A structured approach for building multi-community state-and-transition models to support conservation planning

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Abstract

The global decline in the extent and condition of ecological communities has resulted in an increasing demand for recovery and conservation plans. Conservation plans for ecological communities require a management framework with measurable, time-bound objectives, a targeted management strategy, and indicators that enable actions to be evaluated in relation to objectives. Methods that allow for the transfer of knowledge among similar systems and facilitate consistent and comparable plans are essential, especially when resources are constrained. 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. We demonstrate this approach in a case study where we use the combined expertise of Australian ecologists to build a multi-community State and Transition Model for eucalypt 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. We identify commonalities and differences among three broad woodland sub-types including a set of eight general condition states, a list of drivers of transitions among condition states, and the uncertainties and time-frames associated with each transition. Two key findings across all models are that management is state-dependent, and transition directly to the 'Exemplar' state from any other state is considered highly unlikely. Other examples of State and Transition Models in the literature are focused on single communities or a significantly smaller scale, and this is the first attempt to construct a nationally relevant multi-community State and Transition Model via a structured and consultative process. Based on this case study, we propose a repeatable protocol for developing multi-community State and Transition Models. This process could improve and streamline the development of robust conservation plans for threatened ecological communities more broadly.

Introduction

Globally, ecosystems face increasing rates of degradation and collapse, due primarily to habitat destruction 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 to 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), and 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.

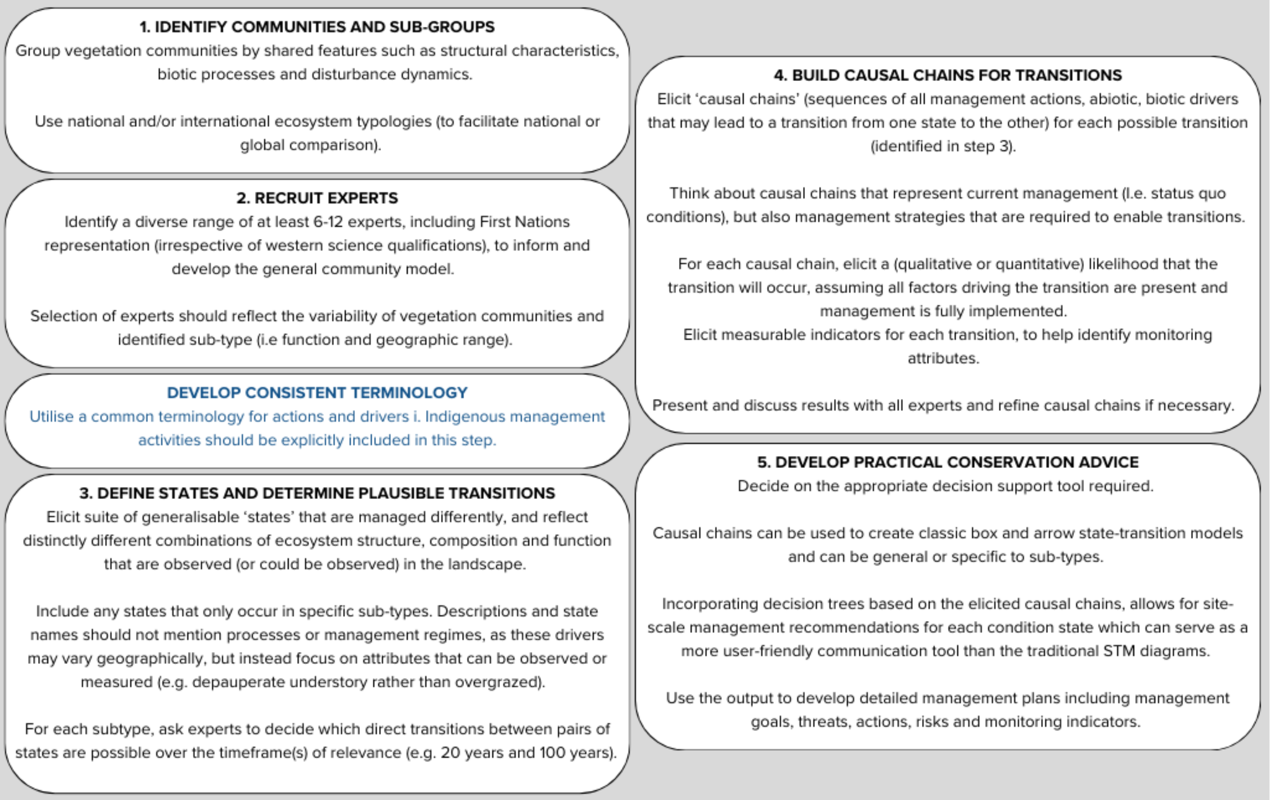
Ecosystems and communities within the same broad type likely share commonalities including their prevailing threats and drivers of change, which suggest there may be opportunities to generalize and transfer understanding from one system to another. Indeed, multi-species and ecosystem planning has been 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).

In this study, we developed a method for creating and evaluating multi-community State and Transition Models, which could serve as a foundation for developing conservation plans for specific vegetation communities. As proof-of-concept we develop a State and Transition Model for eucalypt woodlands in southern Australia. Eucalypt woodlands (species of the closely related genera *Eucalyptus*, *Corymbia* and *Angophora*) 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. Our aim was 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. This approach could enable rapid, consistent and comprehensive development of conservation plans that can be later tailored to individual communities as required.

Methods

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 eucalypt-dominated woodlands (Figure 1).



1. IDENTIFY COMMUNITIES AND SUB-GROUPS
Group vegetation communities by shared features such as structural characteristics, biotic processes and disturbance dynamics.

Use national and/or international ecosystem typologies (to facilitate national or global comparison).

2. RECRUIT EXPERTS
Identify a diverse range of at least 6-12 experts, including First Nations representation (irrespective of western science qualifications), to inform and develop the general community model.

Selection of experts should reflect the variability of vegetation communities and identified sub-type (i.e function and geographic range).

DEVELOP CONSISTENT TERMINOLOGY
Utilise a common terminology for actions and drivers i. Indigenous management activities should be explicitly included in this step.

3. DEFINE STATES AND DETERMINE PLAUSIBLE TRANSITIONS
Elicit suite of generalisable 'states' that are managed differently, and reflect distinctly different combinations of ecosystem structure, composition and function that are observed (or could be observed) in the landscape.

Include any states that only occur in specific sub-types. Descriptions and state names should not mention processes or management regimes, as these drivers may vary geographically, but instead focus on attributes that can be observed or measured (e.g. depauperate understory rather than overgrazed).

For each subtype, ask experts to decide which direct transitions between pairs of states are possible over the timeframe(s) of relevance (e.g. 20 years and 100 years).

4. BUILD CAUSAL CHAINS FOR TRANSITIONS
Elicit 'causal chains' (sequences of all management actions, abiotic, biotic drivers that may lead to a transition from one state to the other) for each possible transition (identified in step 3).

Think about causal chains that represent current management (I.e. status quo conditions), but also management strategies that are required to enable transitions.

For each causal chain, elicit a (qualitative or quantitative) likelihood that the transition will occur, assuming all factors driving the transition are present and management is fully implemented.
Elicit measurable indicators for each transition, to help identify monitoring attributes.

Present and discuss results with all experts and refine causal chains if necessary.

5. DEVELOP PRACTICAL CONSERVATION ADVICE
Decide on the appropriate decision support tool required.

Causal chains can be used to create classic box and arrow state-transition models and can be general or specific to sub-types.

Incorporating decision trees based on the elicited causal chains, allows for site-scale management recommendations for each condition state which can serve as a more user-friendly communication tool than the traditional STM diagrams.

Use the output to develop detailed management plans including management goals, threats, actions, risks and monitoring indicators.

Figure 1. Protocol for synthesizing a multi-community State and Transition Model. Blue text are suggested improvements and were not included in our case study but are explored further in the discussion of this paper.

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 two online surveys 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 (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.

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. 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 (see sample DAGs and reproducible code in Supplementary Material).

The survey responses were subsequently reviewed by the same experts in a face-to-face workshop. 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.

Step 4: Describe how transitions occur – specify causal chains

The next step involved asking experts to systematically describe all the factors that need to occur together or in sequence to drive each of the plausible direct transitions identified in step 3. 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, 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 (e.g. mature tree density) that could be used to identify that transition 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 the causal chain are in place (i.e. if high rainfall is important for the transition, they assumed that high rainfall occurred and estimated the likelihood of the transition accordingly).

Raw causal chain data were processed and analyzed using reproducible code (Supplementary material). 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 I).

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 may require some rearranging to find the simplest possible combination. In general, analysing the suite of causal chains to explore the order of specified management actions will help indicate the ordering of branches, and ensure all actions are accounted for. 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.

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.

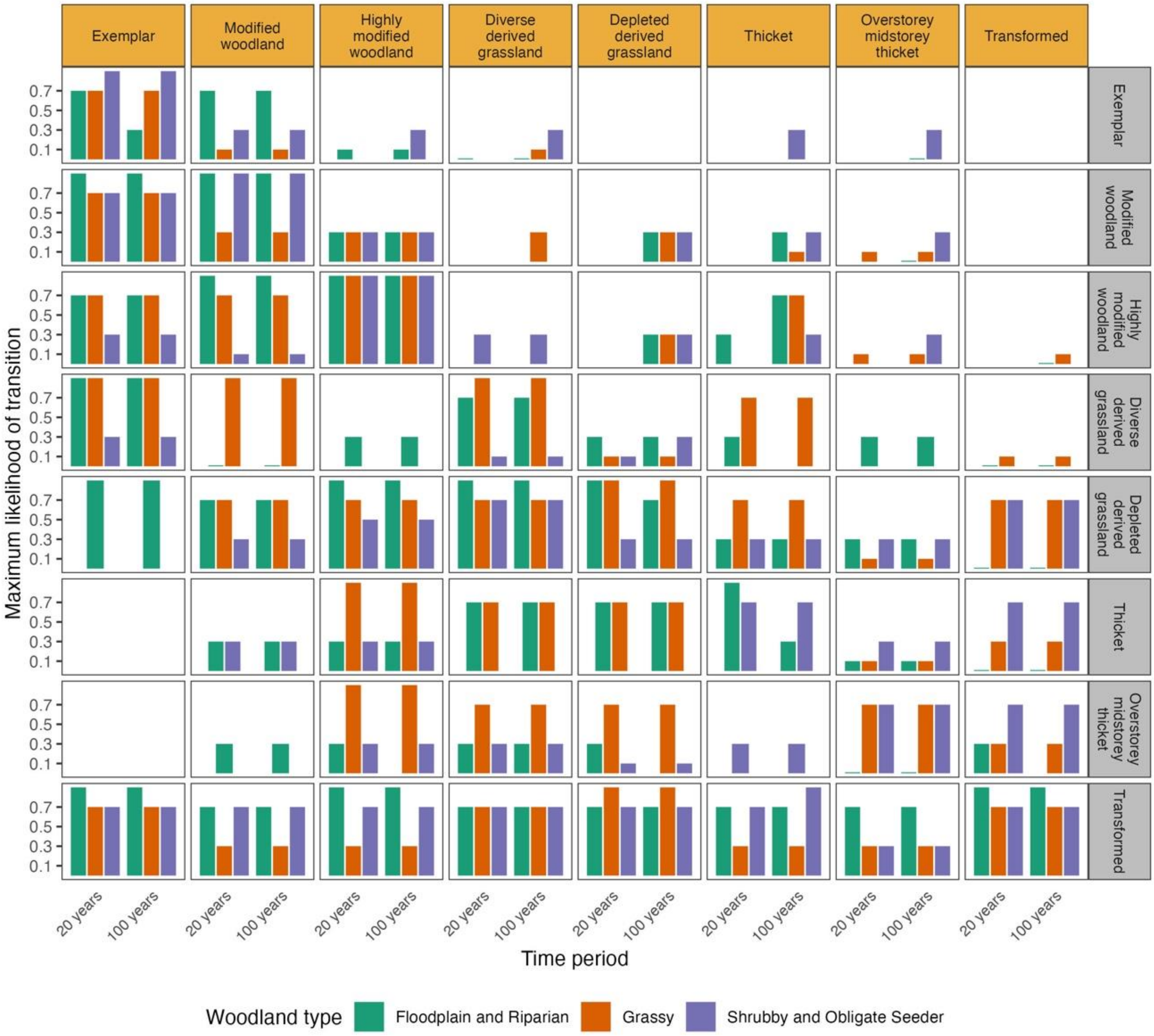


Figure 1. Likelihoods of state transitions for each woodland sub-type for both 20-year and 100-year time-frames. The initial states are along the top (orange shaded), and the final states are along the right side (grey shaded). For transitions where more than one causal chain was described, we included the likelihood assigned to the most likely chain in this plot.

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.

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 3b). 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 3a). 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).

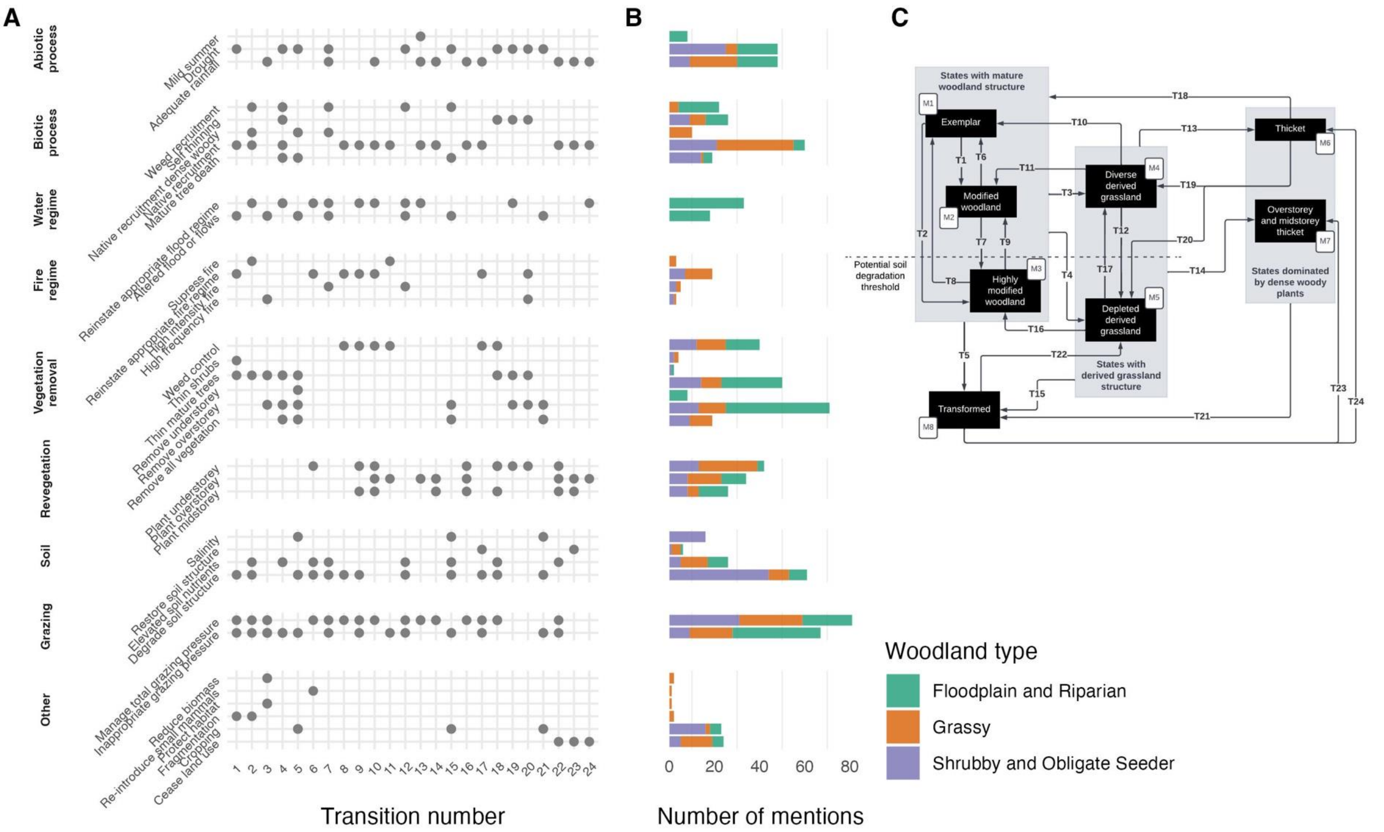
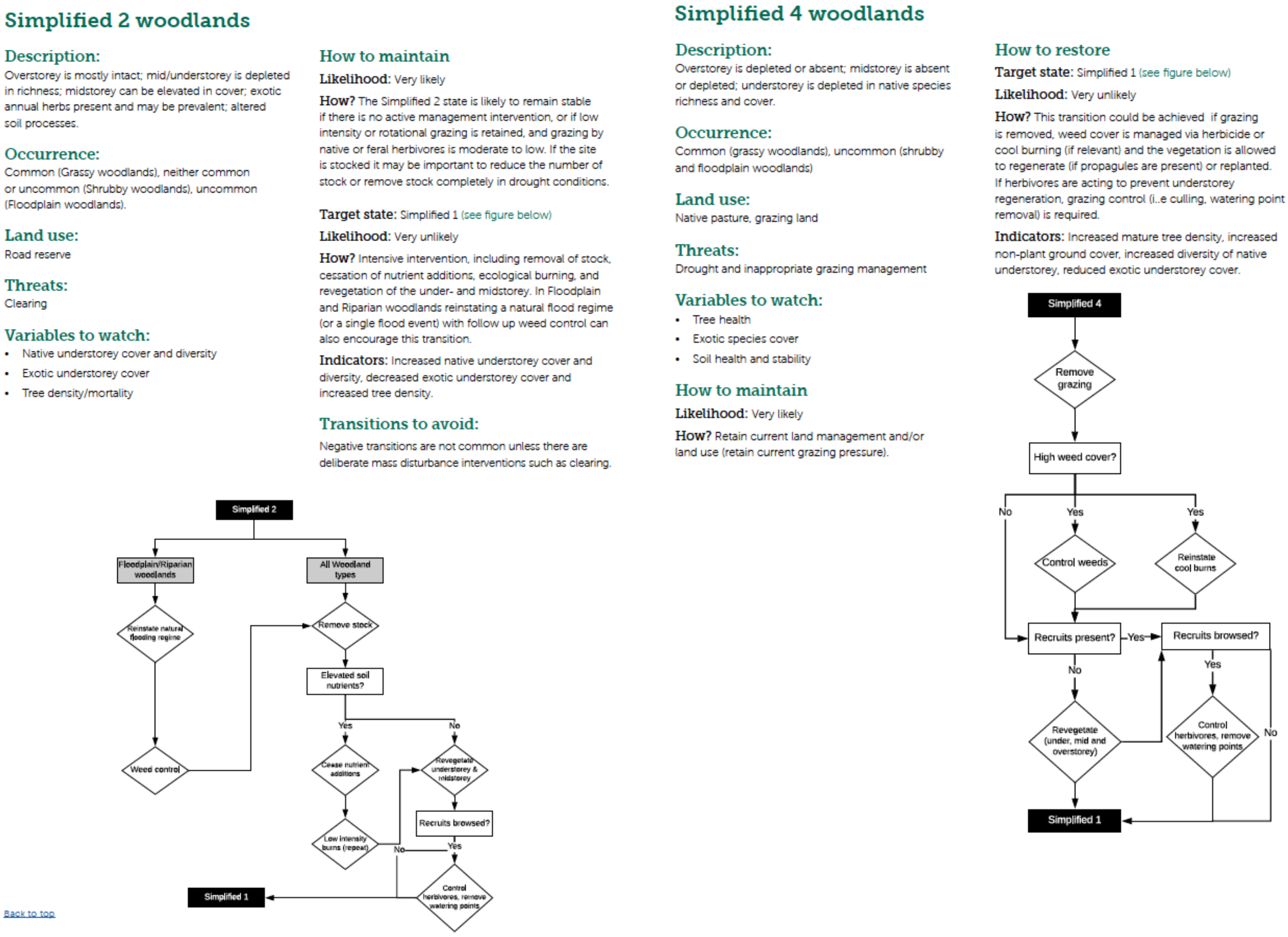


Figure 3. A) A matrix indicating which drivers were associated with each of the transitions in the box and arrow diagram and; B) the number of times each driver was mentioned by experts from the three woodland groups. More detail on differences in the drivers associated with the three woodland sub-types, along with attributes that would indicate the transition is taking place, can be found in Supplementary material 1. C) 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)).

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).



Simplified 2 woodlands

Description:
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.

Occurrence:
Common (Grassy woodlands), neither common or uncommon (Shrubby woodlands), uncommon (Floodplain woodlands).

Land use:
Road reserve

Threats:
Clearing

Variables to watch:

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

How to maintain

Likelihood: Very likely

How? The Simplified 2 state is likely to remain stable if there is no active management intervention, or if low intensity or rotational grazing is retained, and grazing by native or feral herbivores is moderate to low. If the site is stocked it may be important to reduce the number of stock or remove stock completely in drought conditions.

Target state: Simplified 1 (see figure below)

Likelihood: Very unlikely

How? Intensive intervention, including removal of stock, cessation of nutrient additions, ecological burning, and revegetation of the under- and midstorey. In Floodplain and Riparian woodlands reinstating a natural flood regime (or a single flood event) with follow up weed control can also encourage this transition.

Indicators: Increased native understorey cover and diversity, decreased exotic understorey cover and increased tree density.

Transitions to avoid:
Negative transitions are not common unless there are deliberate mass disturbance interventions such as clearing.

Simplified 4 woodlands

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: Simplified 1 (see figure below)

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: Excerpt from The Guide to management (Good et al 2021) showing decision trees and management advice for Highly modified woodlands (Simplified 2),and Depleted derived grassland (Simplified 4).

Discussion

This paper describes a structured process for creating expert elicited multi-community State and Transition Models to streamline the development of more detailed conservation plans. To demonstrate this, we developed a State and Transition Model for eucalypt dominated temperate woodlands across southern Australia. 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, possibly 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 account for the complexity of ecological states and transitions. Applying these decision trees on the ground requires 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 costs.

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 (Travers et al. 2023). 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.

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, which we failed to do in the case study. We instead expected First Nations peoples to participate in a process that has been designed in their absence. 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. 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.

A multi-community model of vegetation condition is plausible, useful and informative. 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.

Hyperlink to preregistered project: https://osf.io/gm4nw/

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Appendix I

Table AI: Details of the grouped transitions across woodland sub-types including all abiotic and biotic factors, interventions and indicators associated with transitions from the start and end states. Any drivers that were specific to a woodland sub-type are indicated in parentheses (Floodplain and Riparian = F, Grassy = G and Shrubby and obligate seeder = S).

Transition	Start and End states	Indicator of transition	Drivers and processes associated with transition		
			Abiotic	Interventions	Biotic processes
M1	Exemplar to Exemplar	Minimal change in cover, richness and diversity of all vegetation layers habitat features and functional processes remain unchanged.	Appropriate flood/flows (F) Average rainfall	Weed control/surveillance Reduce fragmentation impacts (increase area, reduce edge) Appropriate fire regime (G,S) Appropriate grazing pressure Soil disturbance by small native mammals	Recruitment of native propagules sufficient to replace any mortality in all vegetation layers
T1	Exemplar to Modified woodland	Reduction in diversity and cover of native understorey community	Altered flood/flows (F) Below average rainfall	Fragmentation (L) Inappropriate grazing pressure (native or introduced herbivores) Thinning or removal of midstorey Thinning of overstorey trees Soil disturbance - degradation	Mortality of trees Insufficient recruitment of native species
T2	Exemplar to Highly modified woodland	Reduction in diversity and cover of native understorey community, Increased exotic species cover, Reduction in density and diversity of mid-storey	Altered flood/flows (F) Drought	Fragmentation (L) Fire suppression or inappropriate fire regime (G,S) Thinning or removal of midstorey Thinning of overstorey trees Inappropriate grazing pressure (introduced herbivores) Soil disturbance – degradation (fertiliser addition or altered nutrient status from stock)	Mortality of trees and shrubs Dense recruitment of shrubs Insufficient recruitment of native species, Exotic species recruitment Altered soil processes

Transition	Start and End states	Indicator of transition	Drivers and processes associated with transition		
			Abiotic	Interventions	Biotic processes
T3	Exemplar to Diverse derived grassland	Reduction in tree and shrub density Minimal change in diversity and cover of herbaceous ground layer	Average rainfall	Vegetation clearing - overstorey and midstorey Appropriate grazing pressure, biomass management Weed control/surveillance	Recruitment of native propagules sufficient to maintain diversity of herbaceous species
T4	Exemplar to Depleted derived grassland	Very low cover/density of native trees or shrubs Moderate to high exotic groundcover	Altered flood/flows (F)	Vegetation clearing - overstorey and midstorey Inappropriate grazing pressure (introduced herbivores) Soil disturbance - degradation Soil nutrification	Exotic species recruitment and growth Altered soil processes
T5	Exemplar to Transformed	Reduction in cover/density of native trees, shrubs or groundcover Dramatic increase in cover of exotic species or bare soil	Drought	Vegetation clearing – all strata Cropping Fertilisation Inappropriate grazing pressure (introduced herbivores) Soil disturbance - degradation	Insufficient recruitment of native species, Exotic species recruitment and growth Altered soil processes
T6	Modified woodland to Exemplar	Increased cover, richness and diversity of groundstorey	Appropriate flood/flow regime (F)	Manage total grazing pressure Weed control/surveillance Reintroduce small mammals Appropriate fire regime (G,S) Revegetate groundstorey	Recruitment of native propagules sufficient to replace any mortality in all vegetation layers
M2	Modified woodland to Modified woodland	Minimal change in cover, richness and diversity of all vegetation layers, habitat features and functional processes	Average rainfall	Weed control/surveillance Appropriate fire regime (G,S) Manage total grazing pressure	Recruitment of native propagules sufficient to replace any mortality in all vegetation layers
T7	Modified woodland to Highly modified woodland	Reduction in diversity and cover of native understorey community, Increased exotic species cover,	Altered flood/flows (F) Drought	Fire suppression or inappropriate fire regime Mature tree thinning Shrub thinning	Mortality of trees and shrubs or overly dense recruitment of shrubs Insufficient recruitment of native species,

Transition	Start and End states	Indicator of transition	Drivers and processes associated with transition		
			Abiotic	Interventions	Biotic processes
		Reduction in density and diversity of mid-storey		Inappropriate grazing pressure (introduced herbivores) Soil disturbance - degradation Soil nutrification	Exotic species recruitment
T3	Modified woodland to Diverse derived grassland			See above	
T4	Modified woodland to Depleted derived grassland			See above	
T5	Modified woodland to Transformed			See above	
M3	Highly modified woodland to Highly modified woodland	Minimal change in cover, richness and diversity of all vegetation layers	Drought	Status quo Inappropriate grazing pressure (introduced herbivores)	Insufficient recruitment of native species Ongoing exotic species recruitment and growth
T8	Highly modified woodland to Exemplar	Increased cover, richness and diversity of groundstorey and midstorey	Appropriate flood/flow regime (F)	Manage total grazing pressure Weed control/surveillance Reintroduce small mammals Appropriate fire regime (G,S) Restore soil nutrient levels Revegetate groundstorey and midstorey	Recruitment of native propagules sufficient to replace any mortality in all vegetation layers
T9	Highly modified woodland to Modified woodland	Increased cover, richness and diversity of groundstorey and midstorey	Appropriate flood/flow regime (F)	Manage total grazing pressure Weed control/surveillance Reintroduce small mammals Appropriate fire regime (G,S) Restore soil nutrient levels Revegetate groundstorey and midstorey	Recruitment of native propagules sufficient to replace any mortality in all vegetation layers
T4	Highly modified woodland to Depleted derived grassland			See above	
T5	Highly modified woodland to			See above	

Transition	Start and End states	Indicator of transition	Drivers and processes associated with transition		
			Abiotic	Interventions	Biotic processes
	Transformed				
T10	Diverse derived grassland to Exemplar	Increased density of mature trees, Increased cover, richness and diversity of groundstorey and midstorey	Appropriate flood/flow regime (F) Average or above-average rainfall	Revegetate overstorey and midstorey Manage total grazing pressure* Weed surveillance Reintroduce small mammals Appropriate fire regime (G,S)	Recruitment of native propagules sufficient to replace any mortality in all vegetation layers
T11	Diverse derived grassland to Modified woodland	Increased density of mature trees, Increased cover, richness and diversity of groundstorey and midstorey	Appropriate flood/flow regime (F) Average or above-average rainfall	Revegetate overstorey Increased grazing pressure (native or introduced herbivores)	Recruitment of native propagules sufficient to replace any mortality in groundstorey and overstorey
M4	Diverse derived grassland to Diverse derived grassland	Minimal change in cover, richness and diversity of all vegetation layers (ie maintain lack of woody vegetation)	Average rainfall Appropriate flood/flows (F)	Status quo Woody recruitment control/surveillance Weed control/surveillance Manage biomass Appropriate fire regime	Recruitment of native propagules sufficient to maintain native groundstorey species
T12	Diverse derived grassland to Depleted derived grassland	Reduction in diversity and cover of native understorey community, Increased exotic species cover	Drought Altered flood/flows (F)	Fire – high intensity Inappropriate grazing pressure (introduced herbivores) Soil disturbance - degradation Soil nutrification	Recruitment and growth of exotic species
T13	Diverse derived grassland to Thicket	Increase in sapling density	Adequate summer rainfall Mild summer Flood/flow event (F)	Revegetation overstorey species (high density)	Mass eucalypt recruitment event or ongoing above-average eucalypt recruitment
T14	Diverse derived grassland to Overstorey midstorey thicket	Increase in sapling and shrub density	Adequate summer rainfall Mild summer	Revegetation overstorey species (high density) Revegetation midstorey species (high density)	Dense tree and shrub recruitment
T15	Diverse derived grassland to Transformed	Very low to no native groundcover High cover of exotic species or bare soil	Drought	Vegetation clearing – groundstorey Cropping Fertilisation	Insufficient recruitment of native species, Exotic species recruitment and growth Altered soil processes

Transition	Start and End states	Indicator of transition	Drivers and processes associated with transition		
			Abiotic	Interventions	Biotic processes
				Inappropriate grazing pressure (introduced herbivores) Soil disturbance – degradation and nutrification	
T16	Depleted derived grassland to Highly modified woodland	Increase in density of mature trees Minimal change in cover, richness and diversity of groundstorey and midstorey	Adequate summer rainfall Mild summer Flood/flow event (F)	Revegetate overstorey Status quo Inappropriate grazing pressure (introduced herbivores)	Recruitment and growth of overstorey at low density
T17	Depleted derived grassland to Diverse derived grassland	Increased cover, richness and diversity of groundstorey	Appropriate flood/flow regime (F)	Manage total grazing pressure Weed control/surveillance Appropriate fire regime (G,S) Restore soil nutrient levels Revegetate groundstorey	Increase in growth and recruitment of native groundstorey species
M5	Depleted derived grassland to Depleted derived grassland	Minimal change in cover, richness and diversity of all vegetation layers	Average rainfall	Status quo Inappropriate grazing pressure (introduced herbivores)	Insufficient recruitment of native species Ongoing exotic species recruitment and growth
T13	Depleted derived grassland to Thicket			See above	
T14	Depleted derived grassland to Overstorey midstorey thicket			See above	
T15	Depleted derived grassland to Transformed			See above	
T18	Thicket to Modified woodland	Reduction in sapling density Increase in mature tree density Increase in groundstorey cover and diversity	Average rainfall Appropriate flood/flows (F)	Thin saplings Revegetate groundstorey Manage total grazing pressure (Restore soil if needed)	Self thinning and growth of saplings
T18	Thicket to Highly modified woodland			See above	
T19	Thicket to Diverse derived grassland	Reduction in overstorey density	Drought	Clear saplings	Natural mass mortality of saplings

Transition	Start and End states	Indicator of transition	Drivers and processes associated with transition		
			Abiotic	Interventions	Biotic processes
		Increase in groundstorey cover	Or average rainfall	Minimal groundstorey disturbance Revegetation of groundstorey (if required)	Recruitment and growth of native groundstorey
T20	Thicket to Depleted derived grassland	Reduction in overstorey density Increase in groundstorey cover	Drought Or average rainfall	Clear saplings Status quo or increase grazing pressure (introduced herbivores) Soil disturbance - degradation Soil nutrification	Natural mass mortality of saplings Recruitment and growth of native groundstorey
M6	Thicket to Thicket	Minimal change in sapling density	Average rainfall	Status quo	Minimal tree mortality
T21	Thicket to Transformed	Reduction in cover/density of native saplings, shrubs and/or groundcover Reduction in litter Increase in cover of exotic species or bare soil	Drought Or average rainfall	Vegetation clearing – all strata Cropping Fertilisation Inappropriate grazing pressure (introduced herbivores) Soil disturbance - degradation	Insufficient recruitment of native species, Exotic species recruitment and growth Altered soil processes
M7*	Overstorey midstorey thicket to Overstorey midstorey thicket	Minimal change in cover, richness and diversity of all vegetation layers	Adequate rainfall	Status quo	*very unlikely unless shrubs and trees don't grow enough to result in changed structure
T21	Overstorey midstorey thicket to Transformed			See above	
T22	Transformed to Depleted derived grassland	Reduction in bare soil	Adequate rainfall	Cease land use Manage total grazing pressure Revegetation of groundstorey (with exotic or native plants depending on soil degradation, i.e. salinity)	Groundcover plant recruitment and growth
T23	Transformed to Thicket	Increase in sapling density	Adequate summer rainfall Mild summer Flood/flow event (F)	Revegetation overstorey species (high density)	Mass eucalypt recruitment event or ongoing above-average eucalypt recruitment

Transition	Start and End states	Indicator of transition	Drivers and processes associated with transition		
			Abiotic	Interventions	Biotic processes
T24	Transformed to Overstorey midstorey thicket	Increase in sapling and shrub density	Flood/flow event (F) Adequate summer rainfall Mild summer	Revegetation overstorey species (high density) Revegetation midstorey species (high density)	Dense tree and shrub recruitment
M8	Transformed to Transformed	Minimal change in amount groundcover or bare soil		Status quo	