystem Models Framework (Richards et al. 2020) as the basis for defining the overarching community sub-types. We chose three woodland sub-types as follows; 1) Grassy woodlands; 2) Shrubby and Obligate Seeder woodlands and; 3) Floodplain and Riparian woodlands (Good et al. 2017; Prober et al. 2017; Gosper et al. 2018). These differ from the final Australian Ecosystem Models Framework sub-types (Prober et al., 2023), as we broadened the definition for floodplain woodlands to include riparian woodlands and, after iteration in Step 3, we combined shrubby and obligate seeder woodlands because there was substantial overlap in the states and factors influencing transitions in these sub-types.

Step 2: Recruit experts

We recruited 43 woodland experts based on their knowledge of different eucalypt woodland communities across southern Australia, but not all experts participated in all steps of the process. Experts had varying levels of knowledge relating to specific woodland communities, but all had advanced knowledge of multiple communities allowing them to provide explicit and generalizable input for broader woodland sub-types. Experts participated in two workshops and an online survey over a two-year period from 2016-2018.

Step 3: Identify and describe states and transitions (including iteration)

Common woodland states were developed and iterated across workshops. At the first workshop (Workshop 1; with 17 expert participants, in 2016), we presented the woodland condition states described in Rumpff et al. (2011) as a template and experts refined these to broaden their applicability to eucalypt dominated woodlands across southern Australia. To ensure the right balance in model complexity, and to recognize that some states do not have clear ecological thresholds, we focused on eliciting and distinguishing states based solely on when management actions would differ, rather than describing all the possible variations. There were eight woodland condition states identified in this workshop (Table 1).

We then circulated an online survey in 2018 that asked experts to i) identify which woodland sub-type(s) they were familiar with (Grassy, Shrubby and Obligate Seeder, and/or Floodplain and Riparian woodlands), and then for the familiar sub-types ii) specify which direct transitions were plausible for each condition state within 20- and 100-year time-frames. The format and wording of survey questions are included in Appendix S1. Direct transitions were defined as transitions that would plausibly occur over 20- or 100-year time-frames without passing through any of the other states, assuming that resources and effort were not limiting. For example, a direct transition between Exemplar to Transformed is plausible if an area was cleared, but transitioning back from Transformed to Exemplar would likely pass through multiple other states and therefore is not considered a plausible direct transition. We chose these time-frames to represent the scales relevant to management and monitoring, and those that should capture longer term processes (for example the regeneration and growth of woodland trees).

The survey results provided us with 6 responses from Floodplain and Riparian woodlands, 17 from Grassy woodlands, and 6 from Shrubby and Obligate Seeder woodlands. From these data, we built a series of Directed Acyclic Graphs (cause-and-effect diagram made up of nodes and links; DAG) where each state is represented as a node, and if experts stated that the transition from one state to another is plausible, the nodes are linked by an arrow. For each woodland sub-type they provided responses for, participants received one DAG that included just their own responses, and one that included all experts’ responses, each participant also received one DAG that pooled responses across all experts and woodland sub-types. For the multi-expert DAGs, each arrow was annotated with the number of experts who had specified the transition to be plausible (sample DAGs are included in Appendix S2).

The survey responses were subsequently reviewed by the same experts in a face-to-face workshop (Workshop 2). This involved dividing experts into groups, corresponding to the three woodland sub-types. We asked groups to review and compare their individual DAGs with the group's compiled DAG for the respective woodland sub-type, and with the DAG that pooled responses from all experts and woodland sub-types. We then asked them to revise which transitions they considered as plausible direct transitions over the two relevant time-frames, before sharing findings with the broader group. At this stage we did not ask experts to define the likelihood of transitions, simply which were plausible direct transitions. This review was undertaken to help clarify ambiguity in the initial task, and to help experts develop a shared understanding of plausibility of all transitions. Details of Workshop 2 are included in Appendix S3.

Step 4: Describe how transitions occur – specify causal chains

The next step involved asking experts to systematically describe all the factors (specifically management actions, abiotic factors and biotic processes) that need to occur together or in sequence to drive each of the plausible direct transitions identified in step 3 (Step 5, Figure 1). As an example, on a diverse derived grassland site, removal of intensive grazing, followed by above average rainfall, may result in a large recruitment event and a high density of immature stems, and transition to a Thicket state. These pathways (including all variables identified, attributes that might indicate the transition has occurred and their associated likelihoods) were given a unique identifier and are herein referred to as 'causal chains'. The same transition (from one state to another) could have multiple causal chains if it could occur under different combinations of factors (i.e. multiple pathways could be expressed for any one transition). This exercise was undertaken in groups (at Workshop 2), where experts were assigned to one of the three woodland sub-type groups based on their experience and knowledge.

The drivers within the causal chains were classified as: abiotic (e.g. drought), management activity (e.g. grazing), or biotic processes (e.g. nutrient cycling). Participants were asked to be specific regarding the nature and direction of the drivers to assist in classifying differences in models, with the aim of developing practical management advice. For each transition, participants suggested measurable attributes that could be used to determine if a transition had occurred (i.e. as part of a monitoring program). For example, shrub abundance and native understorey diversity could be used to indicate that a transition from Modified to Exemplar woodland had occurred. Finally, for each causal chain, groups estimated the likelihood of this transition occurring for their woodland sub-type, using six ordinal qualitative categories (Almost no chance; Very unlikely; Unlikely; Neither likely nor unlikely; Likely; Very likely). We used qualitative categories to reduce the elicitation burden on experts (Jaspersen & Montibeller 2015), given the number of causal chains. However, there is no reason why quantitative estimates could not be integrated into this approach. Participants were directed to estimate this ‘likelihood’ assuming the set of management and environmental conditions listed in any causal chain are in place (i.e. if high rainfall was specified in a causal chain, experts assumed that high rainfall occurred and estimated the likelihood of the transition accordingly). This was repeated for each causal chain, to capture the range of different plausible combinations of conditions that might result in a particular transition. Specifically, experts were instructed to estimate likelihoods irrespective of the amount of money, effort or willingness that may be required for a set of drivers associated with a given transition.

Raw causal chain data were processed and analyzed using reproducible code (see here). We developed a typology to group the raw drivers that were mentioned by experts and allow for comparisons among woodland sub-types. Each likelihood category was assigned a quantitative score between 0 and 1 for data processing, and we consulted with experts to assign numbers that best represent their understanding of the categories. Given there was an uneven number of categories, experts agreed that ‘Almost no chance’ should be close to zero and an order of magnitude less likely than the next category (Very unlikely), and ‘Neither likely nor unlikely’ should be represented by 0.5. Therefore, when the rest of the categories were evenly distributed around these points, they were assigned the following numbers: Almost no chance = 0.01; Very unlikely = 0.10; Unlikely = 0.30; Neither likely nor unlikely = 0.50; Likely = 0.70; Very likely = 0.90). There were some transitions where several different causal chains were described within a woodland sub-type and for these, we included the maximum likelihood that was assigned. Drivers associated with all possible transitions (including those where several causal chains were described for a single transition) were then merged into one general State and Transition Model, and any drivers that were specific to a given sub-type were denoted within the accompanying transitions table (Appendix S4).

Step 5: Use causal chains to develop management recommendations

We developed a simplified guide (hereafter ‘The Guide’) consisting of relevant management and monitoring information derived from the State and Transition Model (Good et al. 2021). We condensed each element of our results – drivers, likelihoods and indicators of transitions extracted from the causal chains from step 5 – to develop fact sheets including decision trees guiding management for sites in each of the eight condition states, likely transitions and threats, and monitoring suggestions to track progress. Extracting this state-centric management information from the classic State and Transition Model framework is one option for translating a potentially complex model into explicit conservation planning advice without losing important information. We converted expert elicited causal chains into management-focused decision trees using the following steps.

1) **Identify the management-relevant transitions.** These are either ‘favorable’ transitions that require management, same-state ‘transitions’ where management is required to maintain the existing condition state, or ‘unfavorable’ transitions that might occur on their own without careful management. In this paper, we avoid categorizing transitions or drivers as ‘favorable’ or ‘unfavorable’ in the general model as the landscape context and habitat values for a particular woodland community will vary and should be considered when determining which transitions are desirable. However, due to the applied focus, the Guide explicitly identifies ‘favorable’ and ‘unfavorable’ transitions.
2) **Look for similarities and differences between community sub-types.** In our case study, there were instances where drivers were only relevant to one or two community sub-types. For example, an influx of propagules due to flooding is only relevant to Floodplain and Riparian woodlands. Where possible, we include differences between communities as the first element in the decision tree after starting state.
3) **Look for commonalities between causal chains.** In some cases, there is one clear pathway with a couple of variants. For example, an ‘Overstorey thicket’ site is expected to transition into a ‘Highly modified woodland’ state by thinning (either self-thinning or thinning intervention, depending on the circumstance) and, depending on the state of the understory might require understorey planting or not. In other cases, the decision tree is more complex with multiple possible management pathways. For example, the transition between ‘Modified woodland’ and ‘Exemplar’ might involve reinstating a natural flood regime,

herbivore control, burning, controlling feral predators and/or introducing mammals, depending on the exact circumstances. The latter will require a much more complicated branching of a decision tree.

4) **Assemble the decision tree in a sensible order.** Ordering the branches to reduce repetition requires some trial and error and it can help to explore the order used in causal chains to find the simplest possible combination. For example, removal of grazing is commonly mentioned prior to revegetation, but monitoring the effects of grazing by other herbivores (e.g. rabbits) might be required prior to implementing further herbivore management.

Results

Identified condition states

Overall, the states and descriptions arrived at through the expert elicitation process did not deviate much from the states described in Rumpff et al. (2011), although one state was added (Diverse derived grassland), and the names of the states were changed substantially to ensure generality amongst different woodland communities (Table 1). Experts felt it was important to remove reference to land-use (e.g. 'pasture') in the state names and descriptions, so that similarities in management requirements of states that were compositionally, structurally, and functionally similar could be explored, irrespective of history or location.

Table 1: Qualitative state descriptions for the woodland condition states, according to structural, compositional and functional vegetation attributes. These general condition states were described and refined via discussions across the first and second workshops.

Name	Description
Exemplar**	All vegetation strata are intact; species richness is high in all strata and includes disturbance-sensitive species; low weed cover; soil is stable and has a natural nutrient balance
Modified woodland	Overstorey is mostly intact; mid/understorey is depleted in both richness and cover; understorey flora is primarily native; soil nutrient levels are natural, or close to natural
Highly modified woodland	Overstorey is mostly intact; mid/understorey is depleted in richness; midstorey can be elevated in cover; exotic annual herbs present and may be prevalent; altered soil processes
Diverse derived grassland	Overstorey mostly absent; midstorey depleted in richness and cover but understorey remains mostly intact
Depleted derived grassland	Overstorey is depleted or absent; midstorey is absent or depleted; understorey is depleted in native species richness and cover
Thicket	Overly dense overstorey; very low understorey species richness, low under/midstorey cover; understorey suppressed, but may be dominated by natives or exotics; soil stability may be compromised
Overstorey and Midstorey Thicket	Few to no mature trees; high density of shrubs and tree saplings; higher shrub and tree richness compared to Thicket; understorey suppressed but may be dominated by natives or exotics; low native understorey richness
Transformed	Very low to no native vegetation cover in the mid and understorey; overstorey absent sparse, dead or dying, no recruitment, soil is saline, acidic, or highly nutrified.

** Note: the Exemplar state reflects what was considered the least modified of what is remaining in the landscape, not a reflection of pre-1788 (prior to European colonization) conditions. We recognize this does not necessarily align with the goals and aspirations of all stakeholders.

Likelihood of transitions between woodland condition states

The likelihood of transition over 20- year and 100-year time-frames were consistent among woodland sub-types for many of the transitions (Figure 2; for example the transition from Exemplar to Modified woodland in 20-years was considered likely across all sub-types), but some transitions were only considered likely in one or two of the woodland sub-types. For example, transitioning directly from a 'Diverse derived grassland' to a 'Highly modified woodland' was only considered likely in Grassy woodlands, whilst an 'Overstorey and midstory thicket' was only considered likely to transition to 'Diverse derived grassland' in Floodplain and Riparian woodlands.

The most striking pattern is the consistent perception that it is highly unlikely to transition directly from other states to the 'Exemplar' state, and that transitions requiring restoration of the overstorey structure and condition (for example from the 'Derived grassland' states to the 'Woodland' states) are predicted to only occur over very long time-frames (Figure 2). These results highlight a general belief from woodland experts that successfully reversing the loss of woodland structure or understorey diversity is very unlikely, even within 100-year time-frames. Conversely, transitions from all other states to the 'Transformed' state were consistently perceived as very likely even within 20-years.

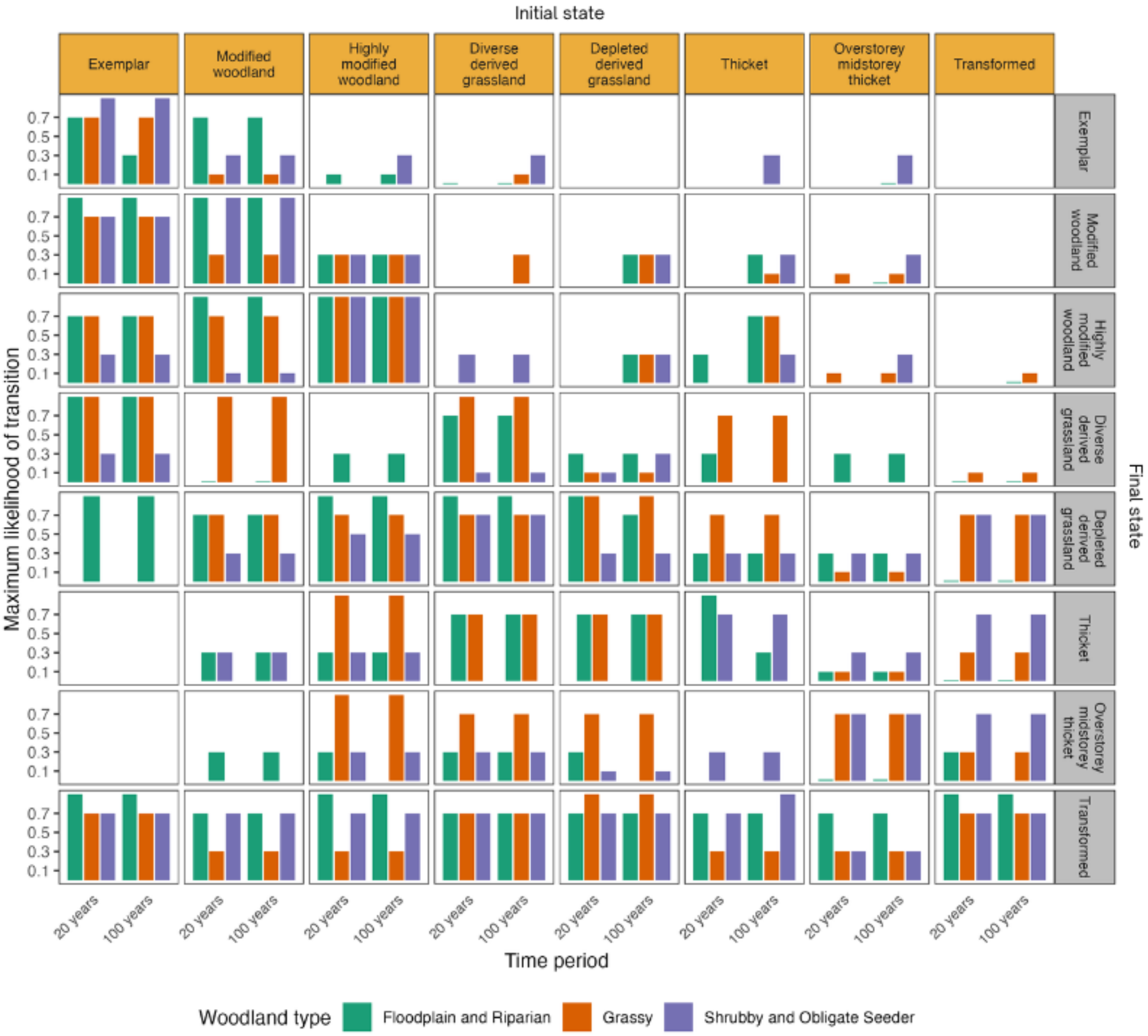


Figure 2. Likelihoods of state transitions for each woodland sub-type for both 20-year and 100-year time-frames. The initial states are along the top (orange shaded), and the final states are along the right side (grey shaded). The box in the top left corner, for example, represents the transition from Exemplar to Exemplar and the box immediately to the right of that represents the transition from Modified Woodland to Exemplar. For transitions where more than one causal chain was described, we included the likelihood assigned to the most likely chain in this plot.

Drivers of transitions

Experts described the drivers associated with a total of 364 unique causal chains (151 Floodplain and Riparian chains; 113 Grassy chains and 100 Shrubby and Obligate Seeder chains). Within these causal chains there were 49 potential drivers of transitions, and these were categorized as biotic processes, abiotic processes, and management activities (Figure 3C). The most common management activities were vegetation clearing (of the overstorey), management of grazing pressure and soil disturbance and degradation, noting that the latter was very frequently mentioned by Shrubby and Obligate Seeder woodland experts. In terms of abiotic processes, drought and adequate rainfall were mentioned frequently in transitions across woodland types. Floodplain and Riparian experts frequently mentioned flood regimes whereas management activities related to fire were not mentioned for Floodplain and Riparian woodlands.

Experts considered management to be state-dependent (Figure 3B). The drivers associated with transitions from mature woodland states to derived grassland states were related to the removal or death of mature trees and shrubs. Transitions from states with no soil nutrification or degradation to states with elevated nutrients or altered structure (for example T2, T7 and T12) generally mentioned ‘soil degradation’, ‘weed recruitment’ and ‘inappropriate grazing pressure’. Transitions from other states towards ‘Exemplar’ or ‘Modified woodland’ states generally involved several active management interventions (revegetation of all vegetation layers, weed control, managing total grazing pressure) as well as reinstating appropriate disturbance regimes (flood or fire).

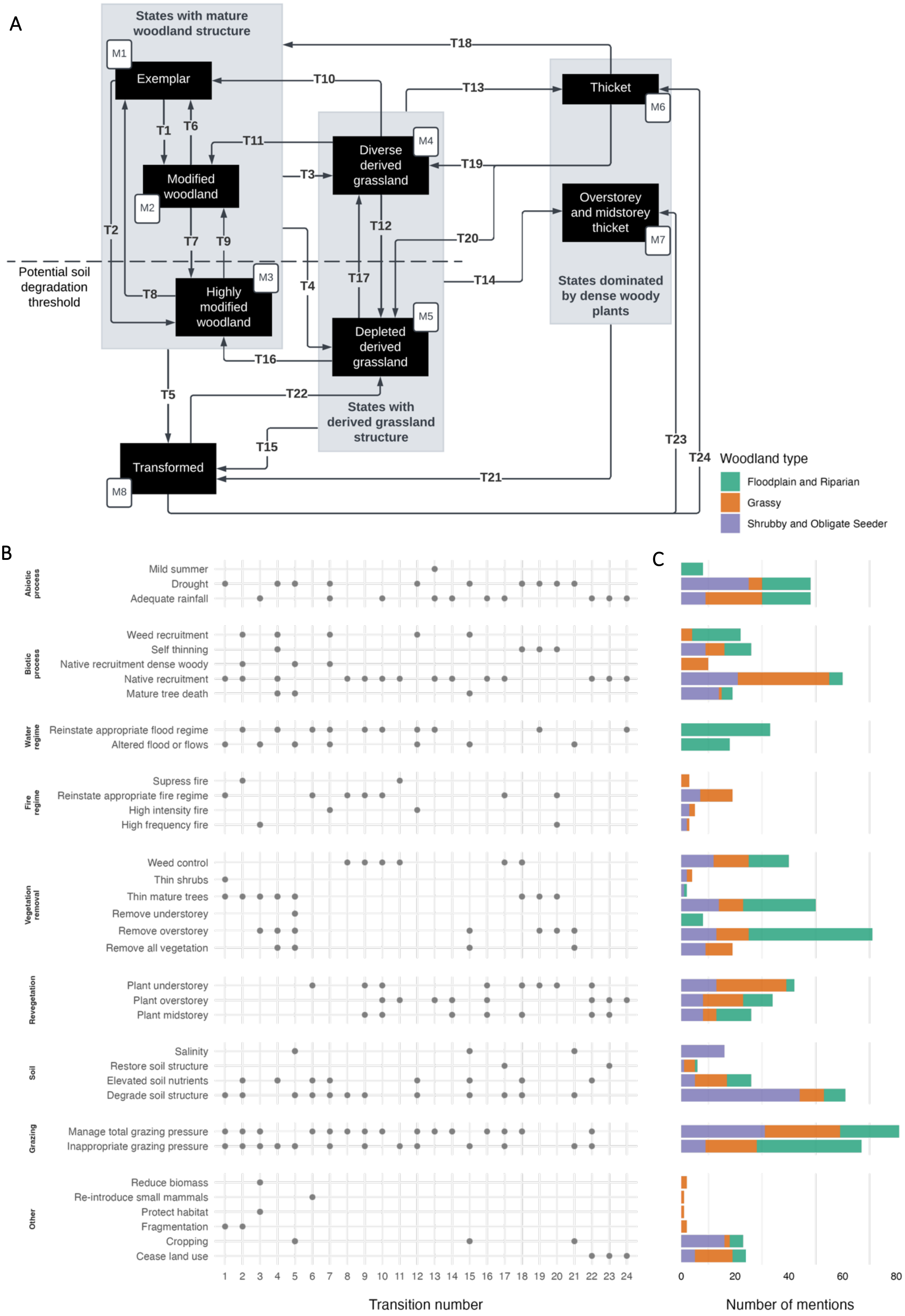

A
States with mature woodland structure
M1
Exemplar
T1
T6
Modified woodland
M2
T2
T7
T9
T8
Highly modified woodland
M3
Potential soil degradation threshold
T3
T4
T5
T10
T11
T12
T13
T14
T15
T16
T17
T18
T19
T20
T21
T22
T23
T24
Diverse derived grassland
M4
Depleted derived grassland
M5
States with derived grassland structure
Thicket
M6
Overstorey and midstorey thicket
M7
States dominated by dense woody plants
Transformed
M8
Woodland type
🟩 Floodplain and Riparian
🟧 Grassy
🟪 Shrubby and Obligate Seeder
B
Abiotic process
Mild summer
Drought
Adequate rainfall
Biotic process
Weed recruitment
Self thinning
Native recruitment dense woody
Native recruitment
Mature tree death
Water regime
Reinstate appropriate flood regime
Altered flood or flows
Fire regime
Supress fire
Reinstate appropriate fire regime
High intensity fire
High frequency fire
Vegetation removal
Weed control
Thin shrubs
Thin mature trees
Remove understorey
Remove overstorey
Remove all vegetation
Revegetation
Plant understorey
Plant overstorey
Plant midstorey
Soil
Salinity
Restore soil structure
Elevated soil nutrients
Degrade soil structure
Grazing
Manage total grazing pressure
Inappropriate grazing pressure
Other
Reduce biomass
Re-introduce small mammals
Protect habitat
Fragmentation
Cropping
Cease land use
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Transition number
C
0
20
40
60
80
Number of mentions

Figure 3. A) Box and arrow diagram showing states and plausible transitions across the three woodland sub-types. Arrows represent transitions (T1 – T24) from one state to another while numbered white boxes (M1 - M8) refer to the drivers associated with 'maintaining' the same state. All states, excluding 'Transformed' are clustered into three groups (grey shaded boxes); states with mature woodland structure, states with derived grassland structure and states dominated by dense woody plants. This broad grouping of states (according to structure) allowed for the grouping of transitions with the same drivers (for example transitions from states with mature woodland structure to Transformed (T5)). B) A matrix indicating which drivers were associated with each of the transitions in the box and arrow diagram and; C) The total number of causal chains that mentioned each driver for each woodland type. For example, 'Manage total grazing pressure' was mentioned in 80 causal chains, and was consistent across woodland types, whereas 'Degrade soil structure' was mentioned in 60 causal chains of which 45 causal chains were from the Shrubby and Obligate Seeder woodland type.

Turning the State and Transition Model into practical conservation advice

We used the management activities, abiotic and biotic processes elicited from experts as the basis for our management guide, which provides a framework to assist the building of recovery plans for woodlands. The Guide contains a series of interactive fact sheets that provide: i) the key threats, management interventions, and monitoring variables for each woodland condition state, and ii) decision trees for a subset of state transitions (those that represent an improvement in condition), to guide management decisions and/or the development of community specific recovery plans. Figure 4 includes two examples of fact sheets from the Guide (Simplified 2 = Highly modified woodland; Simplified 4 = Depleted derived grassland)

Modified woodlands

Description:

The overstorey is mostly intact; mid/understorey is depleted in both richness and cover; understorey flora is primarily native; and soil nutrient levels are natural, or close to natural.

Occurrence:

Uncommon

Land use:

Travelling stock reserves, or areas that have not been subject to continuous disturbance

Threats:

Grazing and agricultural interventions, altered flood or fire regimes

Variables to watch:

- Native understorey cover
- Exotic understorey cover
- Tree density/mortality

How to maintain

Likelihood: Very likely

How? It is possible that vegetation will remain in a Simplified 1 state with no intervention, or if low intensity periodic/rotational grazing is retained, and grazing by native or feral herbivores is kept at a low level.

How to restore

Target state: Exemplar (see figure below)

Likelihood: Very unlikely

How? Livestock removal (allows for passive regeneration). In floodplain and riparian woodlands, reinstate a natural flood regime.

Indicators: Increased shrub abundance and native understorey diversity.

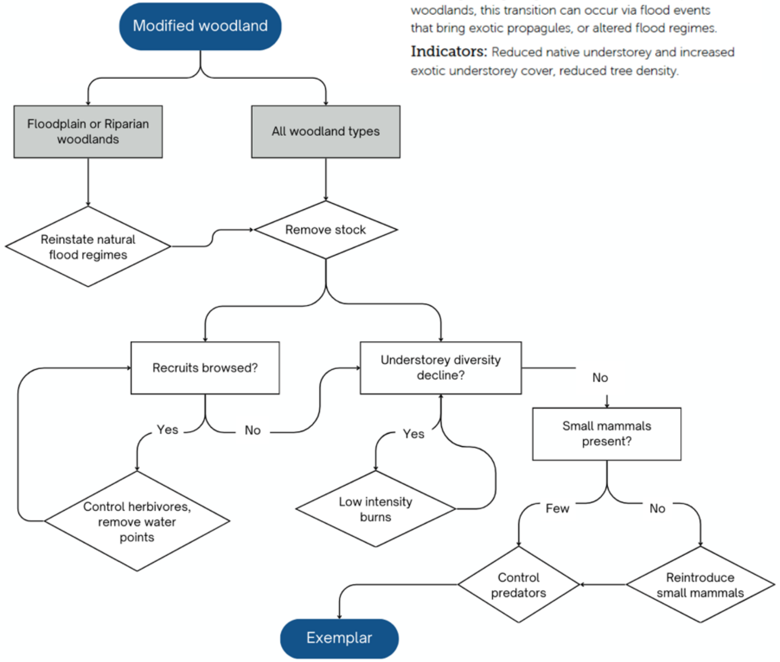
Transitions to avoid:

End state: Highly modified woodlands

Likelihood: Likely

How? Likely to occur due to agricultural interventions, or through benign neglect. In Floodplain and Riparian woodlands, this transition can occur via flood events that bring exotic propagules, or altered flood regimes.

Indicators: Reduced native understorey and increased exotic understorey cover, reduced tree density.



Depleted derived grasslands

Description:

Overstorey is depleted or absent; midstorey is absent or depleted; understorey is depleted in native species richness and cover.

Occurrence:

Common (grassy woodlands), uncommon (shrubby and floodplain woodlands)

Land use:

Native pasture, grazing land

Threats:

Drought and inappropriate grazing management

Variables to watch:

- Tree health
- Exotic species cover
- Soil health and stability

How to maintain

Likelihood: Very likely

How? Retain current land management and/or land use (retain current grazing pressure).

How to restore

Target state: Modified woodlands

Likelihood: Very unlikely

How? This transition could be achieved if grazing is removed, weed cover is managed via herbicide or cool burning (if relevant) and the vegetation is allowed to regenerate (if propagules are present) or replanted. If herbivores are acting to prevent understorey regeneration, grazing control (i..e culling, watering point removal) is required.

Indicators: Increased mature tree density, increased non-plant ground cover, increased diversity of native understorey, reduced exotic understorey cover.

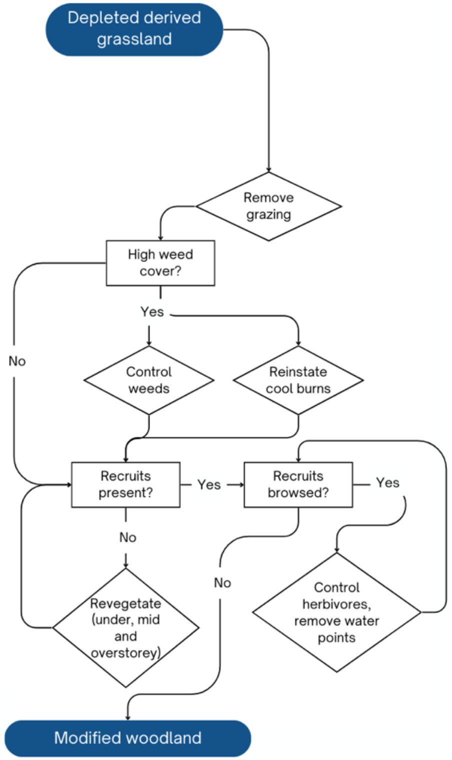


Figure 4: Modified excerpt (with updated state names) from The Guide to management (Good et al 2021) showing decision trees and management advice for Modified woodlands, and Depleted derived grasslands

Discussion

This paper describes a structured process for creating multi-community State and Transition Models to streamline the development of more detailed conservation plans. We demonstrate the application of this method by developing a State and Transition Model for eucalypt dominated temperate woodlands across southern Australia the combined expertise of woodland ecologists. Our findings suggest a generalized model to support conservation planning is possible; a set of eight agreed vegetation condition states exist across eucalypt woodlands of southern Australia, and there are substantial commonalities across woodland sub-types, including the various drivers that lead to transitions and likelihoods of transitions through time. We used the multi-community State and Transition Model to provide high level, site-scale management guidance of the kind that could be included in conservation plans for specific threatened communities within the broad woodland sub-types we describe. The resulting model synthesizes existing ecological knowledge and provides a framework that can be iteratively tested and improved through the use of adaptive management principles (Margoluis et al. 2009; Rumpff et al. 2011; Rice et al. 2020). Furthermore, this approach provides a generalized and reproducible method that can be applied to support the development of multi-community conservation plans in other systems, using hierarchical ecosystem classifications such as the Global Ecosystem Typology as way to group communities (Keith et al. 2020, 2022). Further, a structured framework for building expert elicited State and Transition Models could be applied to the development of predictive spatial mapping which has been developed elsewhere (Daniel et al. 2016; Blankenship et al. 2021).

Decision trees based on this general model are primarily useful for guiding consistent development of conservation plans that provide a framework for articulating goals or objectives for a site or landscape, the threats and risks associated with management, and structuring and interpreting monitoring data. A multi-community model can also provide on-ground practical advice, noting that this may require more nuanced consideration of the type or efficacy of management actions required to meet management goals. For example, it may be possible to transition from an ‘Overstorey thicket’ state to a ‘Modified woodland’ state through ecological thinning, but applying this recommendation is complex. Specifying ‘ecological thinning’ provides no information about the target tree density, method of implementation (mechanical or chemical) or likely costs of the action. Therefore, further details and expertise are required to understand and prioritize what actions work best, and where, for the available resources, time-frame and agreed outcomes. Although we have provided guidance for the implementation of this woodland State and Transition Model in real-world management scenarios, it is important to emphasize that any attempt at a multi-community State and Transition Model requires a trade-off between generality and a loss of specific details and nuance that will limit its ‘off-the-shelf' application. Instead, multi-community State and Transition Models should be treated as high level guidance to be tempered with region and/or community-specific field data, local knowledge and with consideration of additional constraints (e.g. cost, management direction, policy, etc).

State and transition models are generally expert derived, though data can be used to define ecosystem states, where available (Lester & Fairweather 2011; Jones et al. 2023). Any model based on expert knowledge will reflect the knowledge and experience of those experts included in the study (Burgman 2015). This may impact our model in the range of woodland condition states identified, the management required to achieve transitions, and the likelihood of those transitions occurring (Czembor et al. 2011; Travers et al. 2023). Where there is a lack of consensus on the structure or parameterisation of the model (see Czembor et al. 2011), competing models may be specified to capture uncertainty, which can be tested and resolved over time as data is acquired (i.e. through adaptive management; Rumpff et al. 2011).

The scale of our model (covering many different vegetation communities) required an approach that efficiently synthesized the expertise of woodland ecologists with a focus on transparency and updatability. The structured approach we developed encourages involvement from a diversity of experts that can provide information about states and transitions individually (via survey), before sharing and discussing their models with a broader group (via workshops; as outlined in (Hemming et al. 2018). We deliberately avoided asking experts to assign positive or negative values to the condition states, as this is likely to be biased by experts’ personal values about what aspects of condition are valued. Values are likely to vary across stakeholders, especially in relation to the extent of each state in the landscape. Lastly, it is not suggested that the Exemplar state represents the ultimate goal state, nor that it represents values beyond vegetation condition, but serves as a signpost for what might be possible for a given community. One strength of developing state-and-transition models using expert opinion is that it is possible to account for the impact of ongoing environmental change, including that caused by climate change. In this instance, rather than specify climate change as a particular threat, we asked experts to describe the specific drivers, like increased frequency and duration of drought. As the likelihood of transition was elicited for each causal chain, managers may use the model to consider which states and transitions may be more (or less) prevalent under climate change. However, we note that integration of severe climate change driven events, like wildfires, could be integrated into the decision trees.

This case study allowed us to critically assess and refine our process to improve outcomes and efficiency for others developing multi-community State and Transition Models. First, we acknowledge that it is necessary to further refine these models by incorporating dispossession of First Nations peoples and, in some cases, the loss of Indigenous Biocultural Knowledge as the first transition that occurred to threaten ecological communities in Australia (Ens et al. 2015; Bridgewater & Rotherham 2019). First Nations involvement should occur from the time of inception of the project or earlier to ensure the approach is culturally appropriate and culturally relevant. The recovery of the ecosystems addressed in the model is likely to be improved if the next iteration of the model can start by working respectfully with holders of Traditional Ecological Knowledge (Robinson et al. 2021).

The second refinement of our process is the development (in collaboration with participants) or use of an existing catalogue (for example the IUCN red list threat categories; Keith et al. 2022) of possible drivers that can be used to develop the causal chains describing the state transitions. Including a broader suite of drivers associated with climate change into a typology, like severe wildfire, will improve the ability of the model to capture future conditions. Multiple threats, disturbances and system variables operate within ecological communities, and each threat may have multiple synonyms and complex interactions and drivers. A standardized typology would reduce the burden on experts to reclassify drivers according to their own knowledge (Salafsky et al. 2002; Lynch 2011) and ensure experts use consistent terminology and consider the same pool of possible drivers. This will increase our confidence that any divergence among sub-types is not the result of variable expert knowledge or experience.

Last, there is scope to investigate how the states could be verified on ground with spatial vegetation condition datasets, which in turn could be used to help with condition mapping at a landscape scale to support landscape planning, natural capital accounting methods (Hein et al. 2020), or IUCN listing assessments (Rodríguez et al. 2015). Similarly, a structured elicitation of quantitative likelihood estimates could better enable predictive modelling of condition change over time.

We tested our approach on one of the most widespread vegetation types in Australia and demonstrated that developing a multi-community model of vegetation condition is not only plausible but provides a template to elicit the information critical to support conservation planning in a structured, logical and consistent format. Although individual communities are diverse in composition, we focused on the similarities in structure, function, threats and drivers that result in consistency in management approaches. This 'requisite simplicity' enables conceptual clarity and a solid foundation on which to base critical decisions for regional conservation planning. Our framework for identifying and defining community or ecosystem condition states, estimating their prevalence in the landscape, and describing the type and nature (threats, drivers) of transitions between condition states (synthesized as decision trees), provides a framework for considering current and future states in a planning process, and identifying effective management actions through targeted interventions. As the number of threatened ecological communities increases, we advocate for the efficient use of existing knowledge via this multi-community iterative and structured process to streamline the development and transparency of conservation plans.

Supporting Information

Additional supporting information may be found in the online version of the article at the publisher's website.

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