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State and transition models for tussock grasslands and woodlands of the Kimberley: Final project report

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Australia's National
Science Agency

State and transition models for tussock grasslands and woodlands of the Kimberley

Final project report

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Contents

Acknowledgments ix
Executive summary x
1 Introduction 1
1.1 Background 2
1.2 Project aims and outcomes 2
1.3 Location and pasture types 3
2 The Australian Ecosystem Models Framework and State and Transition Models 6
3 State and transition modelling workshop 10
4 Ecosystem states 12
4.1 Archetype models and reference states 12
4.2 Summary of modified states and transitions 19
4.3 Red soil modified states: Wet-dry tropical eucalypt woodlands 25
4.4 Black soil modified states: Rainfall-pulse driven arid and semi-arid tussock grasslands 41
5 Ecosystem transitions 53
6 Next steps 64
6.1 Mapping the spatial extent of ecosystem states 64
6.2 How state and transition models might guide monitoring and evaluation of rangeland condition 66
6.3 Knowledge gaps, lessons learned and conclusions 68
Appendix A State and transition modelling workshop agenda 71
Appendix B Wet-dry tropical eucalypt woodlands archetype 76
Ecosystem dynamics 77
Experts consulted 78
References 78
Appendix C Rainfall-pulse disturbed arid and semi-arid tussock grasslands archetype 80
Ecosystem dynamics 81
Knowledge gaps 82
Experts consulted 82
References 82

Glossary 85

References 88

Figures

Figure 1. A map of pasture types of the Kimberley, Western Australia, with the black outline showing the general area of pastoral leases. This area was the focus for the development of S&TMs with exceptions noted in the text.. 5

Figure 2. Stylised depiction of the relationship between archetype models and dynamic S&TMs. 7

Figure 3. A values framework for defining ecosystem condition, reproduced from Keith et al. (2020). 9

Figure 4. Images from the state and transition modelling workshop held in Perth on the 18th-19th May 2022. 11

Figure 5. Map of 'Red soil' pasture types: Black speargrass pastures (BSGP), Buffel grass pastures (BUGP), Frontage grass pastures (FRGP), Plume sorghum pastures (PLSP), Ribbon grass pastures (RGRP), Tippera tall grass plain pastures (TTGP), White grass bundle-bundle pastures (WGBP); and 'Black soil' pasture types: Blue grass alluvial plain pastures (BGAP), Mitchell grass alluvial plain pastures (MGAP), Ribbon grass alluvial plain pastures (RAPP) across the Kimberley. Note, not all pastures shown in Table 2 are reproduced in the map as areas of these pasture types were too small to map or were combined with similar pasture types (e.g. arid short grass pastures were included in the mapped area of RGRP and Mitchell grass upland pastures were included in the mapped area of MGAP). 13

Figure 6. Conceptual model of a dynamic reference state for Wet-dry tropical eucalypt woodlands (red soils) of the Kimberley. 14

Figure 7. Mixed-age tropical woodland in near reference state (similar for low rainfall or high rainfall areas). 15

Figure 8. Conceptual model of a dynamic reference state for Rainfall-pulse driven arid and semi-arid tussock grasslands (black soils) of the Kimberley. 17

Figure 9. Rainfall-pulse driven arid and semi-arid tussock grassland in near reference state..... 18

Figure 10. Example of the '*Vachellia farnesiana* shrubland/grassland' expression in the Rainfall-pulse driven arid and semi-arid tussock grassland (black soils) reference state with the photo taken during the dry season. 19

Figure 11. Summary of transitions between modified ecosystem states for the Wet-dry tropical eucalypt woodlands ('red soil') ecosystem type. Correspondence between ecosystem states and pasture type and condition (shown in colour) is included (see Table 5)..................................... 22

Figure 12. Summary of transitions between modified ecosystem states for the Rainfall-pulse driven arid and semi-arid tussock grasslands ('black soil') ecosystem type. Correspondence between ecosystem states and pasture type and condition (shown in colour) is included (see Table 5).. 23

Figure 13. Conceptual model of the modified state 'diverse perennial pasture close to reference' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley..... 25

Figure 14. Examples of a 'diverse perennial pasture close to reference' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. Note woody cover is very sparse in these examples but can be up to 20 %. 26

Figure 15. Conceptual model of the modified state 'moderate diversity perennial pasture' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. 27

Figure 16. Examples of a 'moderate diversity perennial pasture' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. Photo on the left is after above average rainfall and on the right after below average rainfall. 28

Figure 17. Conceptual model of the modified state 'native woody thickened' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. 28

Figure 18. Example of a 'native woody thickened' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. Photos were taken in 2011 (left) and 2020 (right), with 3 fires occurring at the site between these time points. 29

Figure 19. Conceptual model of the modified state 'annual sorghum dominant' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. 29

Figure 20. Example of a 'annual sorghum dominant' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. 30

Figure 21. Conceptual model of the modified state '*Aristida contorta*' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. 31

Figure 22. Example of an '*Aristida contorta*' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. Photo: S. Prober. 32

Figure 23. Conceptual model of the modified state 'annual grasses and forbs' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. 33

Figure 24. Example of an 'annual grasses and forbs' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. Photo on the left taken after below average rainfall, and on the right after above average rainfall. 34

Figure 25. Conceptual model of the modified state 'bare soil' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. 34

Figure 26. Examples of a 'bare soil' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. 35

Figure 27. Conceptual model of the modified state 'buffel grass' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. 35

Figure 28. Examples of a 'buffel grass' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. Photo on the left taken after above average rainfall, and on the right after below average rainfall. 36

Figure 29. Conceptual model of the modified state 'Indian couch dominant' (*Bothriochloa pertusa*) for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. 37

Figure 30. Examples of a 'Indian couch' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. Top two photos are examples from the Kimberley

(photo: WARMS photograph collection) and the bottom photo is from Mt Pleasant, QLD (Photo: B. Abbott). 38

Figure 31. Example of a ‘spinifex dominant’ modified state for the ecosystem type ‘Wet-dry tropical eucalypt woodlands’ of the Kimberley. Photo: S. Prober. 39

Figure 32. Conceptual model of the modified state ‘palatable perennials dominant’ for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley.41

Figure 33. Examples of a ‘palatable perennials dominant’ modified state for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley. 42

Figure 34. Conceptual model of the modified state ‘mixed unpalatable perennials dominant’ for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley. 43

Figure 35. Examples of a ‘mixed unpalatable perennials dominant’ modified state for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley.44

Figure 36. Conceptual model of the modified state ‘*Aristida latifolia* dominant’ for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley.44

Figure 37. Examples of a ‘*Aristida latifolia* dominant’ modified state for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley. 45

Figure 38. Conceptual model of the modified state ‘native woody thickened’ for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley. 45

Figure 39. Example of a ‘native woody thickened’ modified state for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley. 46

Figure 40. Conceptual model of the modified state ‘annual grasses and forbs’ for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley. 47

Figure 41. Example of an ‘annual grasses and forbs’ modified state for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley. 48

Figure 42. Conceptual model of the modified state ‘seasonally bare ground’ for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley. 48

Figure 43. Example of a ‘seasonally bare ground’ modified state for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley. 49

Figure 44. Conceptual model of the modified state ‘Indian couch’ for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley. 50

Figure 45. Examples of an ‘Indian couch’ future modified state for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley, taken in Queensland. Photo: B. Abbott. 51

Figure 46. Drivers, uncertainty (more certain is >0.7; uncertain is <0.7, see Table 8) and timeframes for undesirable transitions between ecosystem states in the Wet-dry tropical eucalypt woodlands (red soil) ecosystem type. 54

Figure 47. Drivers, uncertainty (more certain is >0.7; uncertain is <0.7, see Table 8) and timeframes for desirable transitions between ecosystem states in the Wet-dry tropical eucalypt woodlands (red soil) ecosystem type. 55

Figure 48. Drivers, uncertainty (more certain is >0.7; uncertain is <0.7, see Table 9) and timeframes for undesirable transitions between ecosystem states in the Pulse-rainfall driven arid and semi-arid tussock grasslands (black soil) ecosystem type. 60

Figure 49. Drivers, uncertainty (more certain is >0.7; uncertain is <0.7, see Table 9) and timeframes for desirable transitions between ecosystem states in the Pulse-rainfall driven arid and semi-arid tussock grasslands (black soil) ecosystem type. 61

Figure 50. Example of a decision tree for management guidance reproduced from Good et al. (2021a). 67

Figure 51. Example of management actions required to enact a transition from '*Aristida contorta*' to the 'moderate diversity perennial pasture' ecosystem state in the Wet-dry tropical eucalypt woodlands (red soil) ecosystem type. 68

Tables

Table 1. Drivers of landscape change in the Kimberley, as described by experts at the state and transition modelling workshop. 10

Table 2. Pasture types and codes (Ryan et al. 2013) grouped by ecosystem types (Wet-dry tropical eucalypt woodlands and Rainfall-pulse driven arid and semi-arid grasslands) referred to in the AusEcoModels framework, and used as templates for the development of S&TMs for the Kimberley. 12

Table 3 Summary of Wet-dry tropical eucalypt woodland ('red soil') modified ecosystem states and associated ecosystem expressions 20

Table 4. Summary of Rainfall-pulse driven arid and semi-arid tussock grasslands ('black soil') modified ecosystem states and associated ecosystem expressions 21

Table 5. Correspondence between pasture types and their condition with ecosystem states for Wet-dry tropical eucalypt woodlands and Rainfall-pulse driven arid and semi-arid tussock grassland ecosystem types of the Kimberley region. See Attachment 1 for an explanation of the pasture type codes. 23

Table 6. Indicative values for perennial grass basal area, litter cover, species frequency, tree cover, species counts and green and bare fractions for each ecosystem state in the Wet-dry tropical eucalypt woodlands (red soil) ecosystem type under average to above average rainfall (> avg) and below average rainfall (< avg). Data were taken from a representative WARMS site for each ecosystem state (site numbers not shown due to privacy agreements), with two representative sites chosen for the 'moderate diversity perennial pasture' and 'annual grasses and forbs' states. Data were obtained from (1) Landscape function and soil surface assessments undertaken by on-ground monitoring; (2) WARMS survey data; (3) 30m vegetation fractional

cover time series data derived from Landsat {Beutel, 2019 #5506}{Joint Remote Sensing Research Program, 2021 #5507}. Note that WARMS site coordinates represent the centre of a 3 x 3 pixel array used to detect fractional cover, and these were checked to ensure they represented a homogenous landscape area. 40

Table 7. Indicative values for perennial grass basal area, litter cover, species frequency, tree cover, species counts and green and bare fractions for each ecosystem state in the Rainfall-pulse disturbed arid and semi-arid tussock grasslands (black soil) ecosystem type under average to above average rainfall (> avg) and below average rainfall (< avg). Data were taken from a representative WARMS site for each ecosystem state (site numbers not shown due to privacy agreements), with two representative sites chosen for the 'annual grasses and forbs' state. Data were obtained from (1) Landscape function and soil surface assessments undertaken by on-ground monitoring; (2) WARMS survey data; (3) Fractional cover data from remote sensing. 52

Table 8. Detailed transition descriptions for the Wet-dry tropical eucalypt woodland (red soil) state and transition model. Question marks occur where details are unknown. 56

Table 9. Detailed transition descriptions for the Rainfall-pulse driven arid and semi-arid tussock grasslands (black soil) state and transition model. Question marks occur where details are unknown. 62

Table 10. Summary of satellite products useful for the detection and classification of ecosystem states 64

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Executive summary

The Kimberley region in north-west Western Australia is covered by extensive savanna woodlands and tussock grasslands. Approximately half the region is under pastoral leases predominately used for beef production. The Western Australian (WA) government Department of Primary Industries and Regional Development (DPIRD) undertakes lease assessment and inspection to ensure the maintenance of pastoral land condition (maintenance of perennial grass cover that supports livestock grazing and soil condition). This presents several challenges around defining land condition and practices that support and improve long-term ecological sustainability of pastoral lands. The objective of this project was to develop state and transition models (S&TMs) for tussock grasslands and woodlands of the Kimberley as a tool to support DPIRD led monitoring and compliance programs in the Kimberley. The models were developed to meet three key outcomes:

1. A shared understanding (across a range of Departmental staff, scientists and land management experts) of grassland dynamics in the Kimberley, including when observed changes in tussock grasslands and woodlands are driven by natural disturbance cycles or management.
2. Informing management and regulation of grassland ecosystems, including the relationship between pasture types and where they should be grouped or separated for developing quantitative measures of pasture condition, what should be measured to identify a change in ecosystem state, what management actions might result in a transition to an ecosystem state with greater biomass of palatable pasture species, and over what time frame those changes might occur.
3. Options to link information in S&TMs to remote sensing information, including the description of a set of rules that could be used to interpret remotely sensed information for on-ground management.

Two S&TMs were developed for Wet-dry tropical eucalypt woodlands (red soil) ecosystems and Rainfall-pulse driven arid and semi-arid tussock grasslands (black soil) ecosystems, that occur across the west and east Kimberley. The models were developed in a two-day expert elicitation workshop using the Australian Ecosystem Models framework archetype models as templates. 19 states were described, including two reference states and 17 modified states, across both ecosystem types. Each state included information about within-state variability, driven by natural disturbance and recovery processes, captured through descriptions of ecosystem expressions. The S&TMs also described 58 transitions between modified states (38 for the red soil S&TM and 20 for the black soil S&TM). Transitions included information on drivers, pre-conditions and timeframe for transitions, and likelihood of transitions driven by management actions that aim to recover pasture condition. Expert-elicited information on the characteristics (structure, function and composition) of each ecosystem state (and its expressions) was combined with quantitative measurements of species frequency and cover taken from the Western Australian Rangeland Monitoring System (WARMS) dataset and satellite imagery. S&TM information was captured in conceptual diagrams, text, tables and spreadsheets.

Overall, the S&TMs have organised information about tussock grassland and woodland dynamics across the Kimberley that:

1. complement existing classification schemes for pasture type and condition
2. provide a basis for interpretation of landscape change that is due to transitions between ecosystem states that impact landscape values (e.g. cattle production, ecological integrity), *versus* change driven by endogenous disturbances (e.g. fire, drought, flood)
3. provide a structured way to assess pasture condition and a guide to management actions that might be implemented to reverse undesirable changes
4. articulate a method for organising and cataloguing ecosystem dynamics that is transferable to other regions of the WA rangelands.

Several knowledge gaps remain, and next steps should focus on developing quantified measures of ecosystem states (condition), mapping the spatial location of ecosystem states, and shaping the S&TMs into decision trees for informing practical land management, monitoring and evaluation.

1 Introduction

The Kimberley is a large region in north-west Western Australia, covering more than 400,000 km^2 with annual rainfall ranging from 350-1500mm. It is made up of 111 land systems and 39 pasture types (Payne and Schoknecht 2011). The region includes eight Indigenous Protected Areas, as well as national parks and development for industries such as tourism, mining, pearling, horticulture, oil, gas, agriculture and fishing (WA Department of Planning 2015). About half the Kimberley is covered by pastoral and other leases, primarily for beef production, these leases make up 92 stations covering a total area of 21.2 million ha (Office of the Auditor General Western Australia 2017).

The Pastoral Lands Board (PLB) and the WA Minister for Lands administer pastoral leases, supported by the Department of Planning, Lands and Heritage (DPLH) and Department of Primary Industries and Regional Development (DPIRD) (Office of the Auditor General Western Australia 2017). The sustainable management of these leases is regulated under two Acts. Under the *Land Administration Act* (1997) lessees must manage their land to its best pastoral potential and the PLB must ensure that pastoral leases are managed on an ecologically sustainable basis (Office of the Auditor General Western Australia 2017). Under the *Soil and Land Conservation Act* (1945) the Commissioner of Soil and Land Conservation (the Commissioner) is responsible for ensuring land managers prevent and mitigate land degradation. DPIRD provides the Commissioner and the PLB with lease level Rangeland Condition Assessments to ensure that land condition (an indicator of ecological sustainability and defined as the presence of 'perennial plant species attractive to livestock as fodder, and the condition of the soil') is maintained (Office of the Auditor General Western Australia 2017).

An audit of the WA pastoral industry in 2017 assessed whether there was a coordinated and effective approach to protect the ecological sustainability of pastoral lands and found that '*Pastoral lands have been under threat for over 75 years and during that time there has been limited progress to halt the decline in pastoral land condition*' (Office of the Auditor General Western Australia 2017). The key findings were:

- The state does not have good knowledge of lease level land condition.
- Lessees receive limited support to manage the land for long-term productivity.
- Policies and agency information management offer little to support a sustainable pastoral industry.

The Auditor Generals recommendations included the need to develop and implement a rigorous compliance program based on regular land condition monitoring that includes a combination of risk-based and systematic inspections. To address these recommendations, DPIRD in conjunction with the PLB, DPLH and industry representatives developed an Ecologically Sustainable Development framework, based on internationally accepted best practice risk management principles (Fletcher 2022). Under the framework pastoral land monitoring is focused on the most pastorally productive pasture types (key pastures), with pasture condition assessed using quantified measures of pasture condition and the risk of land degradation determined using

quantified measures of pasture condition and land management effectiveness. To assist in developing the quantified measures of condition and in understanding how management can drive land condition DPIRD collaborated with CSIRO to investigate the value of State and Transition Models (S&TMs) for defining ecological sustainability for pastoral lease areas of the Kimberley region, informing monitoring and evaluation of land condition, and synthesising knowledge of good practice land management. This report summarises the outcomes of the project "Developing state and transition models for tussock grasslands and woodlands of the Kimberley", which ran from October 2021 to December 2022.

1.1 Background

DPIRD monitor and assess pastoral rangeland condition over time to ensure sustainable management of the WA pastoral resource. Grassland monitoring occurs primarily in the Kimberley and Pilbara regions and is based on pasture types that can be broadly assigned to soil types, including 'black' soil pastures (such as Mitchell grass alluvial plain pastures), 'red' soil pastures (such as black speargrass pastures) and 'sandy' soil pastures (e.g. curly spinifex plain pastures) (Ryan et al. 2013). DPIRD's current monitoring programs focus on the presence of indicator grasses, soil surface condition and woody cover to describe pasture condition using a subjective scale of 1 to 5 (very good through to very poor). However, there is interest in moving from qualitative indicators of pasture condition to quantitative measures that can better capture variability in grassland composition, structure and function over time. A tool developed by the Australian Department of Climate Change, Energy, the Environment and Water (DCCEEW) and CSIRO: The Australian Ecosystem Models (AusEcoModels) Framework (Richards et al. 2020), has potential to provide a methodology for understanding and evaluating change in pasture condition in the Kimberley.

The AusEcoModels framework has systematically synthesised best-available scientific knowledge about ecosystems in Australia. This knowledge is captured in a set of dynamic conceptual models of ecosystems, which describe the characteristics and drivers of Australian ecosystems in reference states. The dynamic ecosystem models in the Framework provide a template for the development of S&TMs, which depict ecosystem states (and quantitative descriptions of their dynamic attributes related to structure, function, composition etc.) linked by drivers of change in state. These models provide a mechanism for distinguishing variability within an ecosystem state due to natural disturbance and recovery processes, and changes in ecosystem attributes that indicate a transition to another state. Ecosystem states can be described both in terms of condition for biodiversity ('ecological integrity') and capacity to supply ecosystem services such as cattle production (pasture condition), carbon storage, and tourism opportunities. S&TMs capture existing information and re-shape this into a form that can be used for monitoring and evaluation of different management activities or scenario testing.

1.2 Project aims and outcomes

The aim of this project was to combine the methodology developed in the AusEcoModels framework with expertise and extensive monitoring information, such as that captured in the WARMS (Western Australian Rangeland Monitoring System) (Watson et al. 2007) and Rangelands

Condition Assessment (RCA) data, into quantitative, dynamic S&TMs for tussock grasslands and woodlands of the Kimberley.

The S&TMs were developed to include:

- Common understanding of the characteristics and ecology of tussock grassland and woodland ecosystems in the Kimberley, in terms of pastoral land uses.
- Classification of ecosystem states according to pasture condition (along with identification of aspects of composition, structure, function, landscape, physical/chemical processes with a view to condition assessment).
- Identification and quantification of the drivers of transitions between ecosystem states (including threatening processes, management options and timelines).

1.2.1 Outcomes

Meeting the project aims led to three key outcomes for this project:

1. A shared understanding (across a range of Departmental staff, scientists, and land management experts) of grassland and woodland dynamics in the Kimberley, including whether observed changes in tussock grasslands and woodlands are driven by natural disturbance cycles or management actions.
2. Development of a S&TM tool for informing management and regulation of grassland and woodland ecosystems, including what data is needed and what should be measured to identify a change in ecosystem state, and what management actions might result in a transition to an ecosystem state with improved pasture condition (Ryan et al. 2013).
3. Options to link information in S&TMs to spatial information, including the description of a set of rules that could be used to interpret remotely sensed information for on-ground management.

Ultimately, the achievement of these outcomes will contribute to tussock grasslands and woodlands of the Kimberley being managed in a way that ensures long-term ecological sustainability and resilience of the region's industries, communities, and environmental values.

1.3 Location and pasture types

The landform, soils and vegetation of the Kimberley region are described by 111 land systems that have been defined and mapped over several survey periods from 1949 onwards (summarised in Payne and Schoknecht (2011)). Each land system is divided into land units which are classified according to landform, vegetation, and soils. Most land units are not mapped, but the proportion of each land unit in a land system is defined. Thirty-nine pasture types have been identified and described across the Kimberley, with the proportion of each pasture type found in each land unit in each land system also described in Payne and Schoknecht (2011). Maps of land systems and, more recently, pasture types across the Kimberley are used to monitor rangeland condition.

The pasture types of the Kimberley, and a description of their condition categories are found in Ryan et al. (2013). Pastures are categorised as being in very good, good, fair, poor, or very poor condition, depending on the abundance of desirable grass species (palatable, profitable and perennial) and presence of intermediate and undesirable species (Ryan et al. 2013). Pasture condition scores are combined with information on soil erosion extent to produce a rangeland condition score (Payne et al. 1979). The key pasture species of the West Kimberley and associated draft standards are described in (Fletcher et al. 2022).

This project focused on areas of tussock grasslands and woodlands on pastoral leases in the east and west Kimberley (Figure 1, black outline) for the development of S&TMs, and included the pasture types:

- Blue grass alluvial plain pastures
- Black speargrass pastures
- Buffel grass pastures
- Frontage grass pastures
- Mitchell grass alluvial plain pastures
- Mitchell grass upland pastures (not shown in Figure 1)
- Plume sorghum pastures
- Ribbon grass alluvial plain pastures
- Ribbon grass pastures
- Arid short grass pastures
- Tippera tall grass plain pastures
- White grass bundle-bundle pastures
- Annual sorghum hill pastures (not shown in Figure 1)
- Threeawn plain pastures (not shown in Figure 1).

Note that other pasture types mapped for the Kimberley (Figure 1), including spinifex pastures, pindan and saltmarsh areas (such as marine couch and samphire pastures) were not included in the S&TMs except in the case of one state dominated by spinifex that is derived from tussock grassland. While the focus of the description of ecosystem states was mainly confined to areas grazed for cattle production, information from other land uses (especially conservation areas) was included where applicable. States were not described for highly transformed landscapes such as cleared farmland and around towns and mine sites.

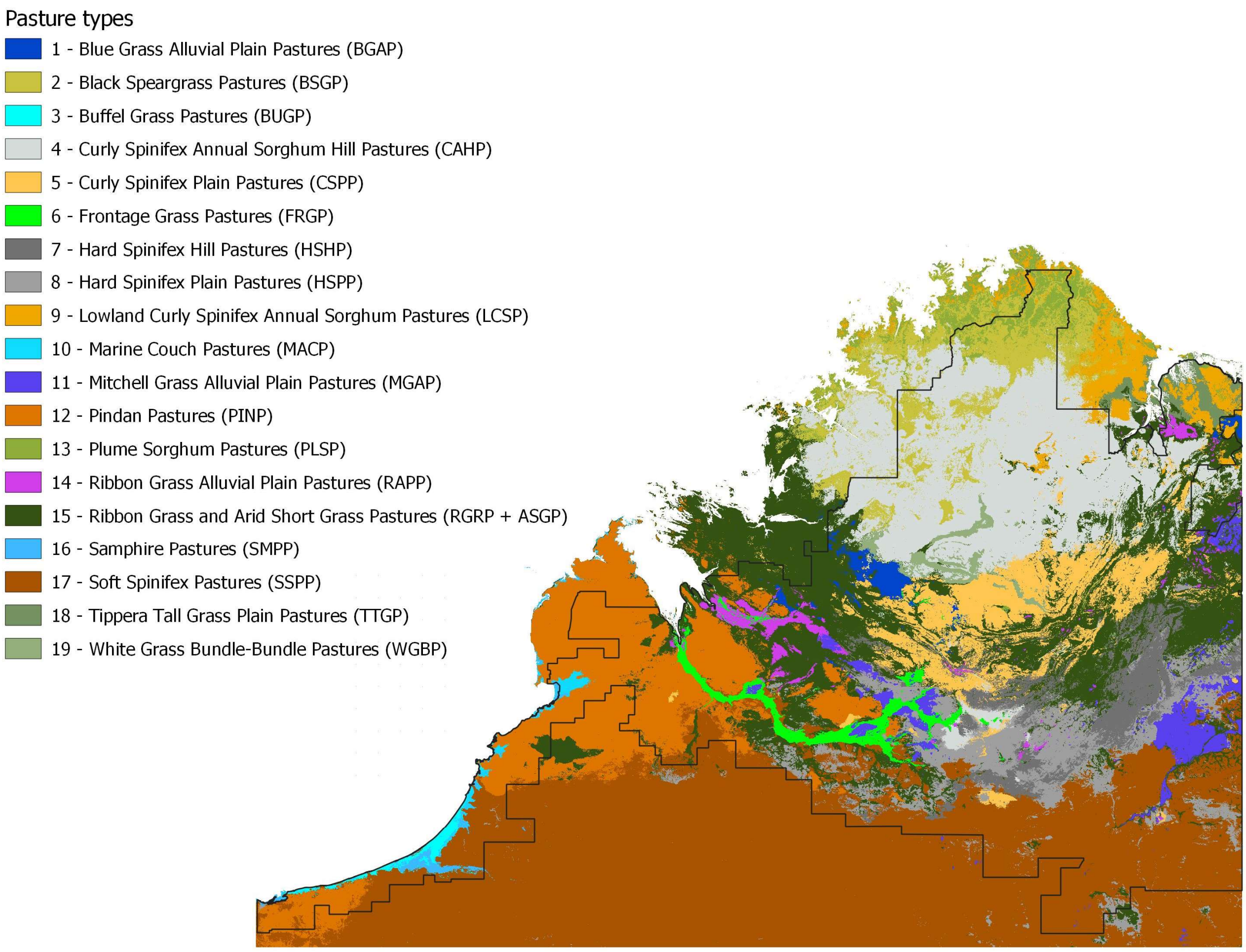


Figure 1. A map of pasture types of the Kimberley, Western Australia, with the black outline showing the general area of pastoral leases. This area was the focus for the development of S&TMs with exceptions noted in the text..

2 The Australian Ecosystem Models Framework and State and Transition Models

Ecosystems are complex and dynamic across space and time because of climate, soil, and disturbance and recovery processes, such as fires, floods and cyclones. These landscape-scale processes influence and modulate finer-scale interactions between species, populations and their environment resulting in dynamic fluxes and feedbacks. At evolutionary time scales, these dynamics result in characteristic ecosystems and the species that inhabit them. More recent disturbance dynamics can maintain, mimic, complement or conflict with the regimes to which ecosystems are adapted, impacting on their condition, integrity, resilience and capacity to provide ecosystem services.

The AusEcoModels Framework project (Richards et al. 2020) describes a nationally comprehensive set of conceptual models (termed 'archetype' models) of ecosystem dynamics in Australia, by synthesising ecological science and land management expertise into decision-ready, system-level knowledge. They articulate an understanding of the dynamic expression of ecosystems under a set of endogenous or reference disturbance regimes. Endogenous disturbances are discrete events (in both space and time) that disrupt ecosystem structure, change resources, substrate availability or the physical environment but maintain ecosystem integrity (White and Pickett 1985, Hobbs and Huenneke 1992, Rogers 1996). They include both anthropogenic and non-anthropogenic-driven disturbances.

The archetype model diagrams document 'ecosystem expressions' that are distinct, recognisable, but transient phases of an ecosystem and describe variability in ecosystem attributes (structure, function, composition) along a disturbance and biomass recovery pathway (Figure 2). For example, an ecosystem expression might describe the attributes of an archetype woodland ecosystem immediately post-fire, while another expression in the same model might describe the attributes of the same ecosystem 10 years after fire. These expressions would have very different quantities for attributes such as ground cover and canopy cover, and capture variability observed in the archetype model.

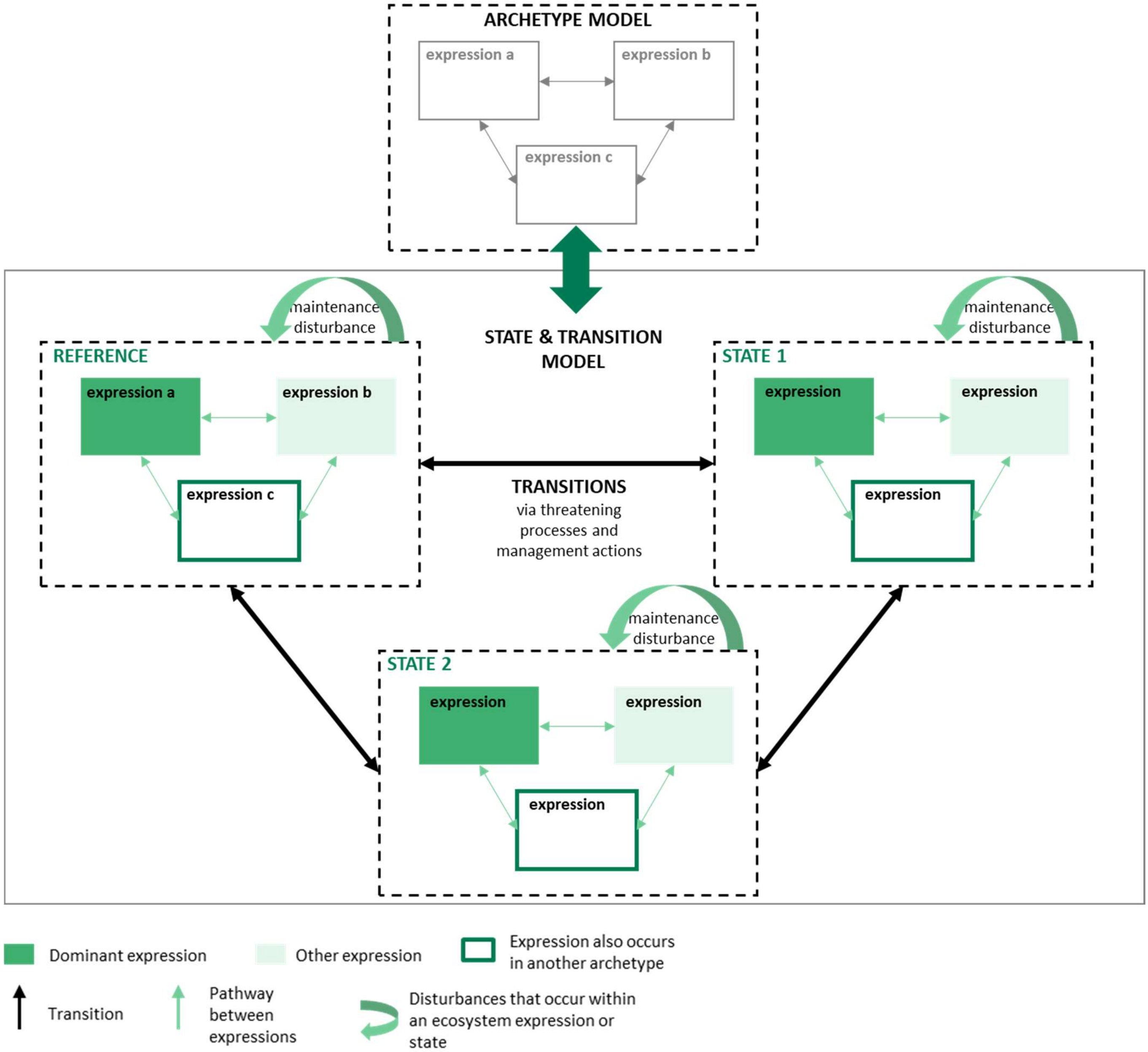


Figure 2. Stylised depiction of the relationship between archetype models and dynamic S&TMs.

Some ecosystem expressions in one archetype model will link to expressions that are also described in another archetype model. These are denoted by clear boxes with thick green borders and often reflect ecotonal or longer-term (century-scale) dynamics. Arrows in the archetype models describe pathways between ecosystem expressions, driven by endogenous disturbances or biomass recovery processes. Endogenous disturbances can also maintain an ecosystem in a particular expression ('maintenance disturbance'), such as a fire regime of one low intensity fire every 5 years. Maintenance disturbances are represented by curved arrows attached to a single box.

Archetype models may also include a description of the landscape composition of ecosystem expressions (the proportion of a landscape, across space and time, that would be in a particular expression under reference conditions). Here, reference condition, defined as 'the condition against which past, present and future ecosystem condition is compared in order to measure relative change over time' (UNCEEA 2021), represents the condition of an ecosystem with the

highest level of ecological integrity. Ecological integrity is defined as ‘the ecosystem’s capacity to maintain its characteristic composition, structure, functioning and self-organisation over time within a natural range of variability’ (Pimentel and Edwards 2000, UNCEEA 2021). Archetype models in the AusEcoModels framework are templates for the description of dynamic ecosystem reference conditions in Australia.

Sets of archetype models have been grouped into 14 umbrella classes to assist in dissemination, and to demonstrate links to published vegetation classification schemes. Umbrella classes represent a consolidation of the National Vegetation Information System (NVIS) Major Vegetation Groups (NVIS Technical Working Group 2017).

Archetype models in the AusEcoModels Framework describe ecosystem reference dynamics at landscape scales that are representative of processes occurring in many different but related ecosystems. They describe a common set of dynamics (endogenous disturbances and ecosystem responses) for a group of ecosystems that may otherwise differ in terms of, for example, their species composition or soil characteristics. Due to the generality of archetype models, they contain descriptive rather than quantitative information, which can be used as a template to understand and predict how ecosystems respond to more recent, transformative disturbance processes.

The AusEcoModels Framework includes a methodology for the application of archetype models to the development of dynamic S&TMs. S&TMs are conceptual tools that describe the state of a particular ecosystem (which may vary, for example, from reference to degraded, in terms of ecological integrity), and the drivers or agents that cause transitions between states (Westoby et al. 1989, Stringham et al. 2003, Bestelmeyer et al. 2017). In S&TMs the reference state description is informed by the relevant archetype model, and a set of alternative ‘modified ecosystem states’ result from the introduction of recent and transformative anthropogenically-driven exogenous disturbances (Rogers 1996) or modification of existing endogenous disturbances. Whether reference or modified, each ecosystem state in the S&TM is described by a relatively stable set of ecosystem expressions linked by pathways of disturbance and recovery. Transitions in S&TMs are difficult to reverse without application of intensive management, an extreme event or long timeframes (Bestelmeyer et al. 2009, Bestelmeyer et al. 2017) and are distinguished from pathways between different ecosystem expressions within states, which often result from slow-acting but incremental successional processes (Rumpff et al. 2011). S&TMs provide a mechanism for working through the profound complexity of contemporary drivers interacting with evolutionary ecological legacies to provide a holistic perspective on the state of Australia’s ecosystems in the contemporary world.

An advantage of S&TMs is that they can describe system understanding in a non-linear fashion (Bestelmeyer et al. 2017) and articulate the proportionally different impacts of drivers according to a range of potential states that an ecosystem may manifest. This supports greater discrimination in ecosystem management decisions, as well as monitoring and evaluation of ecological condition. In this context ecological condition can be defined as ‘a measure of ecological integrity, including the capacity of ecosystem states to maintain biodiversity and ecosystem flows and connections’, and can be measured as ‘the departure of each ecosystem state from the reference state’ in a S&TM (Harwood et al. 2021). With this framing, each state in the S&TM could be described as an ‘ecological condition state’. However, the flexibility of S&TMs enables states

within the models to be characterised by other measures of condition which may align better with management objectives. Keith et al. (2020) describe four different ways to conceptualise ecosystem condition (Figure 3), including concepts related to anthropocentric values framing, such as pasture or rangeland condition. Later in this report we align the S&TMs developed for tussock grasslands and woodlands of the Kimberley with measures of pasture condition (a description of the current vegetation condition compared to the optimal condition that could be expected, for a particular pasture type, in terms of grazing value (Ryan et al. 2013)) used by DPIRD in the management and reporting of rangeland condition in the Kimberley.

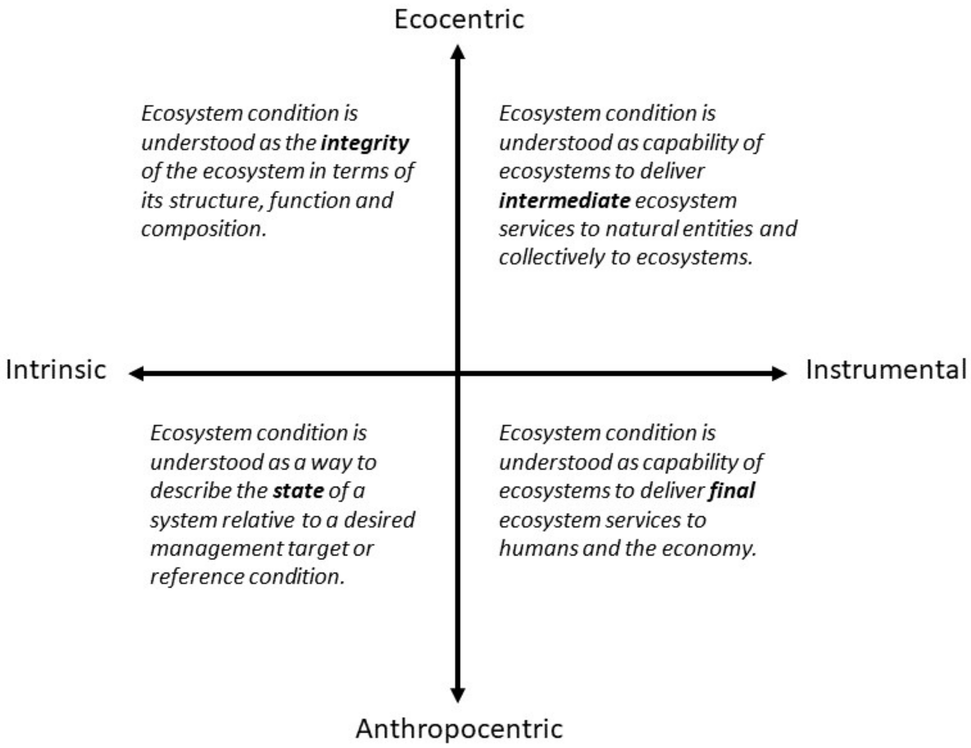


Figure 3. A values framework for defining ecosystem condition, reproduced from Keith et al. (2020).

3 State and transition modelling workshop

To develop S&TMs for tussock grasslands and woodlands of the Kimberley an expert workshop was held in Perth on the 18-19th of May 2022. Sixteen experts from across northern Australia attended the workshop, including experienced pastoralists, current and former state government and CSIRO staff, consultants, and representatives from Kimberley-based Aboriginal corporations. The objective of the workshop was to

1. identify common ecosystem states associated with red-soil (Wet-dry tropical eucalypt woodlands) and black-soil (Rainfall-pulse driven arid and semi-arid tussock grasslands) pasture types in the Kimberley region
2. determine drivers of transitions between ecosystem states (e.g. fire, grazing)
3. quantify characteristics (e.g. dominant species, ground cover etc.) and variability associated with each state.

The agenda for the workshop is reproduced in Appendix A . Prior to the workshop experts were provided with a description of pasture types of the Kimberley (see Attachment 1) and a link to a video explaining the WARMS protocols (Watson et al. 2007; Craig et al. 2008).

The workshop included presentations on the AusEcoModels framework, S&TM development and a description of reference state models developed from two archetypes: 'Wet-dry tropical eucalypt woodlands' (red soil pasture types) and 'Rainfall pulse-driven arid and semi-arid tussock grasslands' (black soil pasture types) (See Section 4.1 for further details). Experts provided feedback on the reference state models before describing common drivers of change in the Kimberley (Table 1 and Figure 4) and developing a list of modified ecosystem states grouped under each reference model. Short videos of different locations in the Kimberley, as well as photographs, were used as provocations for eliciting ecosystem state descriptions from experts. Once a list of modified ecosystem states was finalised, experts worked in small groups to describe each state, including its different ecosystem expressions and attributes (structure, function and composition) (see Attachment 2 and 3). The final exercise for the workshop involved describing likely transitions between ecosystem states, including drivers, timeframes, pre-conditions, and probabilities. Nineteen states (two reference and seventeen modified states) and 58 transitions were described for two S&TMs at the workshop.

Table 1. Drivers of landscape change in the Kimberley, as described by experts at the state and transition modelling workshop.

Environmental drivers	*Socio-economic drivers*
Grazing – Goats, cattle, donkeys, pigs, native grazers, historical sheep grazing	Clearing
Fire – altered regimes, fuel management	Stock management - Supplements and breeds, spelling, water points and fencing, management out of sync with climate
Climate change – altered seasonality, flooding	Livestock market price/access, cashflow/ banking

Erosion	Regulatory programs and land tenure
Exotic plants – Buffel, Sabi grass	Philosophy of land management
Tree dynamics	Policy around land management
Predators and predator control	Indigenous aspirations for land management
	Carbon sequestration programs
	Infrastructure (especially impacts on water flow)
	Knowledge transfer

Figure 4. Images from the state and transition modelling workshop held in Perth on the 18th-19th May 2022.

Following the workshop, feedback on ecosystem states and transition descriptions was sought from two additional experts who couldn't make the workshop, via a short face to face and an online meeting. Information from the workshop and subsequent conversations were compiled into a set of ecosystem state diagrams, accompanying spreadsheets and descriptions.

The DPIRD team used the compiled information on ecosystem states and expressions to identify WARMS sites monitored in specific years, that matched the descriptions (including shifts in expressions driven by drought events). Quantitative information on species composition and cover, as well as photographs, were gathered from the identified WARMS data and used to expand the ecosystem state descriptions.

The quantitative information describing ecosystem state attributes, model descriptions and diagrams were presented to experts who attended the May workshop (as well as other experts who couldn't attend the workshop but requested to be kept informed) in an online presentation on the 5th September 2022. Following the presentation, a final round of written feedback was requested from experts.

4 Ecosystem states

4.1 Archetype models and reference states

The areas referred to as tussock grasslands and woodlands of the Kimberley include savanna woodlands and true grasslands with low to no woody cover. In the AusEcoModels framework, two archetype models: 'Wet-dry tropical eucalypt woodlands' (Prober et al. forthcoming) and 'Rainfall-pulse driven arid and semi-arid tussock grasslands' (Cook et al. forthcoming) describe the disturbance and recovery dynamics of these areas under reference (pre-European) conditions (reproduced in Appendix B and C). The archetype models were used as templates for the description of reference states which include details, such as species and disturbance regimes, specific to the Kimberley region.

Additional published information on pastures of the Kimberley (or northern Australia more broadly) were used to refine the two reference state descriptions, including information contained in Durack (1945), Foran and Bastin (1984), Ford (1992), Speck et al. (1960), Speck et al. (1964), Stewart et al. (1970), Payne and Schoknecht (2011), Hall (2020), Mc Arthur et al. (1994) and Stockwell et al. (1994).

A cross-walk between pasture types and the two archetypes (referred to subsequently as 'ecosystem types') is shown in Table 2. The two ecosystem types: 'Wet-dry tropical eucalypt woodlands' and 'Rainfall-pulse driven arid and semi-arid tussock grasslands' include pasture types on predominantly sands and loams (colloquially referred to as 'red soil' pastures), and cracking clays (colloquially referred to as 'black soil' pastures). Figure 5 shows the location of the red soil and black soil pasture types across the Kimberley.

Table 2. Pasture types and codes (Ryan et al. 2013) grouped by ecosystem types (Wet-dry tropical eucalypt woodlands and Rainfall-pulse driven arid and semi-arid grasslands) referred to in the AusEcoModels framework, and used as templates for the development of S&TMs for the Kimberley.

Wet-dry tropical eucalypt woodlands (Red soil pasture types)	Rainfall-pulse driven arid and semi-arid grasslands (Black soil pasture types)
Black speargrass pastures (BSGP)	Blue grass alluvial plain pastures (BGAP)
Buffel grass pastures (BUGP)	Mitchell grass alluvial plain pastures (MGAP)
Frontage grass pastures (FRGP)	Ribbon grass alluvial plain pastures (RGAP)
Plume sorghum pastures (PLSP)	Mitchell grass upland pastures (MGUP)
Ribbon grass pastures (RGRP)	
Arid short grass pastures (ASGP)	
Tippera tall grass plain pastures (TTGP)	
White grass bundle-bundle pastures (WGBP)	
Annual sorghum hill pastures (ASHP)	

Threeawn plain pastures (TAPP)

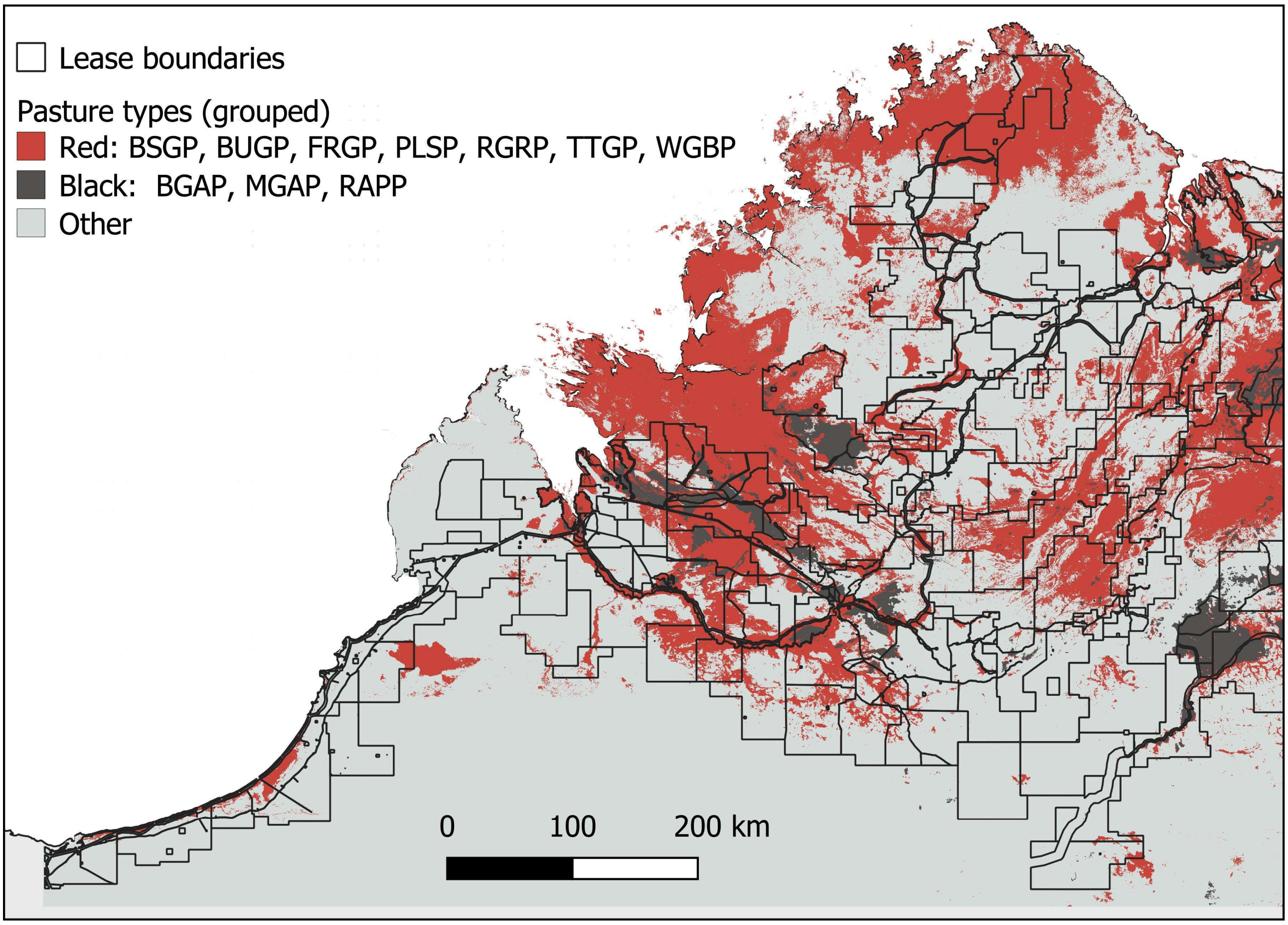


Figure 5. Map of 'Red soil' pasture types: Black speargrass pastures (BSGP), Buffel grass pastures (BUGP), Frontage grass pastures (FRGP), Plume sorghum pastures (PLSP), Ribbon grass pastures (RGRP), Tippera tall grass plain pastures (TTGP), White grass bundle-bundle pastures (WGBP); and 'Black soil' pasture types: Blue grass alluvial plain pastures (BGAP), Mitchell grass alluvial plain pastures (MGAP), Ribbon grass alluvial plain pastures (RAPP) across the Kimberley. Note, not all pastures shown in Table 2 are reproduced in the map as areas of these pasture types were too small to map or were combined with similar pasture types (e.g. arid short grass pastures were included in the mapped area of RGRP and Mitchell grass upland pastures were included in the mapped area of MGAP).

4.1.1 Wet-dry tropical eucalypt woodlands (red soil) reference state

A dynamic reference state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' was developed from an archetype model template described by Prober et al. (forthcoming) to include details, such as disturbance regimes, specific to the Kimberley (Figure 6). Each expression in the reference state is described in more detail in the following sections. For general references on this ecosystem type see Prober et al. (forthcoming) (Appendix B).

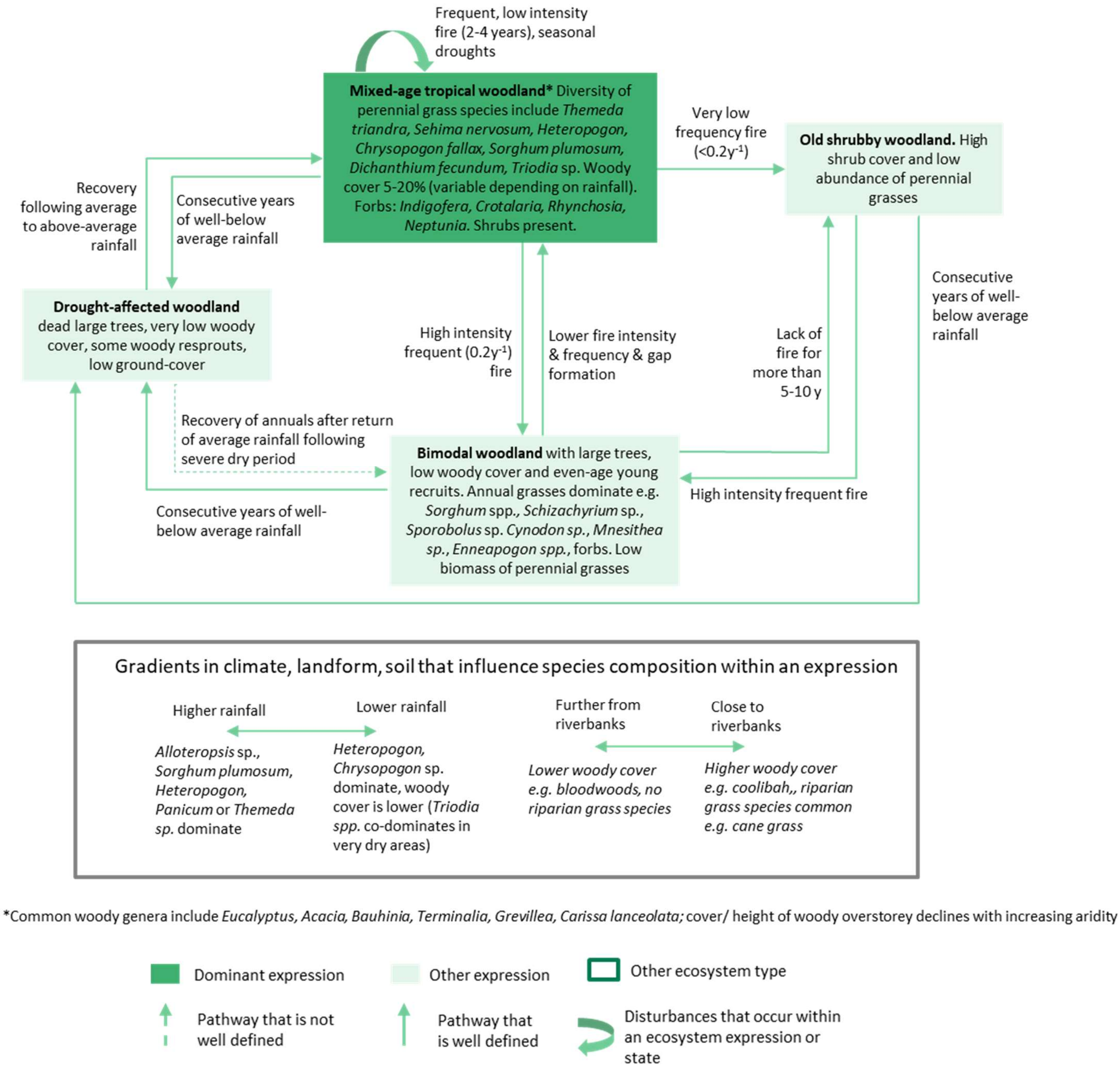


Figure 6. Conceptual model of a dynamic reference state for Wet-dry tropical eucalypt woodlands (red soils) of the Kimberley.

Expression: Mixed-age tropical woodland

In the reference state, the dominant expression of Wet-dry tropical eucalypt woodlands found on red and sandy soils (Figure 7) can range in structure from low-density, low open canopy eucalypt woodland/grassland on plains and hillslopes, to low/moderate density open eucalypt woodland, which usually occur within riparian influenced zones. In the Kimberley, this involves a shift in the dominant tree genera from mixed *Eucalyptus* and *Corymbia* species, *Bauhinia*, *Terminalia* and *Grevillea* on plains and hillslopes, to a dominance by coolibah (*Eucalyptus microtheca*) and other species along riverbanks and levees.

Figure 7. Mixed-age tropical woodland in near reference state (similar for low rainfall or high rainfall areas).

Typically, within lower rainfall areas the understorey of these woodlands is dominated by perennial grasses such as ribbon grass (*Chrysopogon fallax*) and/or speargrass (*Heteropogon contortus*) and/or white grass (*Sehima nervosum*), with spinifex (*Triodia* spp.) co-dominance in some very dry areas. The understory in higher rainfall areas is usually dominated by stands of kangaroo grass (*Themeda triandra*) with other species being co-dominant on occasion (e.g. *Alloteropsis* spp., *Sorghum plumosum* or *Panicum* spp.). Overall cover of perennial grasses may be as high as 80-100% (with tussock basal area, as measured at the soil surface, of 3-5%), annual grass cover <10%, forbs <5%, and minimal bare ground.

Expression: Drought-affected woodland

Consecutive years of well below average rainfall can result in mortality of shrubs and mature eucalypts and reduced overall woody cover. Perennials will likely remain dominant in the understorey with any mortality of tussocks resulting in a loss of grass basal area. Overall understory perennial grass species frequency (the number of times a plant species is present within a given number of sample quadrats of uniform size placed repeatedly across a stand of vegetation (Daubenmire 1968, Mueller-Dombois and Ellenberg 1974) will be maintained. Cover and biomass will be greatly reduced (e.g. <10% ground cover of perennial and annual grasses) with bare ground or plant litter visible between tussocks. Return of average to above average wet season rainfall drives recovery back to the 'mixed-age tropical woodland' expression, or to the annual grass dominant 'bimodal woodland' if dry conditions were particularly intense or extended. Recovery is often led by initial high ground cover of annual and perennial forbs.

Expression: Bimodal woodland

High intensity fires can result in mortality of shrubs and mature eucalypts (reducing woody cover), while leaving some larger trees unaffected. Recruitment in the subsequent wet season, or seasons, following fire results in a midstory of evenly aged tree and shrub seedlings and/or re-sprouts with an upper storey comprised of older trees. Perennial tussocks are present but have

reduced cover and biomass due to fire, with annual grasses and forbs dominating in post fire periods, filling gaps where perennials have contracted. A reduction in the frequency and intensity of fire enables recovery of woody cover and a return to the 'mixed-age tropical woodland' expression.

Expression: Old shrubby woodland

While the upper storey tree canopy is maintained under a low fire frequency (e.g. 1 year in 10), mortality of seedlings and shrubs is reduced, leading to high shrub cover. The higher cover of shrubs introduces competition for space and light which may reduce the abundance and or growth of perennial tussock grasses. Alternatively, very low frequency fire regimes may lead to prolonged build-up of perennial biomass and litter which in turn will have a similar effect. Annual grasses and forbs are usually absent or in very low abundance in this expression. Once the 'old shrubby woodland' expression is established, high intensity fires are required to shift this expression to the 'mixed-age tropical woodland' via the 'bimodal woodland' expression.

Long periods of fire exclusion (from decades to centuries), in areas with sufficient moisture (such as ravines and steep valleys), may result in shifts to monsoon forest or vine thicket from the 'old shrubby woodland' expression. However, monsoon forest/ vine thicket patches are extremely rare or absent in the east and west Kimberley, and this shift was not included as an expression in the reference state.

4.1.2 Rainfall-pulse driven arid and semi-arid tussock grasslands (black soils) reference state

A dynamic reference state for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' was developed from an archetype model template described by Cook et al. (forthcoming) to include details, such as disturbance regimes, specific to the Kimberley (Figure 8). Each expression in the reference state is described in more detail in the following sections. For general references on this ecosystem type see Cook et al. (forthcoming) (Appendix C).

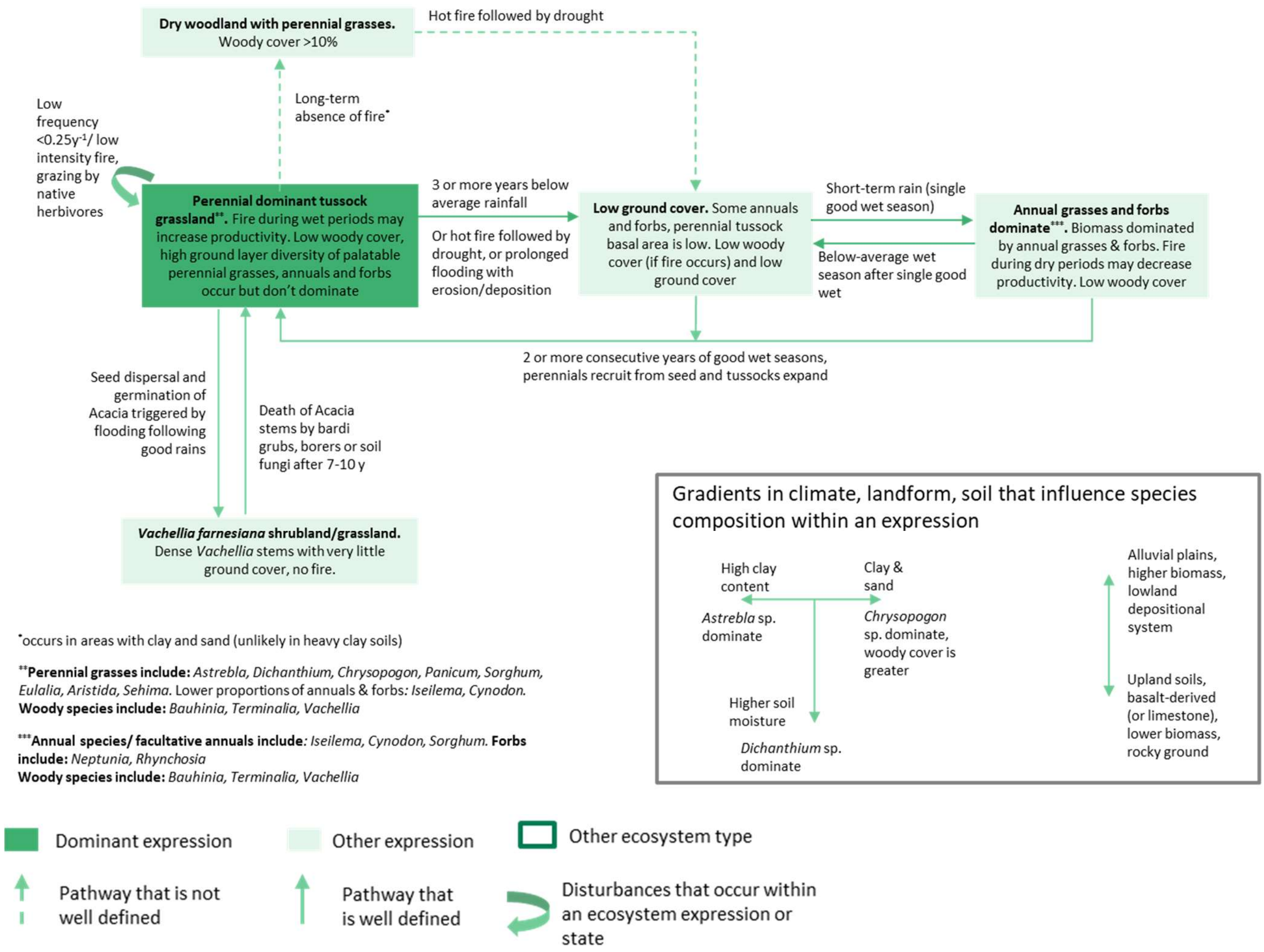


Figure 8. Conceptual model of a dynamic reference state for Rainfall-pulse driven arid and semi-arid tussock grasslands (black soils) of the Kimberley.

Expression: Perennial dominant tussock grassland

In the reference state the dominant expression of Rainfall-pulse driven arid and semi-arid tussock grasslands, found on black, grey or brown heavy, cracking clay soils is the 'perennial dominant tussock grassland'. This expression often has a sparse overstorey of small trees/shrubs of scattered clay and/or cracking clay soil adapted genera present (e.g. *Bauhinia*, *Terminalia, Vachellia*) in a woodland/grassland on open plains and frontages (Figure 9). Within the moderate to low rainfall zones of the black soil grasslands this expression is typically dominated by perennial grasses such as Mitchell grass (*Astrebla* spp.) and/or ribbon grass (*Chrysopogon fallax*) and/or white grass (*Sehima nervosum*), with stands of silky brown top and/or blue grasses (*Eulalia aurea* and *Dichanthium* spp.) becoming dominant under higher rainfall zones or water run-on areas. The ground layer exhibits high perennial tussock grass cover, biomass and basal area. For example, basal cover of Mitchell grass (which dominates the biomass of these grasslands in reference state) may be as high as 10%. The 'perennial dominant tussock grassland' expression also has a high diversity of plant species including other perennial grasses, annual grasses, and forbs.

Figure 9. Rainfall-pulse driven arid and semi-arid tussock grassland in near reference state.

Expression: Low ground cover

Consecutive years of well below average rainfall (drought), hot fire, or prolonged submersion (flooding) can result in a decrease in ground layer biomass, cover, and decreased tussock basal area due to grass mortality as well as reductions in woody cover compared to the reference state. In the ‘low ground cover’ expression, the understorey perennial grasses remain dominant with some tussock death occurring. Some bare or litter patches will be visible between tussocks. Overall understory species frequency will be maintained.

Expression: Annual grasses and forbs dominate

This expression succeeds the ‘low ground cover’ expression following flooding or short-term above average rainfall. Annual grasses and forbs will colonise interstitial spaces (bare or litter), given seed availability, with the initial annual flush of growth becoming dominant or co-dominant (in terms of biomass). Typically, *Iseilema* sp., *Cynodon* sp. or *Sorghum* sp. are the dominant or co-dominant annual species with a mix of native legumes and other forbs also present. Woody cover is sparse in this expression following mortality during the ‘low ground cover’ expression. This expression is usually short lived depending largely on seasonal soil moisture.

Expression: Dry woodland with perennial grasses

The ground layer within this expression is similar in composition to the dominant expression, i.e. perennial grass dominant with high tussock grass ground cover and biomass. The long-term absence of fire required for this expression leads to reduced mortality and improved growth of woody species. Woody canopy cover increases to >10% with clay and/or cracking clay soil adapted genera (e.g. *Bauhinia*, *Terminalia, Vachellia*) present as dominant, co-dominant or mixed stands. This expression is more likely in the sandy clay soils and less so in heavy clays. The dry woodland will return to other less woody expressions following removal of small trees and shrubby layers by high intensity fire. The extent of this expression in the reference state is unclear.

Expression: *Vachellia farnesiana* shrubland/grassland

This expression succeeds the perennial dominant tussock grassland following flooding associated with above average wet years, which disperses *V. farnesiana* seeds and stimulates germination (Figure 10). Fire may also stimulate germination in this species. Once *V. farnesiana* stands are established they can persist for eight or more years forming dense stands with little understorey that are fire resistant (due to low fuel biomass). This expression shifts back to the 'perennial dominant tussock grassland' after death of *V. farnesiana* stems from borers (or Bardi grubs in more arid areas) and soil fungi.

Figure 10. Example of the '*Vachellia farnesiana* shrubland/grassland' expression in the Rainfall-pulse driven arid and semi-arid tussock grassland (black soils) reference state with the photo taken during the dry season.

4.2 Summary of modified states and transitions

Table 3 and Table 4 describe the modified ecosystem states and their component expressions for the Wet-dry tropical eucalypt woodlands ecosystem type and the Rainfall-pulse driven arid and semi-arid tussock grasslands ecosystem type, respectively. Detailed model diagrams and descriptions are included in section 4.3 and 4.4.

Table 3 Summary of Wet-dry tropical eucalypt woodland ('red soil') modified ecosystem states and associated ecosystem expressions

*Expressions were not described for this state in the workshop

Ecosystem state	Ecosystem expression
Diverse perennial pasture close to reference	High cover
	Low cover
	Moribund (high or low cover)
Moderate diversity perennial pasture	High cover
	Low cover
	Altered perennial composition
	Altered annual composition
Native woody thickened	Live trees with bare ground/ forbs
	Dead trees with bare ground/ forbs
Annual sorghum dominant	Annual sorghum dominant cover
	Bare ground
Aristida contorta	*Aristida contorta* dominant cover
	Aristida contorta with short-lived perennials, annuals & spear grass
	Aristida contorta with bare ground & annuals
Annual grasses and forbs	High cover
	Low cover
	Forb dominant cover
	Scattered perennial cover
	Bare ground
Bare soil	Bare ground
	Ephemeral cover
Indian couch	Indian couch high cover
	Low cover
	Mixed species high cover

Ecosystem state	Ecosystem expression
Buffel grass	Buffel grass high cover
	Mixed species high cover
	Low cover
	Bare ground
Spinifex dominant*	

Table 4. Summary of Rainfall-pulse driven arid and semi-arid tussock grasslands ('black soil') modified ecosystem states and associated ecosystem expressions

Ecosystem state	Ecosystem expression
Palatable perennials dominant	High cover
	Low cover
	Annual grasses and forbs dominant
	High woody cover
Mixed unpalatable perennials dominant	High cover
	Low cover
	Annual grasses and forbs dominant
Aristida latifolia dominant	High cover
	Low cover
Native woody thickened	Live tree stands
	Dead tree stands
Annual grasses and forbs	Annual grasses and forbs with sparse relic perennials
	Annuals and forbs only
	Aristida latifolia and annuals
Seasonally bare ground	Bare ground
	Ephemeral cover
Indian couch	Indian couch high cover
	Low cover
	Mixed species high cover

Figure 11 and Figure 12 give a summary of the likely transitions between modified ecosystem states for the Wet-dry tropical eucalypt woodlands ecosystem type and the Rainfall-pulse driven arid and semi-arid tussock grasslands ecosystem type, respectively. More detailed descriptions of these transitions are included in section 5. A table showing the correspondence between each modified ecosystem state and pasture condition for the main pasture types that occur in each ecosystem type is shown in Table 5.

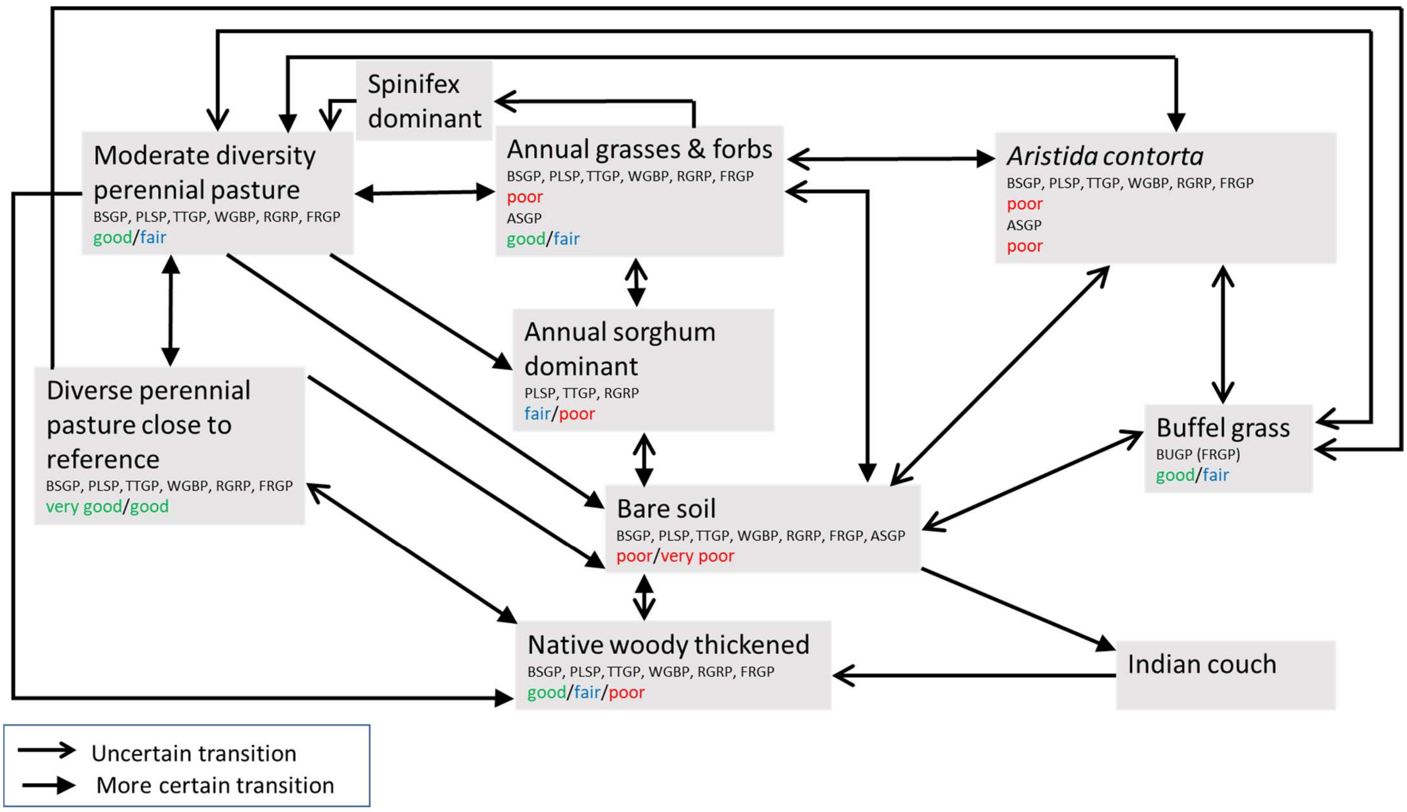


Figure 11. Summary of transitions between modified ecosystem states for the Wet-dry tropical eucalypt woodlands ('red soil') ecosystem type. Correspondence between ecosystem states and pasture type and condition (shown in colour) is included (see Table 5).

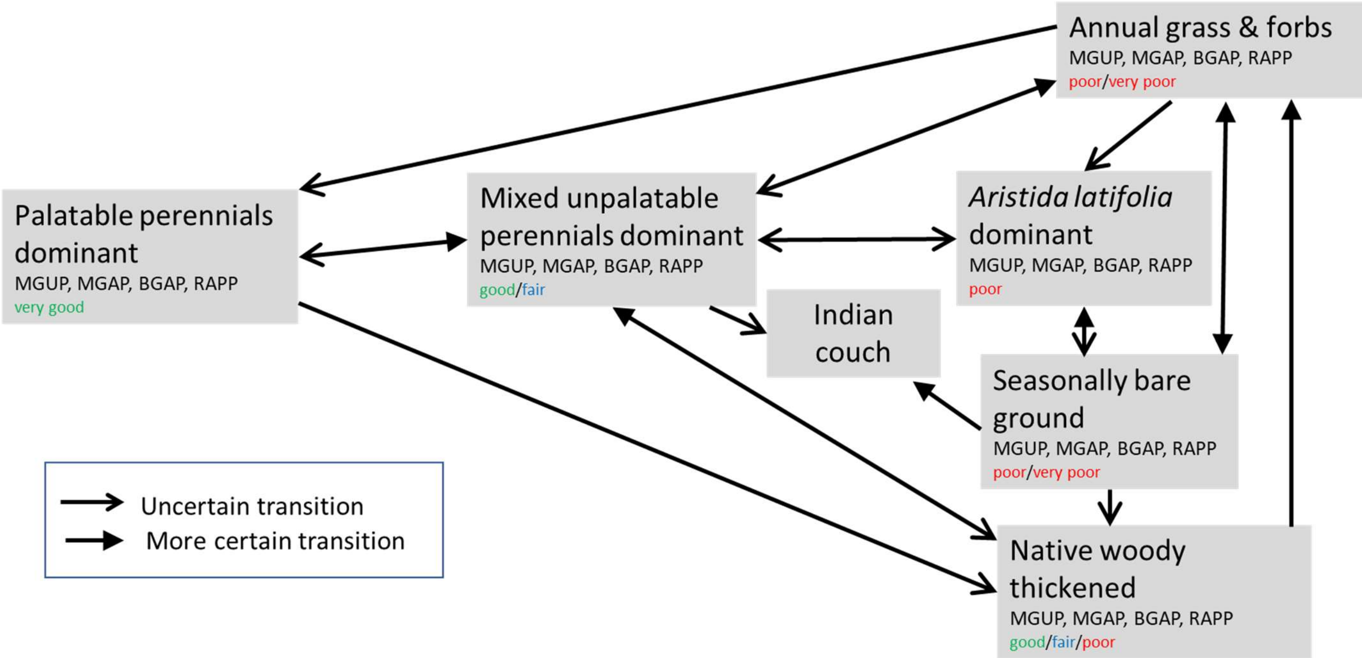


Figure 12. Summary of transitions between modified ecosystem states for the Rainfall-pulse driven arid and semi-arid tussock grasslands ('black soil') ecosystem type. Correspondence between ecosystem states and pasture type and condition (shown in colour) is included (see Table 5).

Table 5. Correspondence between pasture types and their condition with ecosystem states for Wet-dry tropical eucalypt woodlands and Rainfall-pulse driven arid and semi-arid tussock grassland ecosystem types of the Kimberley region. See Attachment 1 for an explanation of the pasture type codes.

Ecosystem type	Ecosystem state	Pasture type and condition
Wet-dry tropical eucalypt woodlands (red soil states)	Diverse perennial pasture close to reference	BSGP, PLSP, TTGP, WGBP, RGRP, FRGP: very good/ good condition
	Moderate diversity perennial pasture	BSGP, PLSP, TTGP, WGBP, RGRP, FRGP: good to fair condition
	Native woody thickened	BSGP, PLSP, TTGP, WGBP, RGRP, FRGP: good, fair and poor condition
	Annual sorghum dominant	PLSP, TTGP, RGRP: fair/poor condition
	Aristida contorta	BSGP, PLSP, TTGP, WGBP, RGRP, FRGP, ASGP: poor condition

	Annual grasses and forbs	BSGP, PLSP, TTGP, WGBP, RGRP: poor condition; ASGP: fair/good condition
	Bare soil	BSGP, PLSP, TTGP, WGBP, RGRP: very poor condition; FRGP, ASGP: poor/very poor condition
	Indian couch	Not applicable
	Buffel grass	BUGP, FRGP: good/fair condition
	Spinifex dominant	Not applicable
Rainfall-pulse driven arid and semi-arid tussock grasslands (black soil states)	Palatable perennials dominant	MGUP, MGAP, BGAP, RAPP: very good/good condition
	Mixed unpalatable perennials dominant	MGUP, MGAP, BGAP, RAPP: good/fair condition
	Aristida latifolia dominant	MGUP, MGAP, BGAP, RAPP: poor condition (sometimes fair condition)
	Native woody thickened	MGUP, MGAP, BGAP, RAPP: good, fair and poor condition
	Annual grasses and forbs	MGUP, MGAP, BGAP, RAPP: poor/very poor condition
	Seasonally bare ground	MGUP, MGAP, BGAP, RAPP: very poor/poor condition
	Indian couch	Not applicable

4.3 Red soil modified states: Wet-dry tropical eucalypt woodlands

The next sections describe in detail each modified state (and component expressions) for the Wet-dry tropical eucalypt woodlands (red soil) ecosystem type. The descriptions and diagrams were developed during the expert elicitation workshop (section 3) using the reference state (section 4.1.1) as a template.

4.3.1 Modified state: Diverse perennial pasture close to reference state

A dynamic (internally variable) modified ecosystem state 'diverse perennial pasture close to reference state' for the Wet-dry tropical eucalypt woodlands in the Kimberley was described from details captured in the reference state (section 4.1.1) that were changed to reflect the impact of exogenous disturbances (Figure 13). Conservative livestock grazing results in a transition to this state from the reference, and it is a desirable state for livestock production. This state is characterised as having a high stock carrying capacity of 8 cattle units (cu) km^2 and native perennial grasses in good pasture condition, although this state may be missing highly palatable perennials, such as *Themeda triandra*, at frequencies observed in the reference. This state will also have a few feral animals and invasive plant species (e.g. *Parkinsonia*) present.

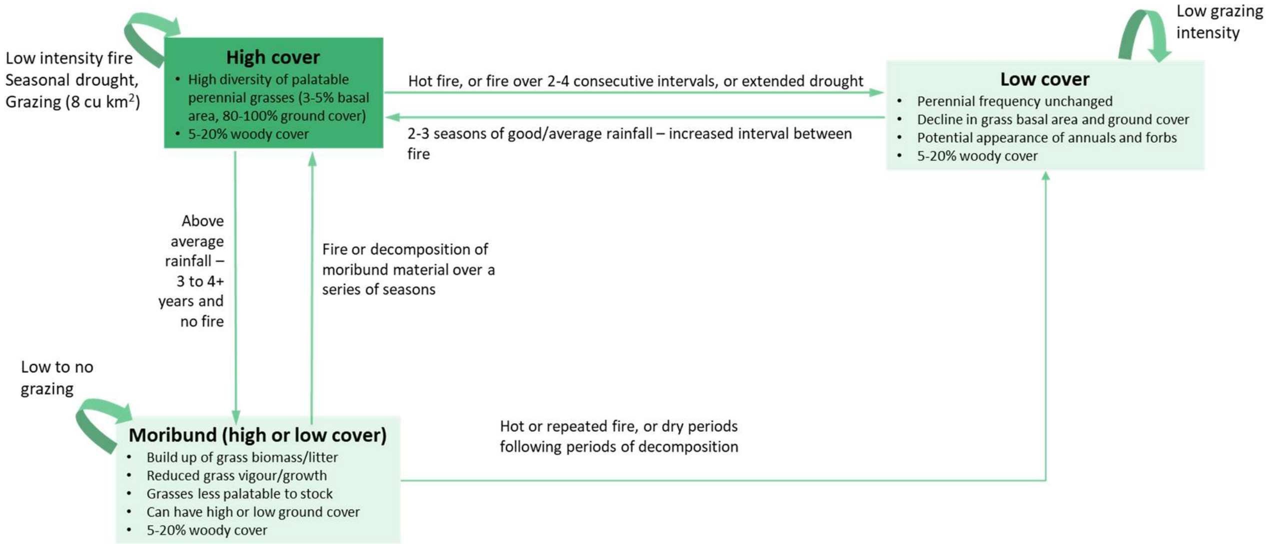


Figure 13. Conceptual model of the modified state 'diverse perennial pasture close to reference' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley.

The 'diverse perennial pasture close to reference' state (Figure 14) is much like the reference state evident in the 'mixed-age tropical woodland' expression. This state has similar dynamics to the reference model, including shifts to the 'lower cover' expression with low ground cover (and lower tree canopy cover, in some cases, due to high intensity fires), and reduced perennial frequency with associated small declines in grass tussock basal area. These changes may occur due to extended dry years or high intensity fire, with understory changes most likely occurring due to interactions with conservative livestock grazing pressure that exemplifies this state. Like the reference state ('old shrubby woodland' expression) the understory in this modified state may also move toward a 'moribund (low or high cover)' expression following periods of average to above average rainfall where no fire, and no or limited grazing is present. However, expressions evident in the reference state such as 'old shrubby woodland' and 'bimodal woodland' may not eventuate

as survival of seedlings to tree saplings is more constrained than in the reference state due to livestock grazing pressure.

Figure 14. Examples of a 'diverse perennial pasture close to reference' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. Note woody cover is very sparse in these examples but can be up to 20 %.

4.3.2 Modified state: Moderate diversity perennial pasture

A dynamic modified ecosystem state 'moderate diversity perennial pasture' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' that occurs in the Kimberley is described in Figure 15. This modified state was described from details captured in the reference state and 'diverse perennial pasture close to reference' state that were modified to reflect the impact of exogenous disturbances. This state often appears following transition from the 'diverse perennial pasture close to reference state' due to moderate levels of livestock grazing with or without extended dry seasons and frequent fire. It is characterised as having a moderate (4 – 8 cu km^{-2}) to low (2.5 – 4 cu km^{-2}) stock carrying capacity and good diversity of palatable perennial grasses. This state may have feral animals and some invasive plant species (e.g. *Acacia*, *Parkinsonia*, *Calotropis*) present.

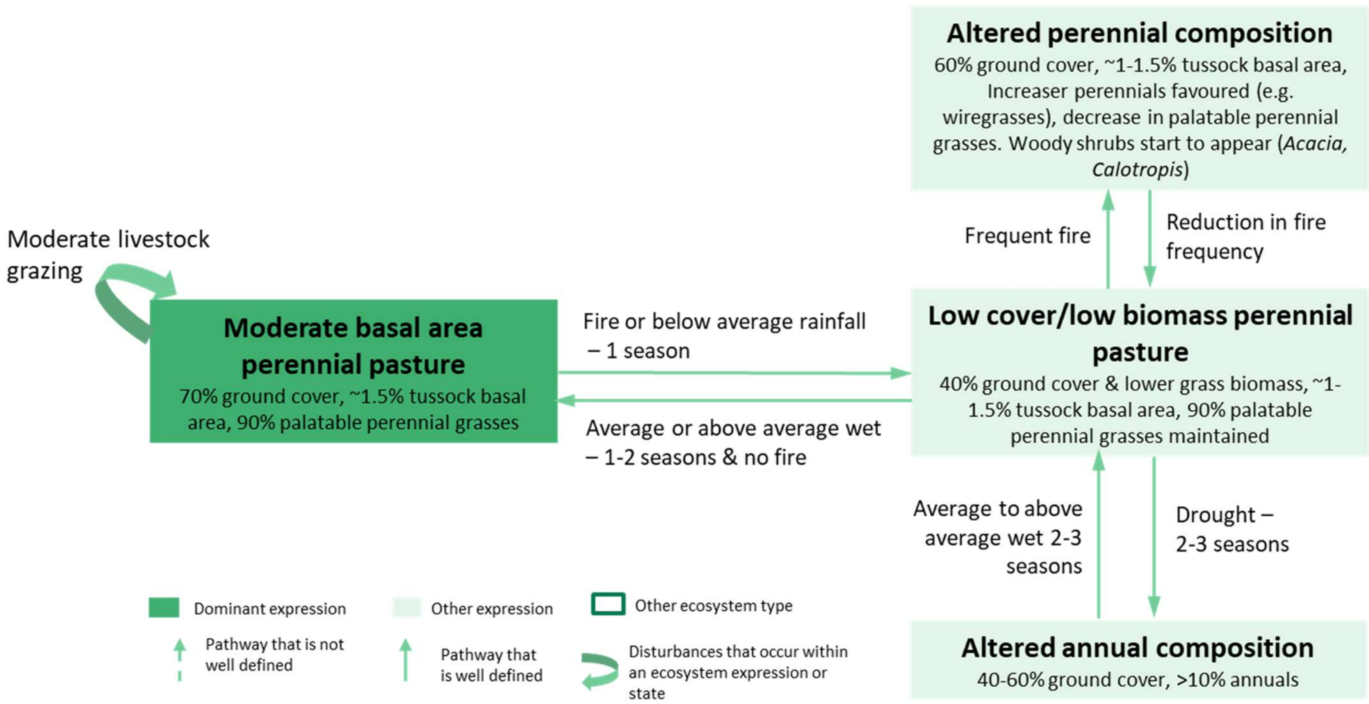


Figure 15. Conceptual model of the modified state 'moderate diversity perennial pasture' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley.

The 'moderate diversity perennial pasture' state could be described as being in good or fair pasture condition, retaining a high proportion of native perennial tussock species as well as high biomass and cover in its most common expression, but with a reduction in grass basal area due to grazing impacts compared to the 'diverse perennial pasture close to reference' state (Figure 16). The grass basal area in this state is typically ~1.5%, in comparison to the 'diverse perennial pasture close to reference' state which is usually >3%. Fire or below average rainfall years can shift the 'high cover' expression of this state to a 'low cover' expression for short periods of time until the return of average or above average rainfall. However, frequent fire or extended drought may also shift the 'low cover' expression into an 'altered perennial composition' expression (increaser perennials appear (a plant that increases in frequency as grazing pressure increases) with a possible increase in woody shrub abundance) or an 'altered annual composition' expression (with the appearance of interstitial annuals on return of rainfall).

Figure 16. Examples of a 'moderate diversity perennial pasture' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. Photo on the left is after above average rainfall and on the right after below average rainfall.

4.3.3 Modified state: Native woody thickened

A dynamic modified ecosystem state 'native woody thickened' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' that occurs in the Kimberley is described in Figure 17. This modified state was described from details captured in the reference state that were modified to reflect the impact of exogenous disturbances.

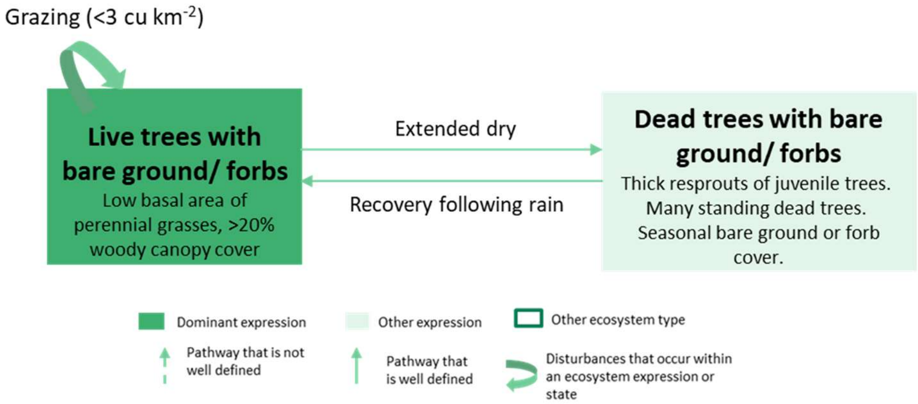


Figure 17. Conceptual model of the modified state 'native woody thickened' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley.

The 'native woody thickened' state commonly represents a transition from the 'diverse perennial pasture close to reference' state. This results from extended lack of fire in conjunction with livestock grazing allowing woody regrowth or woody seedling establishment and growth, and an associated decline in perennial grass abundance (Figure 18). This state is like the 'old shrubby woodland' expression in the reference state, with the difference being that low perennial grass biomass has been maintained by continuous grazing, reducing the chance of fire. Rainfall is the main driver between expressions in this state, with increases in bare ground and forbs during drier years.

Figure 18. Example of a 'native woody thickened' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. Photos were taken in 2011 (left) and 2020 (right), with 3 fires occurring at the site between these time points.

4.3.4 Modified state: Annual sorghum dominant

A dynamic modified ecosystem state 'annual sorghum dominant' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' that occurs in the Kimberley is described in Figure 19. This modified state was described from details captured in the reference state that were modified to reflect the impact of exogenous disturbances.

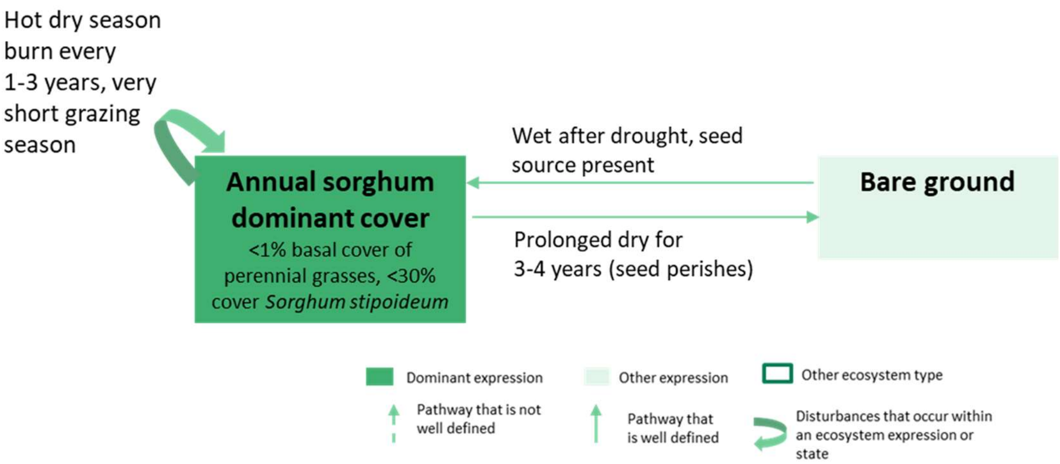


Figure 19. Conceptual model of the modified state 'annual sorghum dominant' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley.

The 'annual sorghum dominant' state most commonly represents a transition from the 'moderate diversity perennial pasture' state driven by frequent fire with or without grazing, although there may be instances where this state naturally occurs on certain soil types and topography. The ground layer is dominated by annual sorghum (*Sorghum stipoideum*) (an increaser species) and can only support livestock grazing during the wet season before the grass hays off (Figure 20). This state is usually restricted to higher rainfall regions of the Kimberley and has very few perennial tussock grasses (<1% total basal cover), such as *Chrysopogon fallax* and *Triodia bitextura*. Being dominated by an annual grass, extended dry years can reduce the pasture to a near 'bare ground' expression. Return of average to above average wet seasons will allow annual sorghum to re-

establish if seed is present and regular fires return. Woody species in this state include *Corymbia* sp., *Grevillea striata* and *Carissa lanceolata*, with an average canopy cover of <5%. Feral animals and invasive forbs may be present (e.g. *Sida acuta*).

Figure 20. Example of a 'annual sorghum dominant' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley.

4.3.5 Modified state: *Aristida contorta*

A dynamic modified ecosystem state '*Aristida contorta*' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' that occurs in the Kimberley is described in Figure 21. This modified state was described from details captured in the reference state that were modified to reflect the impact of exogenous disturbances.

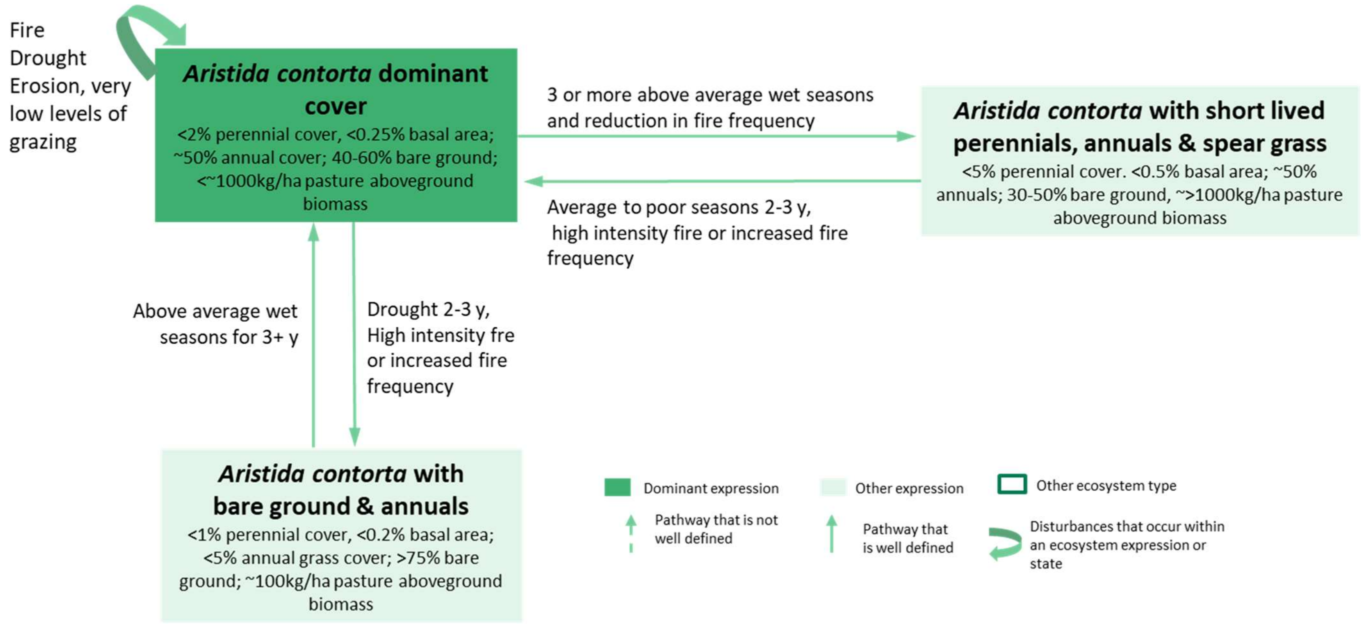


Figure 21. Conceptual model of the modified state '*Aristida contorta*' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley.

The '*Aristida contorta*' state commonly occurs following a transition from the 'moderate diversity perennial pasture' state driven by long term, continuous heavy grazing. This state is considered as being in poor condition, with the loss of a large proportion of native perennial tussock grass species, low to moderate pasture biomass, low cover and very low grass basal area in its dominant expression (Figure 22). The grass basal area in this state is typically ~0.25%. Following successive years of higher rainfall (with no fire) perennials (usually speargrass, *Heteropogon contortus*) can increase marginally with some improvement in grass basal area, cover and biomass compared to the dominant expression within this state. Drought years, intense fires, or increased fire activity leads to a loss in perennial grasses, with an associated decrease in grass basal area, and major decreases in biomass and cover (less than 25% ground cover). *Aristida contorta* and annual grasses will also decrease to very low levels of abundance.

Figure 22. Example of an '*Aristida contorta*' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. Photo: S. Prober.

4.3.6 Modified state: Annual grasses and forbs

A dynamic modified ecosystem state 'annual grasses and forbs' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' that occurs in the Kimberley is described in Figure 23. This modified state was described from details captured in the reference state that were modified to reflect the impact of exogenous disturbances.

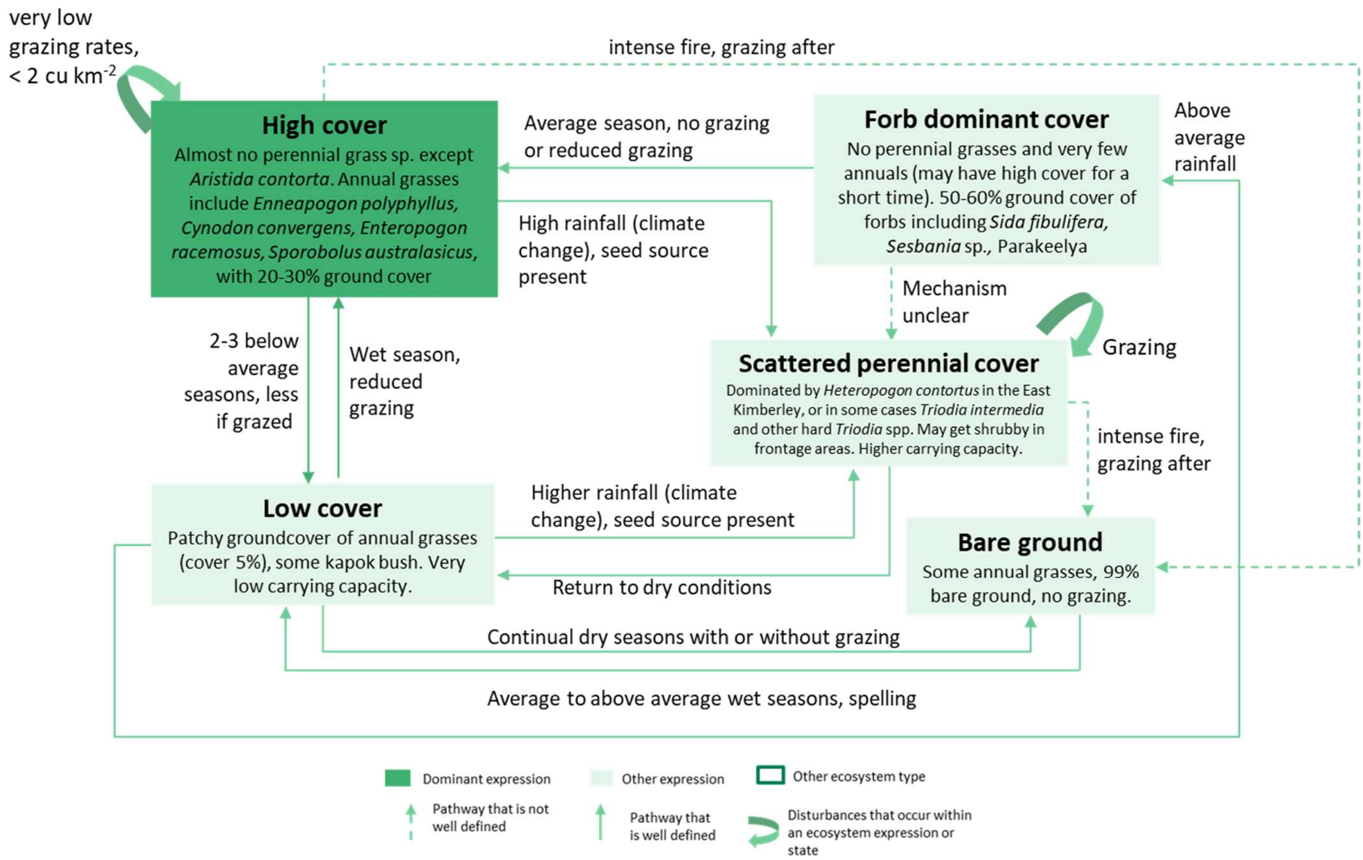


Figure 23. Conceptual model of the modified state 'annual grasses and forbs' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley.

The 'annual grasses and forbs' state usually occurs after prolonged landscape degradation most likely through heavy continuous stocking, although fire and drought conditions will also contribute over extended periods (Figure 24). It is usually a precursor to the 'bare soil' state. The dominant expression within this state under average wet season conditions usually has a high ground cover of annuals and forbs, during the mid to late part of the wet season, with some bare ground present. The annual plants form litter cover as they senesce. Periods of low rainfall combined with sustained grazing pressure will reduce the ground cover of annuals and forbs, while extended dry, with grazing or fire may lead to larger bare areas being prevalent. Extended periods of above average rainfall may see patches of perennial grasses (primarily *H. contortus*) appear with a maximum basal area of 3-5%. A return to drier conditions results in a shift back to the 'low cover' expression which has very few perennial grasses.

Figure 24. Example of an 'annual grasses and forbs' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. Photo on the left taken after below average rainfall, and on the right after above average rainfall.

4.3.7 Modified state: Bare soil

A dynamic modified ecosystem state 'bare soil' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' that occurs in the Kimberley is described in Figure 25. This modified state was described from details captured in the reference and other states that were modified to reflect the impact of exogenous disturbances.

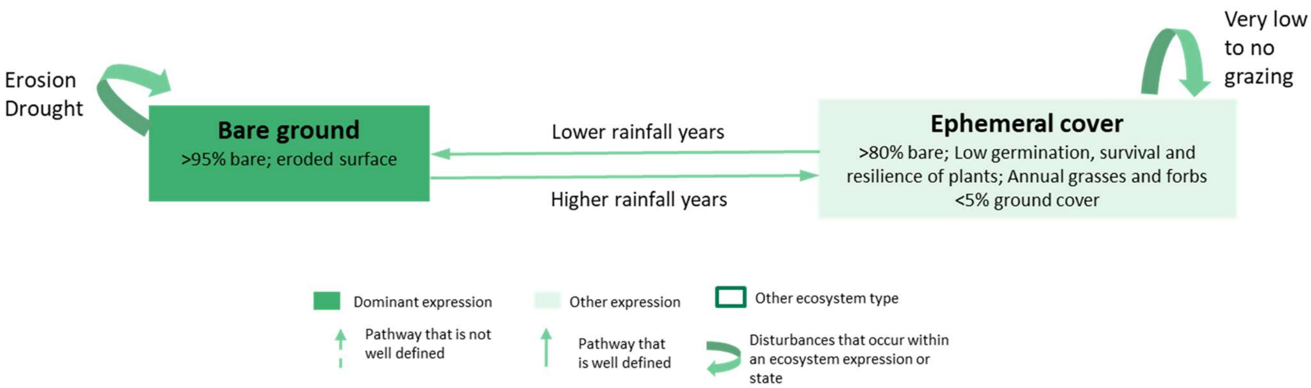


Figure 25. Conceptual model of the modified state 'bare soil' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley.

The 'bare soil' state can occur after a transition from most other states e.g. 'native woody thickened', 'annual sorghum dominant', '*Aristida contorta*', 'annual grasses and forbs' or 'Indian couch'. These transitions can be driven by several factors including increased fire frequency or intensity, drought, high intensity grazing or a combination of these. This state could be described as being in very poor condition (Figure 26), usually with erosion processes evident on the soil surface, and the loss of all, or a large proportion, of plant biodiversity. Any changes from or to the dominant expression are driven solely by rainfall, moving between a few annual grasses and forbs present following rainfall to largely bare ground in drier periods.

Figure 26. Examples of a 'bare soil' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley.

4.3.8 Modified state: Buffel grass

A dynamic modified ecosystem state 'buffel grass' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' that occurs in the Kimberley is described in Figure 27. This modified state was described from details captured in the reference state that were modified to reflect the impact of exogenous disturbances.

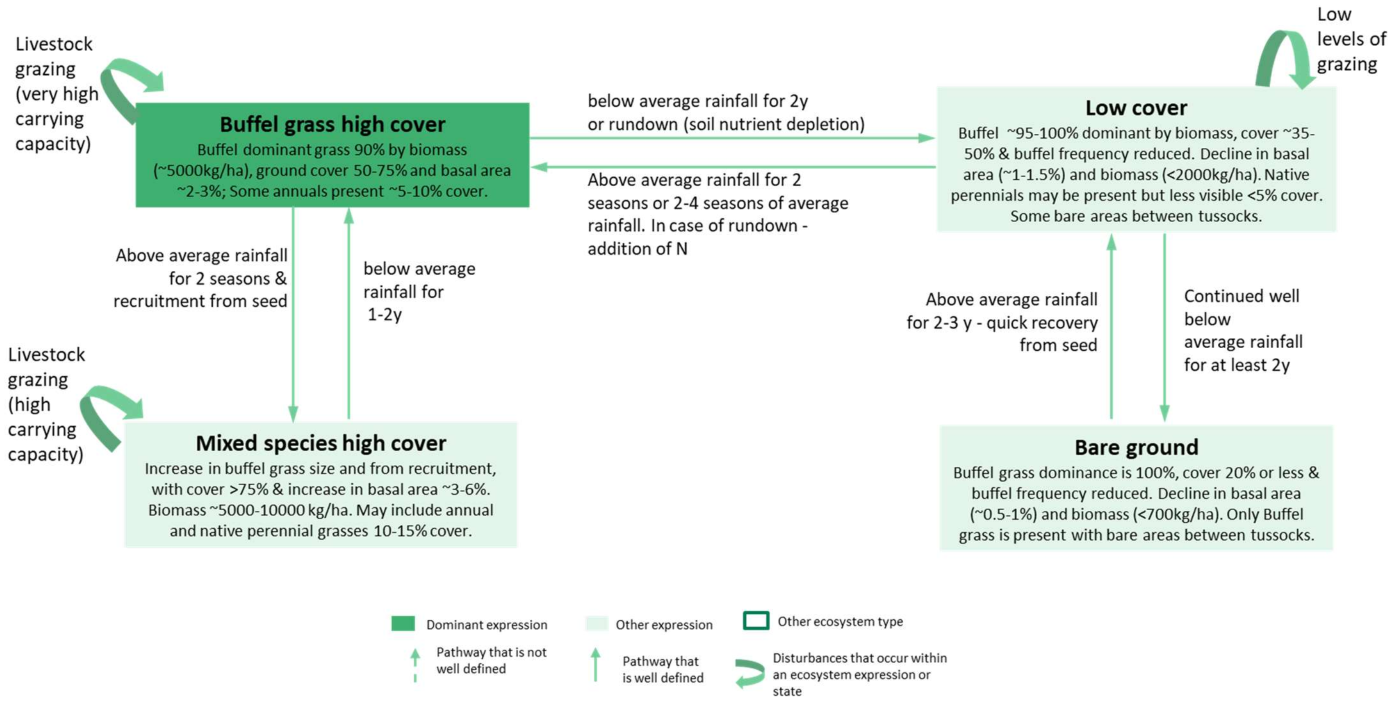


Figure 27. Conceptual model of the modified state 'buffel grass' for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley.

The 'buffel grass' state represents a modified state for parts of the Kimberley where Buffel grass (*Cenchrus ciliaris*) and or Birdwood grass (*Cenchrus setiger*) are the dominant ground cover species (Figure 28). Buffel grass is an exotic pasture grass which has become naturalized in the Kimberley following plantings from the 1950s onwards to support cattle grazing (planting is now prohibited), usually in highly degraded areas where few perennial grasses remained. It is usually associated

with frontage areas on sandy/loam soils close to natural water courses and in its dominant expression the ‘buffel grass’ state is highly productive, with a high stock carrying capacity (>8 cu km^{-2}). Most shifts between expressions in the ‘buffel grass’ state are driven by changes in rainfall or flooding interacting with livestock grazing, but depletion of soil nitrogen pools (nutrient rundown) may also cause a shift to a ‘low cover’ expression, if soil nutrient pools are not replenished, this shift could cause a permanent transition to a low biomass buffel grass state (not articulated here). It is unclear if this transition is occurring in the Kimberley.

Figure 28. Examples of a ‘buffel grass’ modified state for the ecosystem type ‘Wet-dry tropical eucalypt woodlands’ of the Kimberley. Photo on the left taken after above average rainfall, and on the right after below average rainfall.

4.3.9 Future modified state: Indian couch

A dynamic modified ecosystem state ‘Indian couch’ (*Bothriochloa pertusa*) for the ecosystem type ‘Wet-dry tropical eucalypt woodlands’ that could occur in the Kimberley is described in Figure 29. This modified state was described from details captured in the reference state that were modified to reflect the impact of exogenous disturbances and captured understanding of this state from Queensland rangelands.

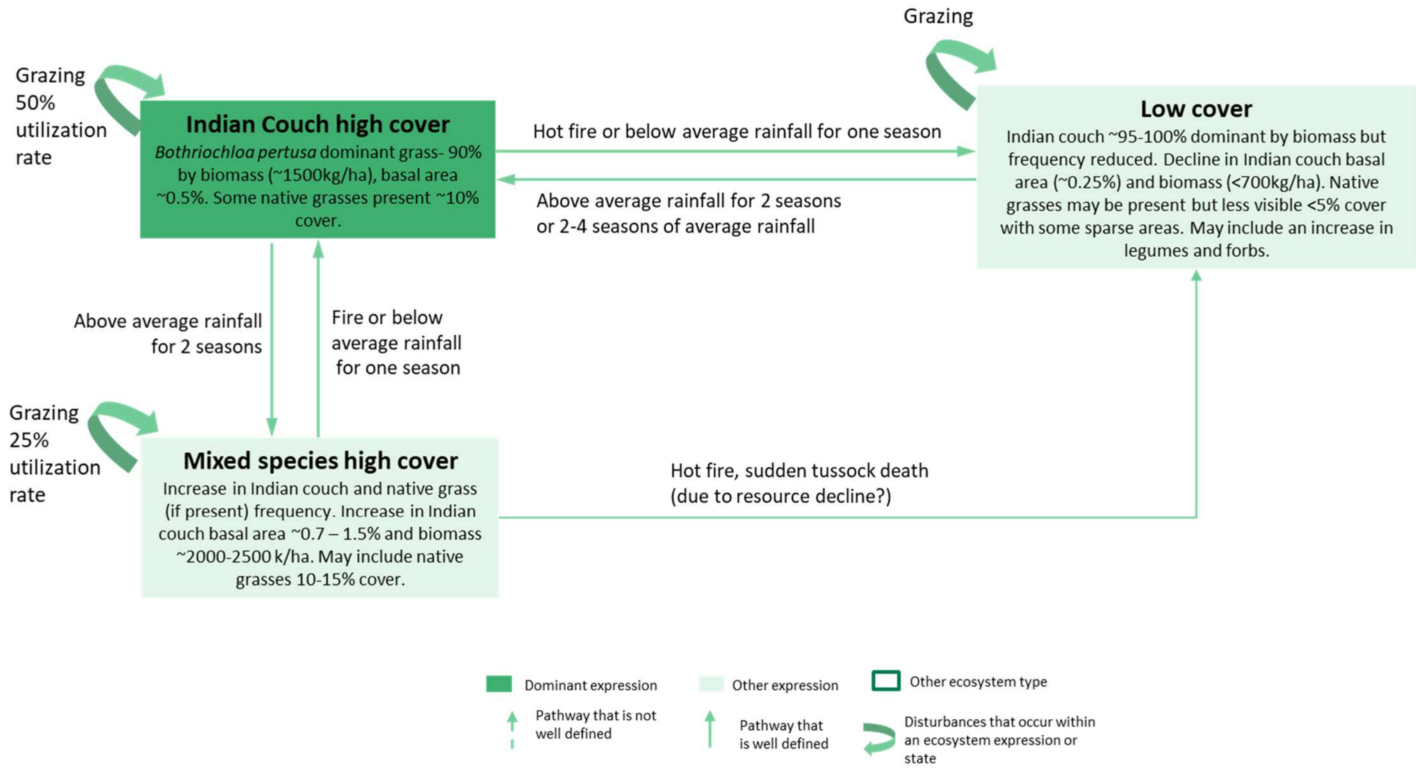


Figure 29. Conceptual model of the modified state 'Indian couch dominant' (*Bothriochloa pertusa*) for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley.

The 'Indian couch' state represents a possible future state for parts of the Kimberley (most likely areas >450mm rainfall) (Figure 30). *B. pertusa* is an exotic invasive grass which has become dominant (through direct sowing and natural seed movement) on large swathes of land from central to northern Queensland. Observations of its ecology from Queensland have informed the description of the 'Indian couch' state. Here, it is usually associated with areas that have been exposed to intensive grazing or decline from fire or drought, by firstly invading spaces between tussocks, then outcompeting and replacing existing native pasture. Evidence also suggests that it will invade moderately grazed and ungrazed areas, although at a slower rate. The dominant expression of this state is predominantly Indian couch, with a small proportion of native perennials, annuals, and forbs. Biomass is moderate and cover is high to very high (*B. pertusa* is stoloniferous and covers ground effectively at low biomass) but grass basal area remains low. The dominant expression can change quickly (with one season of very low rainfall) to the 'low cover' expression with associated decline in grass basal area. The 'mixed species high cover' expression is equally driven by rainfall (above average) becoming apparent in as little as two years. Interestingly, the 'mixed species high cover' expression can suffer from sudden death of *B. pertusa* plants if the expression is maintained for several years. The exact mechanism causing the die-off is unknown but may be related to nutrient run down (resource decline) seen in other exotic pastures.

Figure 30. Examples of a ‘Indian couch’ modified state for the ecosystem type ‘Wet-dry tropical eucalypt woodlands’ of the Kimberley. Top two photos are examples from the Kimberley (photo: WARMS photograph collection) and the bottom photo is from Mt Pleasant, QLD (Photo: B. Abbott).

4.3.10 Modified state: Spinifex dominant

A dynamic modified ecosystem state ‘spinifex dominant’ for the ecosystem type ‘Wet-dry tropical eucalypt woodlands’ that occurs in the Kimberley has been partially described. This state occurs when hard spinifex (*Triodia intermedia*) increases in dominance in the ‘annual grasses and forbs’ state (Figure 31). This often occurs in grasslands that abut *T. intermedia* pastures and where fire frequency is low. It is thought that this transition is most likely to occur in areas where grazing removes palatable perennial grass species. The removal of other perennial grass species enables *T. intermedia* to establish. This species is unpalatable to stock and tends to capture soil and nutrients in patches where it has established. It is possible that soil amelioration under *T. intermedia* may allow a transition back to the ‘moderate diversity perennial pasture’ state on red soil over 100 years or more. It is unclear if the dynamic described here is better captured as a separate state or is part of the ‘perennial invasion’ expression in the ‘annual grasses and forbs’ state (Figure 31).

Figure 31. Example of a 'spinifex dominant' modified state for the ecosystem type 'Wet-dry tropical eucalypt woodlands' of the Kimberley. Photo: S. Prober.

4.3.11 Quantification of ecosystem attributes for modified states of Wet-dry tropical eucalypt woodlands (red soil states)

In order to quantify characteristics of structure, function and composition of ecosystem states and their expressions (beyond details captured during the workshop – see Attachment 2), the project team used on-ground monitoring data to identify WARMS sites that were representative of a particular ecosystem state over a certain timeframe of monitoring. Within the monitoring timeframe, when a WARMS site was in a particular ecosystem state, the team obtained values for different characteristics (on-ground cover estimates, species richness, fractional cover etc.) that corresponded to below average rainfall years or above average rainfall years. These represent the most observed drivers of shifts between expressions described in the conceptual models for each ecosystem state. The characteristics of each ecosystem state are summarised in Table 6.

Table 6. Indicative values for perennial grass basal area, litter cover, species frequency, tree cover, species counts and green and bare fractions for each ecosystem state in the Wet-dry tropical eucalypt woodlands (red soil) ecosystem type under average to above average rainfall (> avg) and below average rainfall (< avg). Data were taken from a representative WARMS site for each ecosystem state (site numbers not shown due to privacy agreements), with two representative sites chosen for the 'moderate diversity perennial pasture' and 'annual grasses and forbs' states. Data were obtained from (1) Landscape function and soil surface assessments undertaken by on-ground monitoring; (2) WARMS survey data; (3) 30m vegetation fractional cover time series data derived from Landsat (Beutel et al. 2019, Joint Remote Sensing Research Program 2021). Note that WARMS site coordinates represent the centre of a 3 x 3 pixel array used to detect fractional cover, and these were checked with aerial photography to ensure they represented a homogenous landscape area.

	Landscape function		Soil Surface assessment		WARMS		WARMS		WARMS		WARMS		WARMS	WARMS – species richness					Fractional cover		Fractional cover	
State	**Perennial grass basal area (%)**		**Litter %**		**Frequency – Perennial Grass desirables**		**Frequency – Perennial Grass undesirables**		**Frequency – Perennial intermediates**		**Frequency – annual grasses, forbs**		**Tree cover (%)**	**All species (count of species)**					Green fraction % (dry season)		Bare soil fraction % (dry season)	
	> avg	**< avg**	**> avg**	**< avg**	**> avg**	**< avg**	**> avg**	**< avg**	**> avg**	**< avg**	**> avg**	**< avg**	**Range of total cover**	**Perennial Grass***	**Perennial Forbs**	**Tree/Shrub**	**Perennial Sedge**	**Total**	**> avg**	**< avg**	**> avg**	**< avg**
Reference	10-16	22	1 - 10%	<1%	95-100	80	1-15	6	10-55	18	0-5	0-3	9-17	7 (4)	1 - 3	8 - 13	0	16 - 24	20 - 25	8 - 15	2 - 10	15 - 20
Diverse perennial pasture close to reference	5-9	13	<1%	<1%	60-90	90	2-7	0	15-70	70	1	0	2-8	5	0 - 1	2 - 8	0	7 - 15	15 - 20	5 - 10	5 - 10	30 - 50
Moderate diversity perennial pasture	6-9	3-8	10-25%	<1%	55-75	60-75	0	0	70-95	65-90	10-50	0	0	3	1	0	1	6	10 - 15	2 - 8	5 - 10	25 - 30
	1-10	6	<1%	<1%	30-75	38	0-5	1	30-75	75	10-20	0-20	7-25	4	0	5 - 8	0	10 - 13	15 - 25	8 - 15	15 - 30	50 - 60
Native woody thickened	6-20	6	10-25%	10-25%	80-95	90	0	0	15-35	20	0	0	0.3-22	4	2	1 - 7	0 - 1	7 - 14	25 - 35	15 - 20	5 - 15	20 - 30
Annual sorghum dominant	2-6	3	10-25%	25-50%	50-70	60	0	0	30-65	20-60	35-100	55-100	8-18	3	4	5 - 9	1 - 3	15 - 21	25 - 35	10 - 20	5 - 15	35 - 40
Aristida contorta	1-5	2	1-10%	<1%	15-55	20	55-85	35	20-75	75	40-85	10	5-17	6	1 - 2	3 - 7	0	11 - 18	15 - 20	4 - 10	20 - 30	20 - 50
Annual grasses and forbs	0	0	<1%	<1%	10-95	0-10	0-80	0-50	4-8	0-5	50	15	0.7-8	3	1	2 - 4	0 - 1	6 - 10	10 - 15	2 - 8	10 - 25	40 - 50
	1-5	N/A	1 - 10%	<1%	5-7	5	25-30	11	5-20	22	90	20	2.5-11	5 - 12	2 - 6	3 - 6	0 - 1	11 - 26	10 - 20	5 - 10	15 - 25	40 - 50
Bare soil	0-1	0	1-25%	<1%	1-35	0-20	20-35	0-15	15-75	25-30	0	0	11-23	5(2)	0	2 - 5	0	7 - 10	20 - 30	15 - 20	20 - 30	35 - 55
Indian couch	2-20	2	1-10%	1-10%	20	9	50-30	20	15-50	30	35-75	20	13-18	8	2 - 3	2 - 5	0	14 - 20	15 - 20	5 - 8	5 - 10	30 - 40
Buffel grass	3-19	11	1-10%	1-10%	60-85	55-65	0-2	0-1	30-65	30-75	0-2	0	6-14	8(4)	0	4	0 - 1	12 - 13	15 - 25	10 - 12	5 - 20	30 - 55
Spinifex dominant	8-36	13	1 - 10%	<1%	10-75	30-50	15-50	35-55	0-18	0-4	5-15	10-25	7.5-16	2 - 5	0 - 2	6	0 - 1	8 - 14	15 - 25	5 - 15	15 - 30	40 - 50

* bracketed number is species count in below average rainfall seasons
N/A - This site not assessed for landscape function in a dry year

4.4 Black soil modified states: Rainfall-pulse driven arid and semi-arid tussock grasslands

The next sections describe in detail each modified state (and component expressions) for the Rainfall-pulse driven arid and semi-arid tussock grasslands (black soil) ecosystem type. The descriptions and diagrams were developed during the expert elicitation workshop (section 3) using the reference state (section 4.1.2) as a template.

4.4.1 Modified state: Palatable perennials dominant

A dynamic modified ecosystem state 'palatable perennials dominant' for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' that occurs in the Kimberley is described in Figure 32. This modified state was described from details captured in the reference state that were modified to reflect the impact of exogenous disturbances.

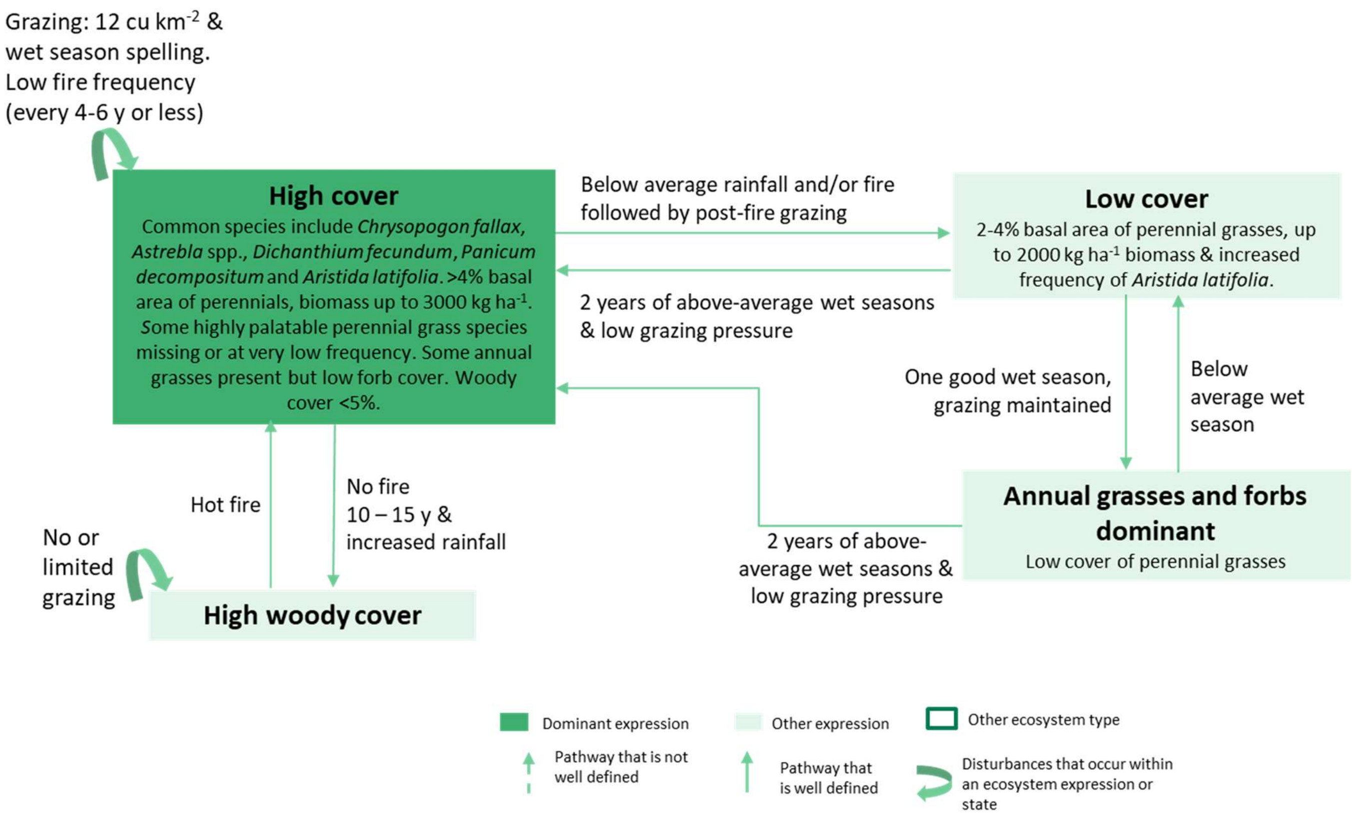


Figure 32. Conceptual model of the modified state 'palatable perennials dominant' for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' of the Kimberley.

The 'palatable perennials dominant' state commonly results from a transition from the reference state due to the impact of moderate livestock grazing (annual utilization of 10-20%), with or without fire (Figure 33). This state has similar dynamics to the reference state but with higher frequency of unpalatable perennial grasses, reduced richness of palatable perennial species, some bare areas and some woody thickening occurring. It can support a high stock carrying capacity and pasture condition would be described as good to very good. Changes in rainfall or fire (interacting with livestock grazing pressure) drive shifts between expressions, including to a 'lower cover' expression, or to reduced perennial grasses and increased annual (e.g. *Iseilema vaginiflorum,*

Sorghum stipoideum, Cynodon convergens) and forb (e.g. *Neptunia* sp., *Rhynchosia* sp.) frequency and associated small declines in grass tussock basal area (‘annual grasses and forbs dominant’ expression). Like the reference state, the overstorey may also move toward a woodland expression with increased woody cover (common species include *Bauhinia* sp. and *Vachellia suberosa*) following periods of average to above average rainfall where no fire and no, or limited, grazing is present. Most expressions contain some invasive species, such as *Calotropis procera* but few feral animals.

Figure 33. Examples of a ‘palatable perennials dominant’ modified state for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ of the Kimberley.

4.4.2 Modified state: Mixed unpalatable perennials dominant

A dynamic modified ecosystem state ‘mixed unpalatable perennials dominant’ for the ecosystem type ‘Rainfall-pulse driven arid and semi-arid tussock grasslands’ that occurs in the Kimberley is described in Figure 34. This modified state was described from details captured in the reference and ‘palatable perennials dominant’ state that were modified to reflect the impact of exogenous disturbances.

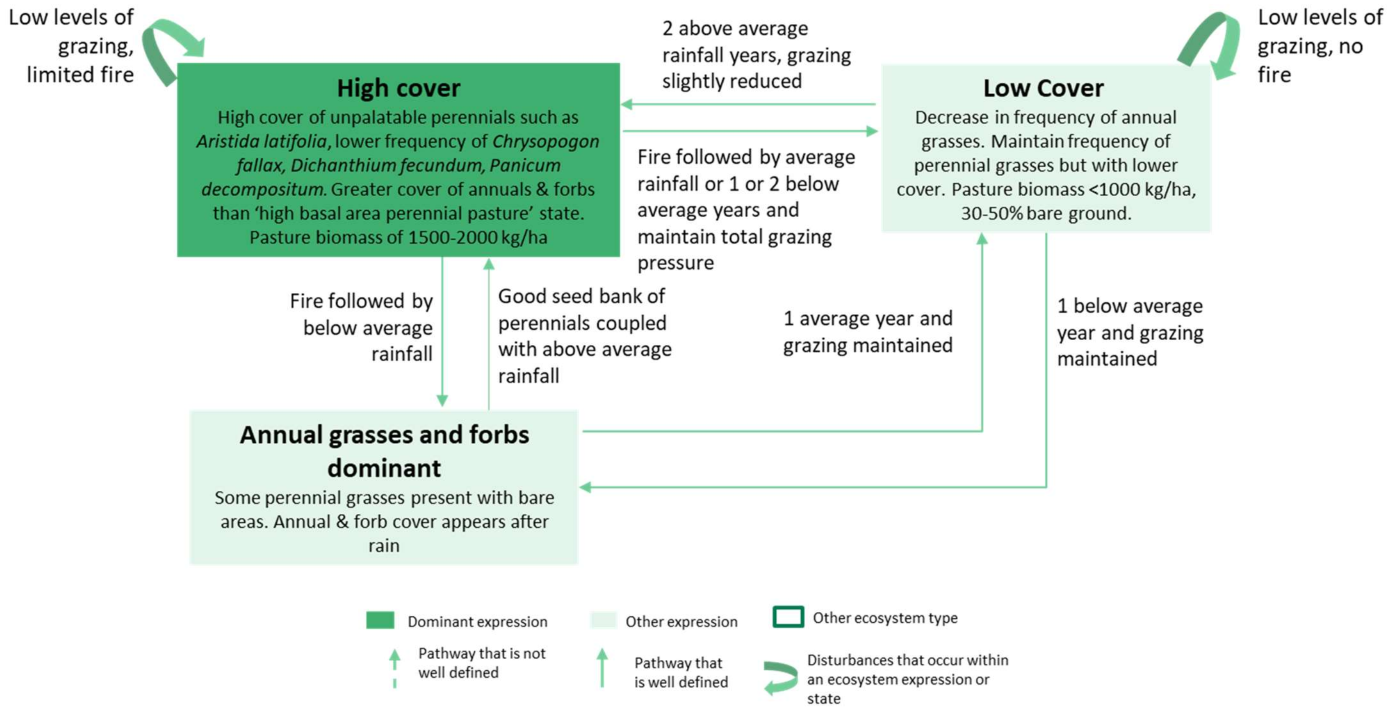


Figure 34. Conceptual model of the modified state 'mixed unpalatable perennials dominant' for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' of the Kimberley.

The 'mixed unpalatable perennials dominant' state is a transition from the 'palatable perennials dominant' state usually driven by cattle grazing, with or without fire (Figure 35). This state is described as fair condition (it has a low stock carrying capacity), retaining most the of native perennial tussock species found in the reference state, with moderate to high biomass and cover in its dominant expression, but with a reduction in grass basal area due to grazing impacts (biomass removal and trampling reducing plant growth), and lower frequency of palatable perennial grasses (notably missing *Astrebla* spp.). The grass basal area in this state is typically ~1.5% (the 'palatable perennials dominant' state is usually >3%). Fire or below average rainfall years can move the dominant expression of this state to a 'low cover' expression for short periods of time before the return of average or above average rainfall. However, continued drought may also move the 'low cover' expression into an expression with some bare ground, and annuals and forbs persisting during average wet seasons ('annual grasses and forbs dominant' expression).

Figure 35. Examples of a 'mixed unpalatable perennials dominant' modified state for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' of the Kimberley.

4.4.3 Modified state: *Aristida latifolia* dominant

A dynamic modified ecosystem state '*Aristida latifolia* dominant' for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' that occurs in the Kimberley is described in Figure 36. This modified state was described from details captured in the reference that were modified to reflect the impact of exogenous disturbances.

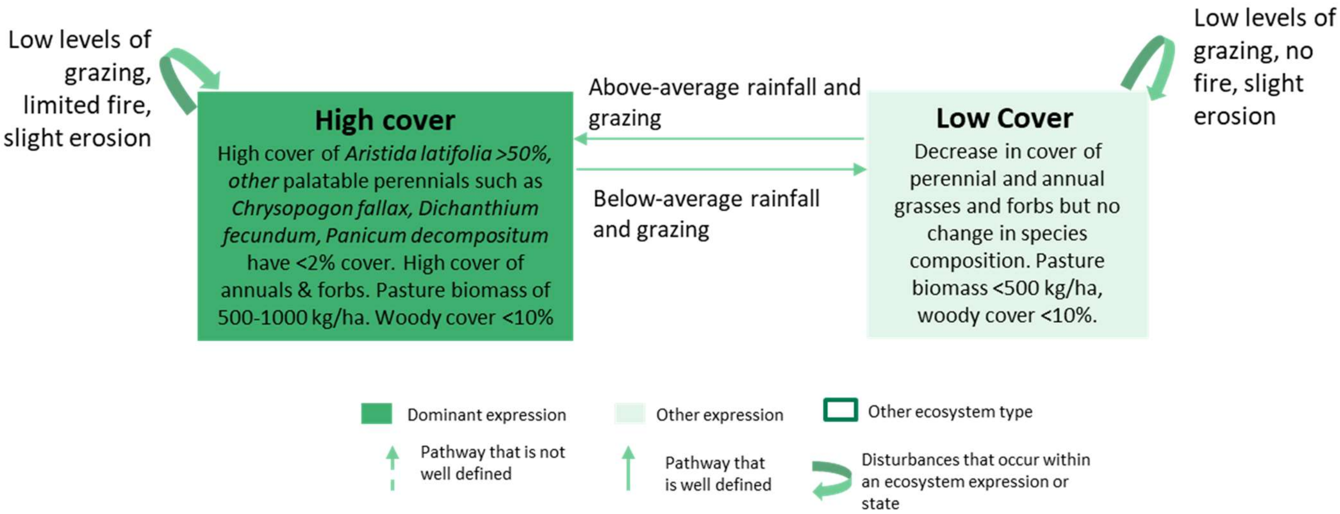


Figure 36. Conceptual model of the modified state '*Aristida latifolia* dominant' for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' of the Kimberley.

The '*Aristida latifolia* dominant' state is a transition from the 'mixed unpalatable perennials dominant' state usually driven by high livestock grazing pressure (Figure 37). This state is described as poor pasture condition, due to dominance by Feathertop (*Aristida latifolia*), an unpalatable perennial grass species. The main dynamic in this state is between the 'high cover' and 'low cover' expressions, driven by seasonal rainfall, interacting with low levels of livestock grazing. Both expressions maintain a low frequency and cover of palatable perennial grass species and annual grasses, such as *Iseilema vaginiflorm, Sorghum stipoideum, Cynodon convergens*, as well as forbs such as *Neptunia* sp., *Rhynchosia* sp., *Indigofera* sp., and *Ptilotus* sp. Woody species include the invasive *Calotropis procera* and *Vachellia farnesiana*.

Figure 37. Examples of a '*Aristida latifolia* dominant' modified state for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' of the Kimberley.

4.4.4 Modified state: Native woody thickened

A dynamic modified ecosystem state 'native woody thickened' for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' that occurs in the Kimberley is described in Figure 38. This modified state was described from details captured in the reference state that were modified to reflect the impact of exogenous disturbances.

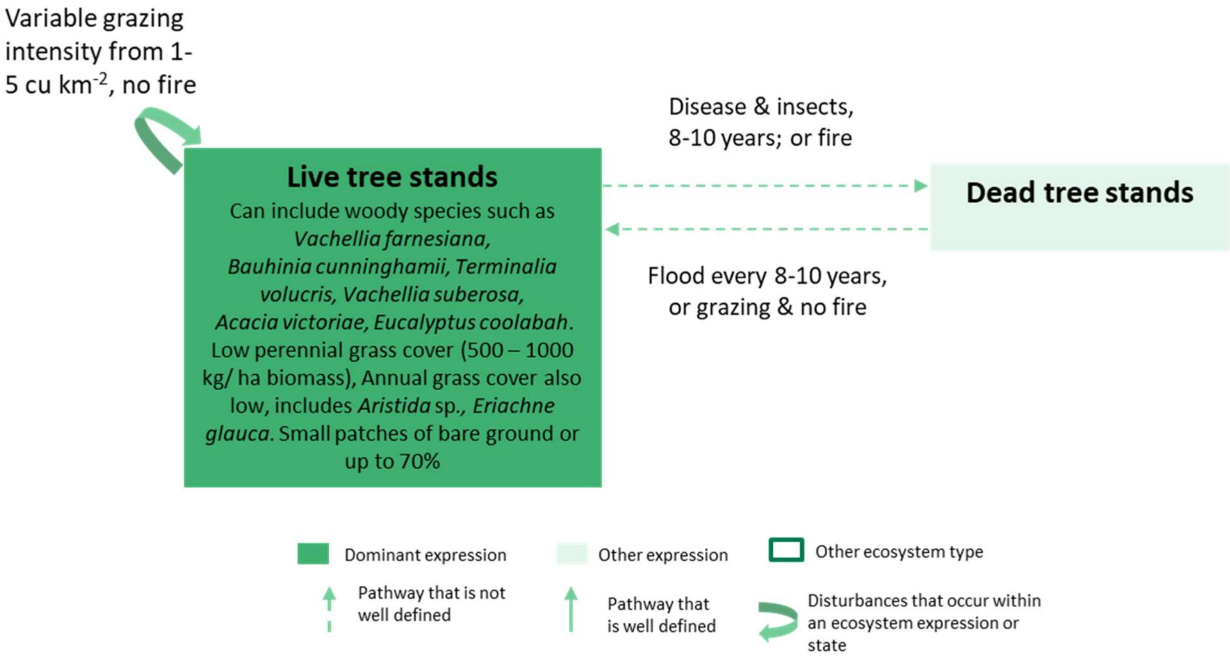


Figure 38. Conceptual model of the modified state 'native woody thickened' for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' of the Kimberley.

The 'native woody thickened' state most likely represents a transition from the 'mixed unpalatable perennials dominant' state where grazing, lack of fire and/or extensive flooding promote woody seedling establishment and growth with associated declines in perennial grass abundance (Figure 39). Development of this state is similar to formation of the '*Vachellia farnesiana* shrublands/grasslands' expression in the reference state, with the addition that pasture biomass has been initially reduced and maintained at low levels through livestock grazing, reducing the

chance of fire. Higher rainfall causing flooding is the main driver between expressions here, with perennial grass cover and biomass remaining low due to grazing and increased competition from the woody layer. Bare ground patches will appear in drier years, being replaced by annuals and forbs in wetter years. Stands of *V. farnesiana* will naturally senesce after 8-10 years due to disease and/or insect attack leading to the 'dead tree stands' expression. This expression may also occur after high intensity fire. A return to the 'live tree stands' expression occurs following recruitment of woody species, stimulated by flooding.

Figure 39. Example of a 'native woody thickened' modified state for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' of the Kimberley.

4.4.5 Modified state: Annual grasses and forbs

A dynamic modified ecosystem state 'annual grasses and forbs' for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' that occurs in the Kimberley is described in Figure 40. This modified state was developed from details captured in the reference state that were modified to reflect the impact of exogenous disturbances.

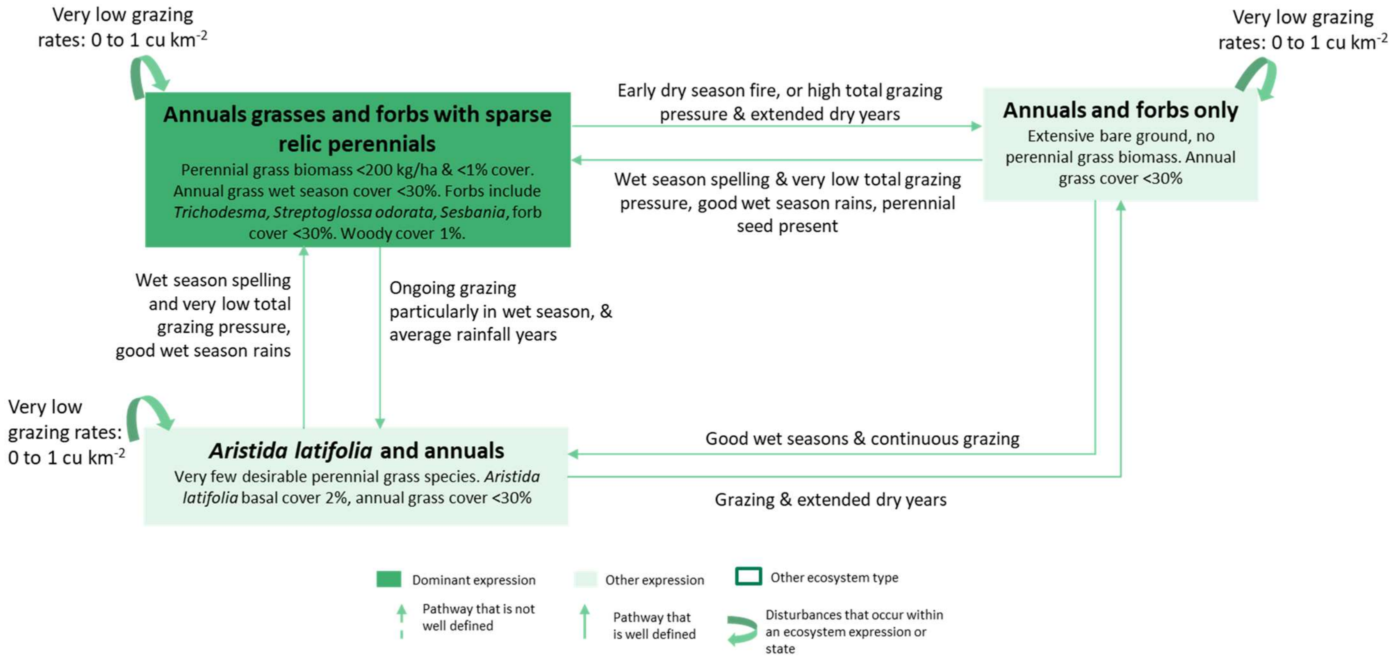


Figure 40. Conceptual model of the modified state 'annual grasses and forbs' for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' of the Kimberley.

The 'annual grass and forbs' state most likely represents a transition from the 'mixed unpalatable perennials dominant' state due to heavy and continuous grazing or frequent fire and is characterised by the dominance of annual grass species with some sparsely distributed perennial grasses remaining (Figure 41). Early season fire can reduce the pasture to a near bare ground expression (with annuals and forbs only), as can extended dry years and increases in grazing intensity or continuous grazing pressure without rest. Wetter years with reduced grazing and little or no fire will, however, allow for some perennial grass recruitment (if a seed source is present) returning to the dominant expression. Continuous grazing of the dominant expression without rest, particularly in good to average wet season years, may see undesirable perennial grasses such as *Aristida latifolia* becoming dominant or co-dominant and replacing more desirable perennial tussocks leading to the '*Aristida latifolia* and annuals' expression. This expression may also occur following a shift from the 'annuals and forbs only' expression in good rainfall years.

Figure 41. Example of an 'annual grasses and forbs' modified state for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' of the Kimberley.

4.4.6 Modified state: Seasonally bare ground

A dynamic modified ecosystem state 'seasonally bare ground' for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' that occurs in the Kimberley is described in Figure 42. This modified state was described from details captured in the reference and other states that were modified to reflect the impact of exogenous disturbances.

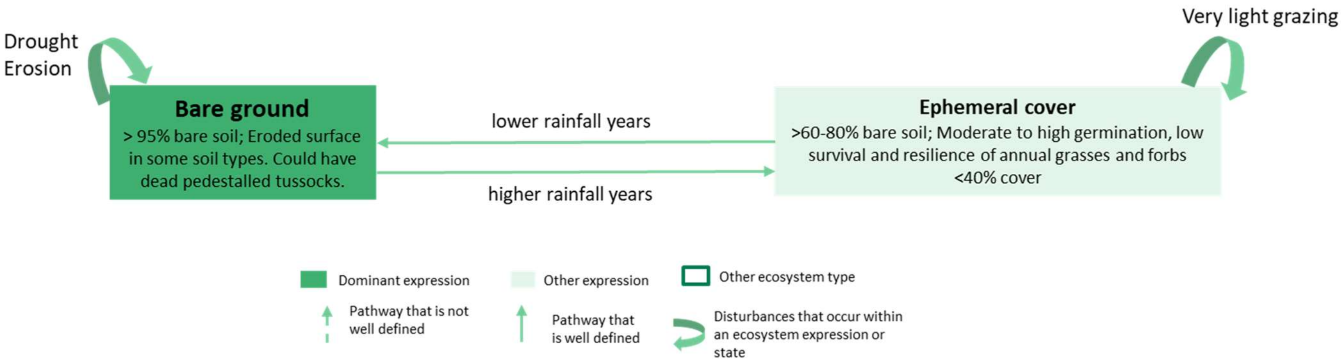


Figure 42. Conceptual model of the modified state 'seasonally bare ground' for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' of the Kimberley.

The 'seasonally bare ground' state represents a possible transition from several other states, such as '*Aristida latifolia* dominant' and 'annual grasses and forbs'. Transition to the 'seasonally bare ground' state from these other states may be driven by several factors including increased fire frequency or intensity (infrequent given the low grass biomass in parent states), drought, heavy and continuous grazing, or a combination of these. This state could be described as in very poor condition, usually with soil erosion processes evident (although this is less obvious on self-mulching surfaces), and the loss of nearly all plant diversity (Figure 43). Any changes from the dominant expression are driven solely by rainfall. If seed is present, germination can be quite high

on some black soils with flushes (reasonably high ground cover) of annuals and forbs occurring during high soil moisture periods, perennial grasses however, remain rare or absent.

Figure 43. Example of a 'seasonally bare ground' modified state for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' of the Kimberley.

4.4.7 Future modified state: Indian couch

A dynamic future modified ecosystem state 'Indian couch' for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' that occurs in the Kimberley is described in Figure 44. This future modified state was described from details captured in the reference state that were modified to reflect the impact of exogenous disturbances.

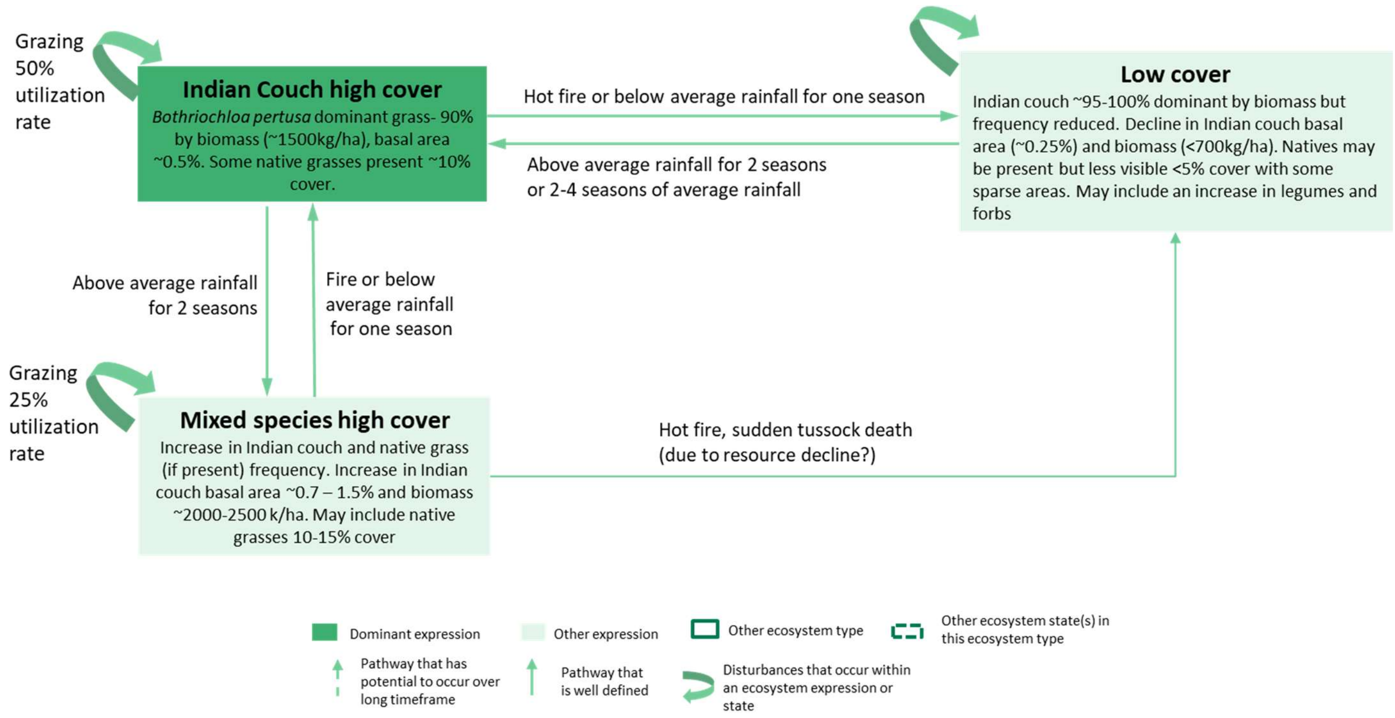


Figure 44. Conceptual model of the modified state 'Indian couch' for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' of the Kimberley.

The 'Indian couch' state represents a possible future state for parts of the Kimberley (most likely in areas with >450mm rainfall). Indian couch (*Bothriochloa pertusa*) is an exotic invasive grass which has become dominant on large swathes of land from central to northern Queensland (Figure 45). It is either actively planted or spread naturally and usually associated with areas that have been subject to overgrazing or decline from fire or drought. *B. pertusa* colonises sites initially by invading the space between tussocks, then outcompeting and replacing existing native species. Evidence suggests that it will also invade moderately grazed and ungrazed areas although at a slower rate. The dominant expression of this state is predominantly Indian couch, with a small proportion of native perennials, annuals, and forbs. Biomass is moderate and cover is high to very high (*B. pertusa* is stoloniferous and covers ground effectively at low biomass) but grass basal area remains low. The dominant expression can change quickly (with one season of very low rainfall) to the 'low cover' expression with associated decline in grass basal area. The 'mixed species high cover' expression is equally driven by rainfall (above average) becoming apparent in as little as two years. Interestingly, the 'mixed species high cover' expression can suffer from sudden death of *B. pertusa* if the expression is maintained for several years. The exact mechanism driving Indian couch death is unknown but may be related to nutrient run down following better rainfall years (resource decline) seen in other exotic pasture types. It typically re-establishes within 2-4 seasons of average to high rainfall.

Figure 45. Examples of an 'Indian couch' future modified state for the ecosystem type 'Rainfall-pulse driven arid and semi-arid tussock grasslands' of the Kimberley, taken in Queensland. Photo: B. Abbott.

4.4.8 Quantification of ecosystem attributes for modified states of Rainfall-pulse driven arid and semi-arid tussock grasslands (black soil states)

A range of quantitative ecosystem characteristics for each ecosystem state for the Rainfall-pulse driven arid and semi-arid tussock grasslands are shown in Table 7 (beyond details captured during the workshop – see Attachment 3). These include information on characteristics for below average rainfall years and average to above average rainfall years as these represent the most observed drivers of shifts between expressions described in the conceptual models for each ecosystem state. Further details on the method for collating the data in Table 7 are included in section 4.3.11.

Table 7. Indicative values for perennial grass basal area, litter cover, species frequency, tree cover, species counts and green and bare fractions for each ecosystem state in the Rainfall-pulse disturbed arid and semi-arid tussock grasslands (black soil) ecosystem type under average to above average rainfall (> avg) and below average rainfall (< avg). Data were taken from a representative WARMS site for each ecosystem state (site numbers not shown due to privacy agreements), with two representative sites chosen for the 'annual grasses and forbs' state. Data were obtained from (1) Landscape function and soil surface assessments undertaken by on-ground monitoring; (2) WARMS survey data; (3) 30m vegetation fractional cover time series data derived from Landsat (Beutel et al. 2019, Joint Remote Sensing Research Program 2021). Note that WARMS site coordinates represent the centre of a 3 x 3 pixel array used to detect fractional cover, and these were checked with aerial photography to ensure they represented a homogenous landscape area.

	Landscape function		Soil surface assessment		WARMS		WARMS		WARMS		WARMS		WARMS	WARMS – species richness					Fractional cover		Fractional cover	
State	Perennial grass basal area (%)		Litter %		Frequency – Perennial Grass desirables		Frequency – Perennial Grass undesirables		Frequency – Perennial intermediates		Frequency – annual grasses, forbs		Tree cover (%)	All species (count of species)**					Green fraction % (dry season)		Bare soil fraction % (dry season)	
	> avg	< avg	> avg	< avg	> avg	< avg	> avg	< avg	> avg	< avg	> avg	< avg	Range of total cover	Perennial Grass	Perennial Forbs	Tree/ Shrub	Perennial Sedge	Total	> avg	< avg	> avg	< avg
Reference	10-18	8	<1 - 10~	<1	95-100	95	0-20	0	5-40	0	5-20	2	0	6 (3 in dry)	3	NA	NA	9	20-25^	2-8	2-15	35-45
Palatable perennials dominant	5-15	2.5	<1 - 10~	<1	90-100	90	0-40	0-35	2-20	0-10	2-20	2	0	5 (3 in dry)	2	NA	NA	7	20-25#	2-8	2-25	35-45
Mixed unpalatable perennials dominant	2.7-6	2-3	1 - 50	<1 - 10	40-70	10-50	2-70	2-40	10-70	5-40	15-20	2-10	1-2.5	7	1 or 2 (0 to 2 in dry)	0 to 3	0 to 1 (0 in dry)	10	10-15	2-8	10-25	30-50
Aristida latifolia dominant	4-12	2-4	1 - 25	1 - 10	35-55	10-40	25-55	5-25	50-70	50-60	25-70	15	0	5	4	NA	NA	11	7-10	2-8	15-25	50-70
Native woody thickened	0.5-10	0.5	<1 - 10 (<1)*	<1 (<1) *	0-80	70	0-35	5	5-15	5	5-20	10	1-25	4	2	4	NA	10	8% green at start (1988), increasing to 25% with tree cover increase*		40% bare soil at start (1988), reducing to 25% with tree cover increase*	
Annual grasses and forbs	0.4	0.3-1.7	10-50	10-100	0-1	0	5	0	14	2	68-98	88	0 -3.4	3	5	6	0	16	5-25	2-10	5-20	15-20
	1.2-3.8	0.6-2.7	1-50	<1-25	0-2	&10-20	0-5	0	70-90	56			0	5	2	0	2	10	5-25	2-5	5-20	2-5
Seasonally bare ground	0-0.2	0	1-25	1 - 10	0	0	0-2	0	0	0	25-70	70	0-0.2	0	1	0	1	3	10-20	2-8	10-15	50-60

**bracketed number is species count in below average rainfall seasons

* litter under *Acacia* and *Vachellia* genera

~ some litter observed to be extensively incorporated into soil, else slight incorporation

& site seems to be increasing in desirable perennials

^ peak green cover 30% in 2000

peak green cover 25% in 2000 and 2004

5 Ecosystem transitions

In the elicitation workshop experts were asked to take the modified state descriptions for each ecosystem type (see section 4.3 and 4.4) and using the drivers discussed previously (Table 1), determine whether it was possible to transition from one state to another. A transition is a shift from one state to another that is not reversible without active management intervention, an extreme event or an unacceptably long timeframe (Bestelmeyer et al. 2009). If a transition was possible, experts were asked to list the drivers of the transition (this could be a management action e.g. wet season spelling and low intensity grazing or a threatening process e.g. drought followed by high intensity fire). Experts were also asked to estimate the time for a transition to occur, and what pre-conditions might be required for a particular transition e.g. certain transitions may only occur near rivers or if there is good wet season rainfall. For those transitions that resulted in an improvement to the ecological integrity (condition) of an ecosystem state, experts were asked to estimate the likelihood that the specified transition would occur.

This section summarises the transitions between ecosystem states for each ecosystem type in diagrams and tables. Transition diagrams are separated into desirable and undesirable transitions with respect to land degradation outcomes.

5.1 Wet-dry tropical eucalypt woodlands 'red soil' state and transition model

5.1.1 Undesirable transitions

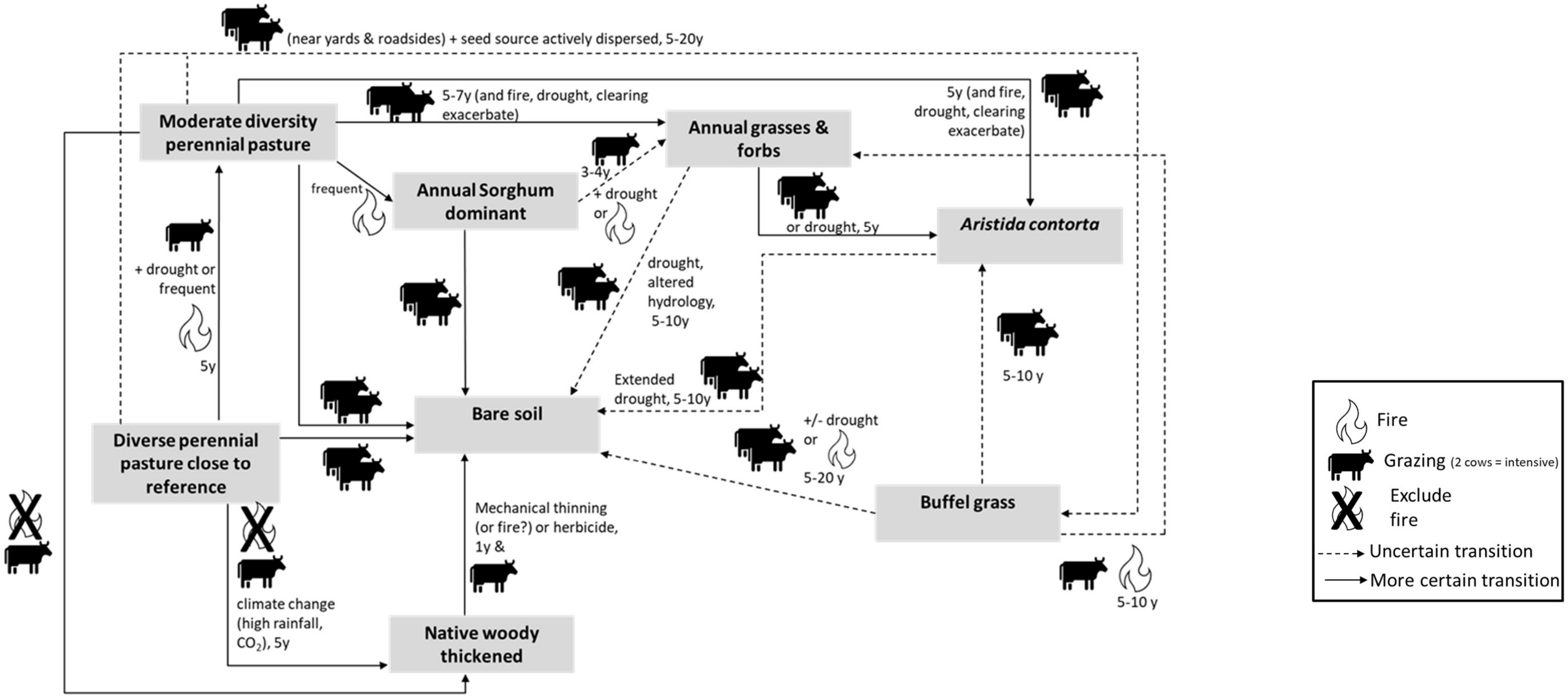


Figure 46. Drivers, uncertainty (more certain is >0.7; uncertain is <0.7, see Table 8) and timeframes for undesirable transitions between ecosystem states in the Wet-dry tropical eucalypt woodlands (red soil) ecosystem type.

5.1.2 Desirable transitions

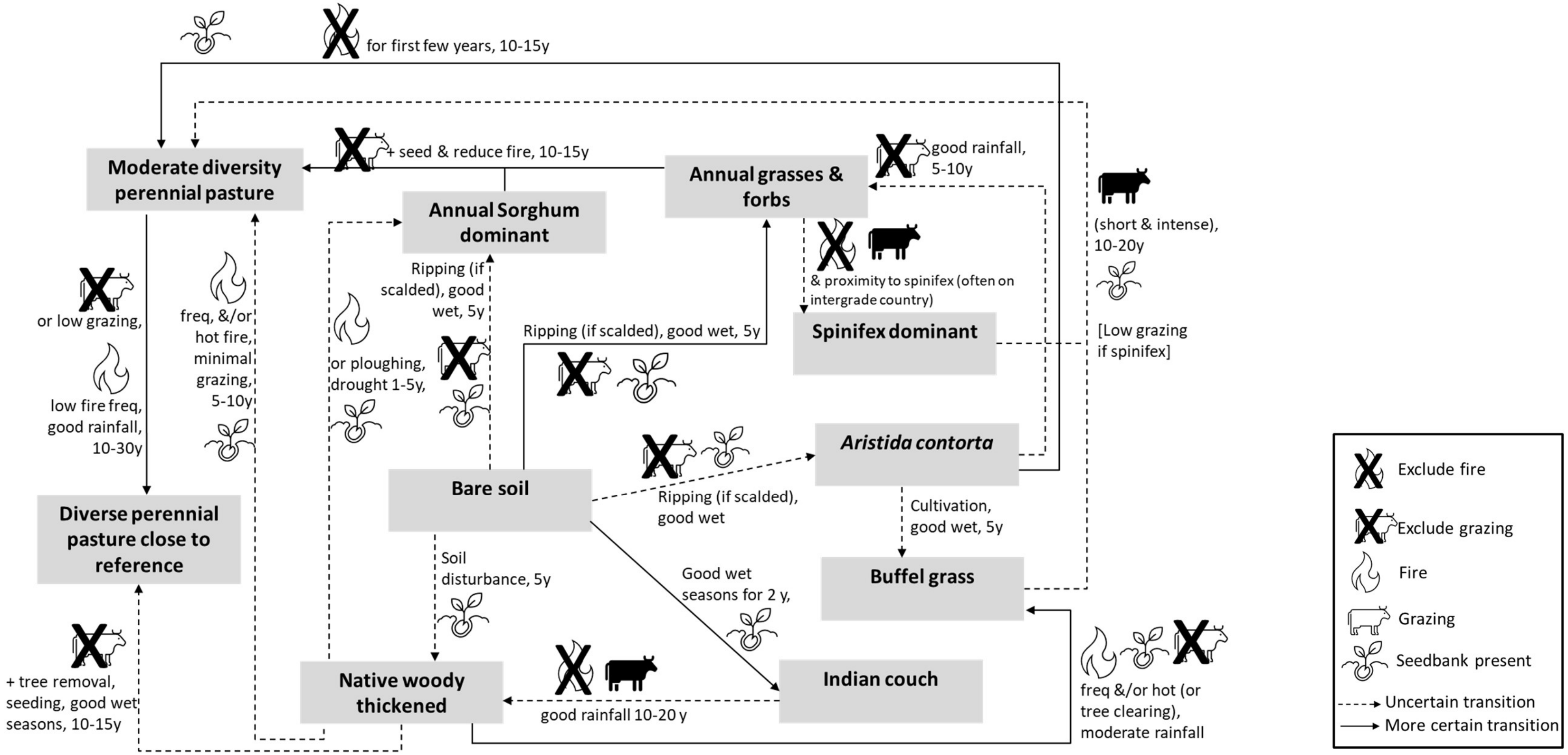


Figure 47. Drivers, uncertainty (more certain is >0.7; uncertain is <0.7, see Table 8) and timeframes for desirable transitions between ecosystem states in the Wet-dry tropical eucalypt woodlands (red soil) ecosystem type.

5.1.3 Transition details

Table 8. Detailed transition descriptions for the Wet-dry tropical eucalypt woodland (red soil) state and transition model. Question marks occur where details are unknown.

From state	To state	Driver	Pre-conditions	Time frame	Conditional probability (Likelihood)
Annual grasses & forbs	*Aristida contorta* dominated	Heavy continuous grazing or extended drought	-	5 y	0.7-0.8
Annual grasses & forbs	Bare soil	Heavy continuous grazing or extended drought and/or altered surface hydrology from erosion	-	5-10 y	0.6
Annual grasses & forbs	Moderate diversity perennial pasture	Remove grazing and reduce fire risk, re-seed	-	10-15 y	0.7-0.8
Annual grasses & forbs	Spinifex	Lack of fire, grazing	Occurs on intergrade country between savanna and hummock grasslands, must have spinifex nearby	?	?
Annual sorghum dominant	Annual grasses & forbs	Grazing and extended drought or hot fire	High fuel loads, below average rainfall	3-4 y	0.6-0.7
Annual sorghum dominant	Bare soil	Heavy grazing	-	?	0.7-0.8
Annual sorghum dominant	Moderate diversity perennial pasture	Remove grazing and reduce fire risk, re-seed	-	10-15 y	0.7-0.8
***Aristida contorta* dominant**	Annual grasses & forbs	Exclude grazing	Average to above average wet seasons	5-10 y	0.6-0.7
Aristida contorta	Bare soil	Heavy/continuous grazing with or without extended drought	-	5-10 y	0.6
Aristida contorta	Buffel grass	Spreading and/or planting buffel grass propagules	Average to above average wet seasons	5 y	0.6-0.7
Aristida contorta	Moderate diversity perennial pasture	Remove grazing and reduce fire risk for first few years post-removal of grazing. If soil is sealed and/or shallow assume undertake ripping/ mechanical disturbance. May also be achieved through low intensity grazing (e.g. wet season spelling and carrying	Seedbank/ seed source of perennial grasses present, good wet season rains (at least half of timeframe is good years, 2 to 5y first up of good rain then spread out). Good wet season rainfall early on most important if grazing continues.	10-15 y (assuming mechanical disturbance if soil sealed); 20 y (sealed soil and no mechanical treatment applied)	0.7-0.8 (assuming mechanical disturbance if soil sealed); 0.6 (sealed soil and no mechanical treatment applied)

From state	To state	Driver	Pre-conditions	Time frame	Conditional probability (Likelihood)
		capacity matched to stocking rate)			
Bare soil	Annual grasses & forbs	Exclude grazing and rip soil if scalded	Seedbank/ seed source present, good wet season rains	5 y (no scalding), 5 y+ (scalded with mechanical ripping)	0.6-0.8
Bare soil	Annual sorghum dominant	Exclude grazing and rip soil if scalded	Seedbank/ seed source present, good wet season rains	1-5 y	0.5
Bare soil	*Aristida contorta*	Exclude grazing and rip soil if scalded	Seedbank/ seed source present, good wet season rains	1-5 y	< 0.5
Bare soil	Indian couch	-	Good wet seasons and seed source present	2 y	0.8-1
Bare soil	Native woody thickened	Soil disturbance	Seedbank/ seed source present	5 y	< 0.1
Buffel grass	*Aristida contorta*	Heavy and continuous grazing	-	5-10 y	0.5-0.6
Buffel grass	Moderate diversity perennial pasture	Short periods of intense grazing	Seed source/ seedbank present	10-20 y	0.6-0.7
Buffel grass	Annual grasses & forbs	Grazing and fire	-	5-10 y	0.5-0.6
Buffel grass	Bare soil	Heavy and continuous grazing with or without fire or drought	-	5-20 y	0.5-0.6
Indian couch	Native woody thickened	Woody species become established with grazing and lack of fire	Good rainfall	10-20 y	0.6
Moderate diversity perennial pasture	Annual grasses & forbs	Heavy grazing with or without extended drought, repeated fires or mechanical clearing	-	5-7 y	0.8
Moderate diversity perennial pasture	Annual sorghum dominant	Frequent fire	-	?	?
Moderate diversity perennial pasture	*Aristida contorta*	Heavy grazing with or without extended drought,	-	5-7 y	0.8

From state	To state	Driver	Pre-conditions	Time frame	Conditional probability (Likelihood)
		repeated fires or mechanical clearing			
Moderate diversity perennial pasture	Bare soil	Heavy grazing with or without extended drought and repeated fires; or Mechanical clearing	-	5 y (heavy grazing) 10 y (fires and drought only) 1 y (mechanical clearing)	Heavy grazing: 0.6 Extended drought: 0.2 Repeated fires: 0.2 Clearing 1.0
Moderate diversity perennial pasture	Buffel grass	Heavy grazing near road sides and yards (actively disturbed areas) and buffel grass seed dispersed in or cultivated	-	10 y	0.5
Moderate diversity perennial pasture	Native woody thickened	Lack of fire, grazing and climate change impacts (altered rainfall, CO2)	-	5 y	0.8-0.9
Moderate diversity perennial pasture	Diverse perennial pasture close to reference	Manage total grazing pressure (cattle and native grazers) through low intensity appropriate grazing management or exclude grazing, low fire frequency (cool fires, ~ 5 yearly). If *Heteropogon contortus* is present may need a number of drier seasons before adding fire.	Good seasons (at least half of timeframe is good years, 5y first up of good rain then spread out), seedbank of perennials present. Single fire may be all that is required if preceding season is dry (if wetter season then may need to repeat fire).	10-30 y	0.7-0.9 (note if *Heteropogon contortus* dominates then 0.6)
Native woody thickened	Annual sorghum dominant	Remove trees via hot repeated fire or ploughing	Seed source present, dry years (drought)	1-5 y	0.5
Native woody thickened	Bare soil	Mechanical thinning or herbicide and grazing; Fire?		1 y	0.8-1
Native woody thickened	Buffel grass	Remove trees via clearing or hot and repeated fire, exclude grazing and cultivate with buffel grass seed	Moderate rainfall	1 y	0.9
Native woody thickened	Moderate basal perennial pasture	Remove trees via clearing or hot and repeated fire, reduced grazing	Seedbank/ seed source present	5-10 y	0.6

From state	To state	Driver	Pre-conditions	Time frame	Conditional probability (Likelihood)
Native woody thickened	Diverse perennial pasture close to reference	Exclude grazing, tree removal and re-seeding	Good wet seasons	10-15 y	0.5
Diverse perennial pasture close to reference	Bare soil	Heavy grazing with or without extended drought and repeated fires; or Mechanical clearing	-	5-10 y (heavy grazing) 20-25 y (fires and drought only) 1 y (mechanical clearing)	Heavy grazing: 0.6 Extended drought: 0.2 Repeated fires: 0.2 Clearing 1.0
Diverse perennial pasture close to reference	Buffel grass	Heavy grazing near roadsides and yards (actively disturbed areas) and buffel grass seed dispersed in or cultivated	-	5-20 y	0.5
Diverse perennial pasture close to reference	Moderate diversity perennial pasture	Grazing continuous and drought or frequent fire	-	5 y	0.8-0.9
Diverse perennial pasture close to reference	Native woody thickened	Lack of fire, grazing and climate change impacts (altered rainfall, CO_2)	-	5 y	?
Spinifex	Moderate diversity perennial pasture	Low grazing rates	Seed source/ seedbank present	?	?

5.2 Pulse-rainfall driven arid and semi-arid tussock grasslands 'black soil' state and transition model

5.2.1 Undesirable transitions

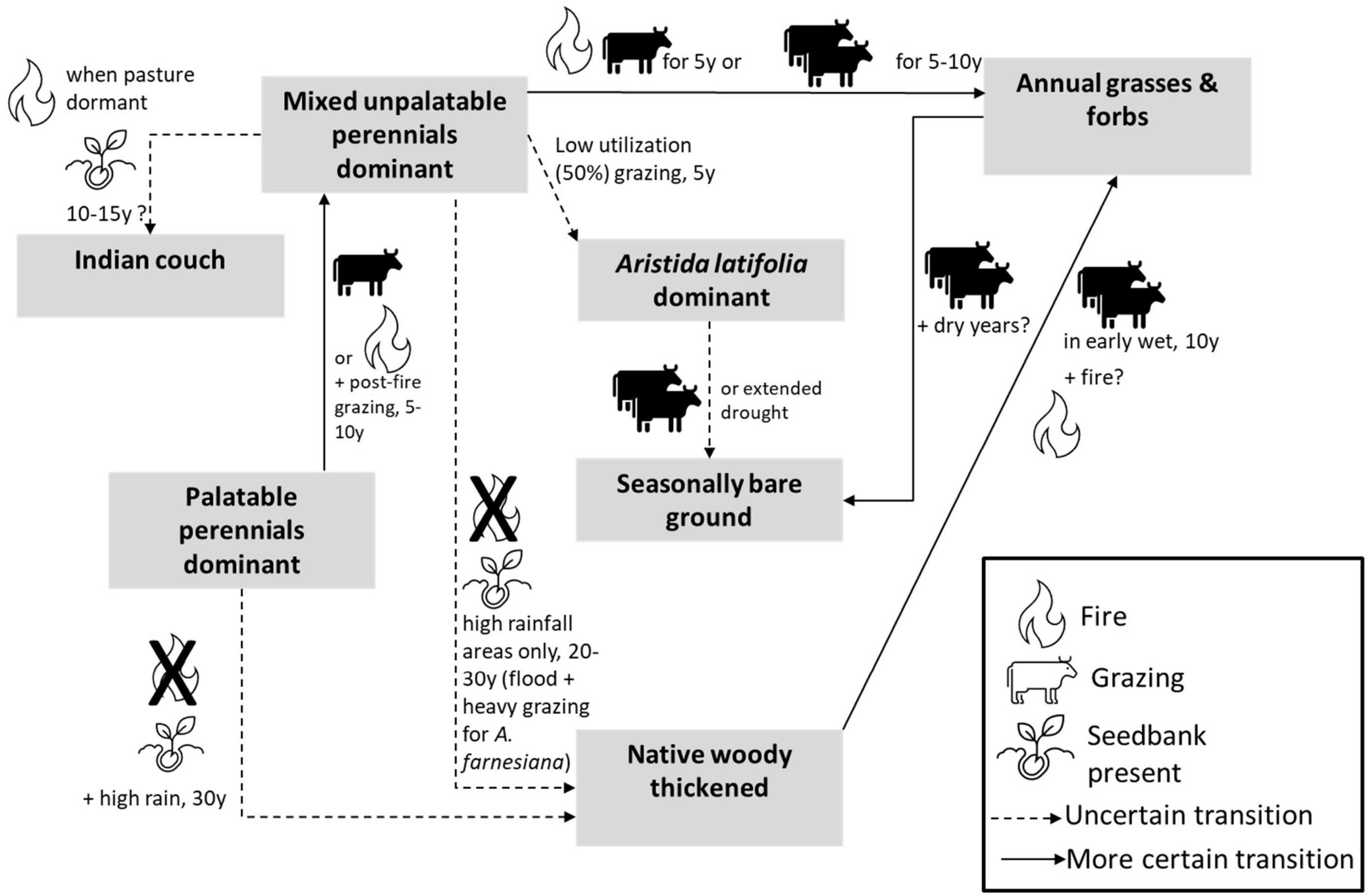


Figure 48. Drivers, uncertainty (more certain is >0.7; uncertain is <0.7, see Table 9) and timeframes for undesirable transitions between ecosystem states in the Pulse-rainfall driven arid and semi-arid tussock grasslands (black soil) ecosystem type.

5.2.2 Desirable transitions

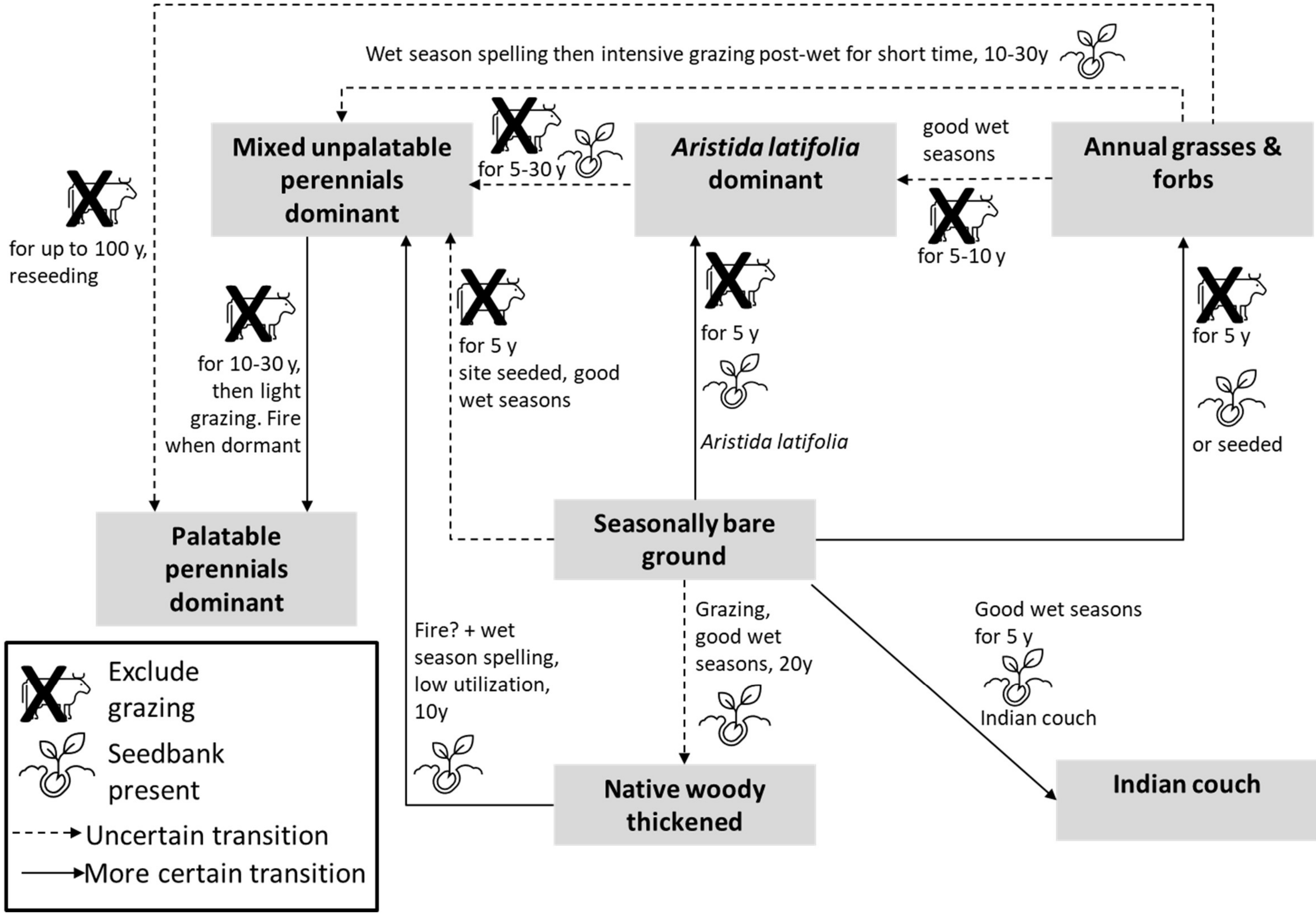


Figure 49. Drivers, uncertainty (more certain is >0.7; uncertain is <0.7, see Table 9) and timeframes for desirable transitions between ecosystem states in the Pulse-rainfall driven arid and semi-arid tussock grasslands (black soil) ecosystem type.

5.2.3 Transition details

Table 9. Detailed transition descriptions for the Rainfall-pulse driven arid and semi-arid tussock grasslands (black soil) state and transition model. Question marks occur where details are unknown.

From state	To state	Driver	Pre-condition	Time frame	Conditional probability (Likelihood)
Annual grasses and forbs	*Aristida latifolia* dominant	Exclude grazing	Good wet seasons	?	?
Annual grasses and forbs	Palatable perennials dominant	Grazing exclosure & re-seeding		100 y	very unlikely
Annual grasses and forbs	Mixed unpalatable perennials dominant	Wet season spelling, large number of cattle for short period (post wet)	Seed source present	10-30 y	0.1
Annual grasses and forbs	Seasonally bare ground	High utilization grazing	Dry years	?	?
***Aristida latifolia* dominant**	Mixed unpalatable perennials dominant	Exclude grazing or low intensity grazing (at an annual scale) with best practice management (i.e. match grazing pressure to long-term carrying capacity), hot fire (every 3-5 y initially, assuming sufficient fuel)	Below-average rainfall of at least 2 consecutive years followed by good wet seasons. Seed source of preferred perennials present	5-30 y	0.7-0.8 (if insufficient good wet seasons e.g. half the timeframe is good years, then probability is 0.5)
Palatable perennials dominant	Mixed unpalatable perennials dominant	30-50% utilisation grazing or fire with post-fire grazing	-	5-10 y	0.7
Palatable perennials dominant	Native woody thickened	No fire	Good wet seasons; Seedbank present	30 y	0.5
Mixed unpalatable perennials dominant	Annual grasses and forbs	High utilisation (80%), continuous grazing	-	5-10 y	1
Mixed unpalatable perennials dominant	Annual grasses and forbs	Fire and grazing	-	5 y	1
Mixed unpalatable perennials dominant	*Aristida latifolia* dominant	Low utilisation grazing (50%)	-	5 y	0.7
Mixed unpalatable perennials dominant	Palatable perennials dominant	Exclosure or exclude grazing (including all grazing for 2 years), can have light stocking (10% utilisation) after 2 years following best practice grazing management (e.g. wet season spelling)	At least 2 to 5 big wet seasons to stimulate recruitment and assuming seed source of desirable perennials available. Fire when pasture dormant at low frequency (after good wet seasons)	10-30 y	0.6-0.8
Mixed unpalatable perennials dominant	Indian couch	Low frequency fire when pasture dormant	grows on black soil; seedbank present	10-15 y	0.8

From state	To state	Driver	Pre-condition	Time frame	Conditional probability (Likelihood)
Mixed unpalatable perennials dominant	Native woody thickened	No fire, conservative grazing (or flooding and moderate to heavy grazing for *Vachellia farnesiana* only)	Seedbank present; occurs in high rainfall areas only; good rainfall & in soils with slightly lower clay content	20-30 y (For *V. farnesiana* only: 5 y)	0.5-0.75
Native woody thickened	Annual grasses and forbs	Early wet season, heavy grazing and fire?		10 y	>0.8
Native woody thickened	Mixed unpalatable perennials dominant	Fire? and wet season spelling, with low utilisation: < 5 cu km^2	Seedbank of perennial grasses present	10 y	>0.8
Seasonally bare ground	Annual grasses and forbs	Grazing exclusion and/or re-seeding	Seed bank present (or re-seeded), good wet season rains	5 y	1
Seasonally bare ground	*Aristida latifolia* dominant	Grazing exclusion	High Aristida latifolia seedbank present, good wet season rains	5 y	1
Seasonally bare ground	Indian couch	-	Seedbank present; grows on black soil, good wet season rains, occurs in wetter regions only	5 y	1
Seasonally bare ground	Mixed unpalatable perennials dominant	Grazing exclusion and re-seeding	Good wet season rains	5 y	0.7
Seasonally bare ground	Native woody thickened	Grazing	Tree seedbank present, good wet season rains	20 y	0.5

6 Next steps

This section provides detail around the next steps needed to apply the information in the S&TMs developed in the project to the management of tussock grasslands and woodlands of the Kimberley. Next steps include methods to map the spatial location of ecosystem states, options to convert the S&TM information to decision trees, and a synthesis of remaining knowledge gaps.

6.1 Mapping the spatial extent of ecosystem states

Classification and mapping of ecosystem states through on ground monitoring, observation, and measurement of soil and vegetation metrics at small to moderate site scales is a relatively straight forward process. However, this approach becomes untenable, in terms of both time and expense when moving to mapping spatial extents of these metrics at regional scales.

Remote sensing can often provide a link between small scale observations and the larger landscape. Currently there are several freely available satellite sources (primarily MODIS 250m, Landsat 30m and Sentinel-2 10m) that are used for landcover classification and detection of structure, pattens and function of landscapes using band ratios (e.g. Normalised differential vegetation index (NDVI), simple algorithms, and more complex machine learning techniques (Table 10). The temporal range of this imagery (particularly Landsat at >30y) can be used to detect changes occurring over time at the landscape scale which may be linked to smaller scale on-ground measurements such as effects on biodiversity and landscape condition. The freely available earth observation satellites described above are of spectrally low resolution, so it is not possible to identify species accurately and therefore there is a reliance on ground data validation. Detection at the species level requires additional hyperspectral imagery, which can be expensive, and the development of species level spectral datasets for correct classification.

Table 10. Summary of satellite products useful for the detection and classification of ecosystem states

Sensor	Spatial resolution (pixel size)	Spectral resolution	Temporal resolution	Swath size	Suitability	Derived condition related products
MODIS	250 m-1 km	36 spectral bands between 0.405 and 14.385 µm – first 7 bands useful for land	Every 16 days from the year 2000	2330 km	Land cover types at global or national scales	- USGS land products - NDVI and EVI - CSIRO fractional cover dataset - Land Condition Index algorithm - CSIRO Habitat Condition Assessment System (HCAS) - Burnt Area and Approximate Day of Burn

		cover and condition				
LANDSAT TM & ETM	30 m	7 spectral bands	Every 16 days from the year 1982	183 km	Regional scale to national mapping, vegetation communities and cover – some dominant species	- Vegetation health indices NDVI, EVI - JRSRP fractional persistent green and ground cover (seasonal and monthly blended with Sentinel from years 2015 onwards, not available in WA) - DEA fractional cover (monthly) - Dynamic reference cover method - Compere method - ANU – Wald fractional woody cover
SENTINEL-2	10-60 m	13 spectral bands	Every 5 days from the year 2016	290 km	Regional scale to national mapping, vegetation communities and cover – some dominant species – provides continuity of LANDSAT type image data	-Vegetation health indices - All methods or products produced with LANDSAT can likely be used with SENTINEL-2

* MODIS, LANDSAT and SENTINEL-2 pre-processed (atmospherically corrected) imagery are available for free from several servers globally, in Australasia Geosciences Australia - https://cmi.ga.gov.au/data-products/dea - and the National computational infrastructure server - https://dapds00.nci.org.au/thredds/catalog.html - contain most available datasets. Most analysis derived datasets can be found on these servers also with further land cover related datasets available on TERN - https://portal.tern.org.au/ - or CSIRO data portals - https://data.csiro.au/.

Currently remote sensing of condition states in Australia is centred around the use of fractional cover indices which have been found to be effective in describing some condition states in grazing lands (Beutel et al. 2021) by detecting temporal vegetation cover changes over time. Some advances are being made by including further layers to augment cover imagery, for example the Habitat Condition Assessment System for Australia (HCAS) (Harwood et al. 2016, Williams et al. 2021), now in version 2, uses additional climate, vegetation and topographical layers within the model to improve accuracy. Apart from detecting landscape condition states, fractional cover can also be useful in looking at degradation or improvement of ecological condition due to management over time. Bastin et al. (2012) presented a dynamic cover-reference method for tracking management over time using fractional cover with removal of rainfall effects. This method has recently been improved upon by the Donohue et al. (2022) COMPERE method with the inclusion of land use, tree cover and topographic layers to define and compare alike management areas. Lastly, a promising approach using 'vegetation indices' derived from Landsat correlated with on-ground measurements of pasture condition in the Kimberley region has been investigated by Ramzi and Holmes (2021). While the method couldn't distinguish all pasture condition categories, and was a point in time analysis, it provides a prospective way forward for spatially mapping ecosystem states.

The WARMS data, being temporally coincident with existing imagery, provides a good opportunity to investigate changes over time on-ground whilst providing linkages to, and validation of, any remote sensing that may be used to predict and map ecosystem states on larger scales.

Conceptual next steps to map ecosystem states spatially include:

- Analysis of WARMS data for identification of historical and current ecosystem states via:
  – temporal data analysis for locating state transition periods or other states within the time period (1990 onwards)
  – test for relationships between identified transitions and change in vegetation cover or other attributes (see method described in Ramzi and Holmes (2021)).
- Stratify the landscapes into areas with similar abiotic characteristics with existing spatial layers using CSIRO-BIOCLIM (including rainfall) (Harwood 2019), vegetation type and woody cover, topographic and soil type data. Additionally, stratify by perennial and annual grass landscapes using changes in fractional green/brown ratios or seasonal timing of green persistence and cover variability in the ground layer.
- Examine compiled ecosystem states from WARMS data analysis for relationships (within areas with similar abiotic characteristics) against existing remote sensing bands, ratios, and models (e.g. NDVI or EVI (enhanced vegetation index), HCAS, fractional cover) using correlation, multiple regression and/or machine learning.
- Apply relationships, assuming they exist, and check for accuracy and error.

6.2 How state and transition models might guide monitoring and evaluation of rangeland condition

In the previous section an approach was outlined for mapping the spatial location of ecosystem states across the Kimberley using satellite and on-ground measurement validation. In this section we provide an example of the application of S&TMs to guide management interventions.

Figure 50 reproduces an example from Good et al. (2021a), where information from a S&TM for eucalypt woodlands of southern Australia (Good et al. 2021b) was used to describe step-by-step management actions for recovery of degraded ecosystem states. In addition to recovery actions, Good et al. (2021a) outline actions required to maintain an area of eucalypt woodland in a particular desirable state (for example, maintaining herbivore and weed management). These practical guidelines are suitable for translation of S&TM information to a tool that is useful for land managers. They can also be used to inform adaptive management, where information on the drivers of transitions is uncertain (based on elicited likelihoods from experts- see section 5). Here, assessment points could be identified in the decision tree, where indicators of transition trajectories could be assessed and, if not met, additional or alternative actions implemented. An example of a draft decision tree for actions needed to drive a transition from the '*Aristida contorta*' state to the 'moderate diversity perennial pasture' state in Wet-dry tropical eucalypt woodlands (red soil) ecosystems is shown in Figure 51. In this decision tree, actions implemented will depend on whether the soil is sealed or not, followed by management of grazing intensity and fire frequency.

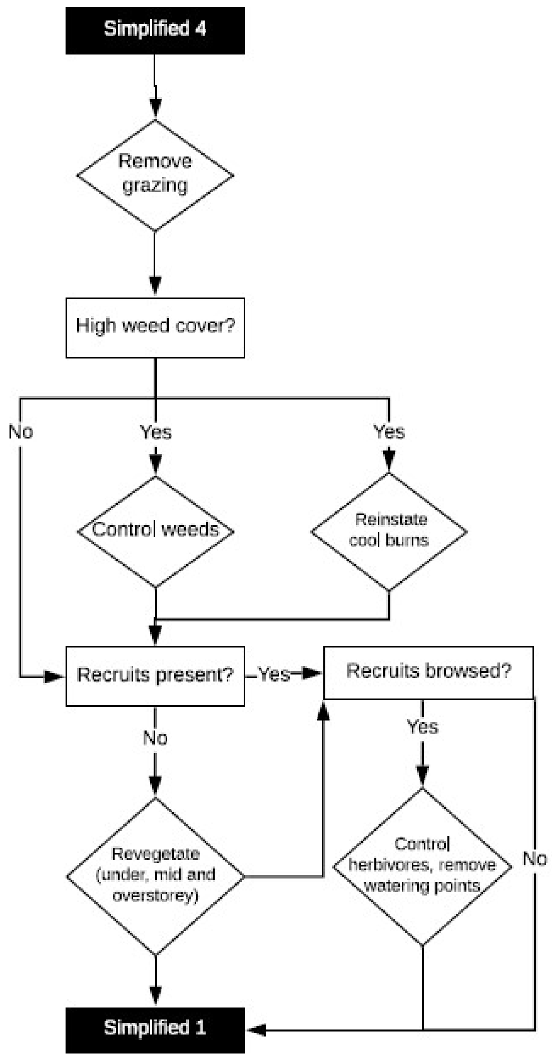


Figure 50. Example of a decision tree for management guidance reproduced from Good et al. (2021a).

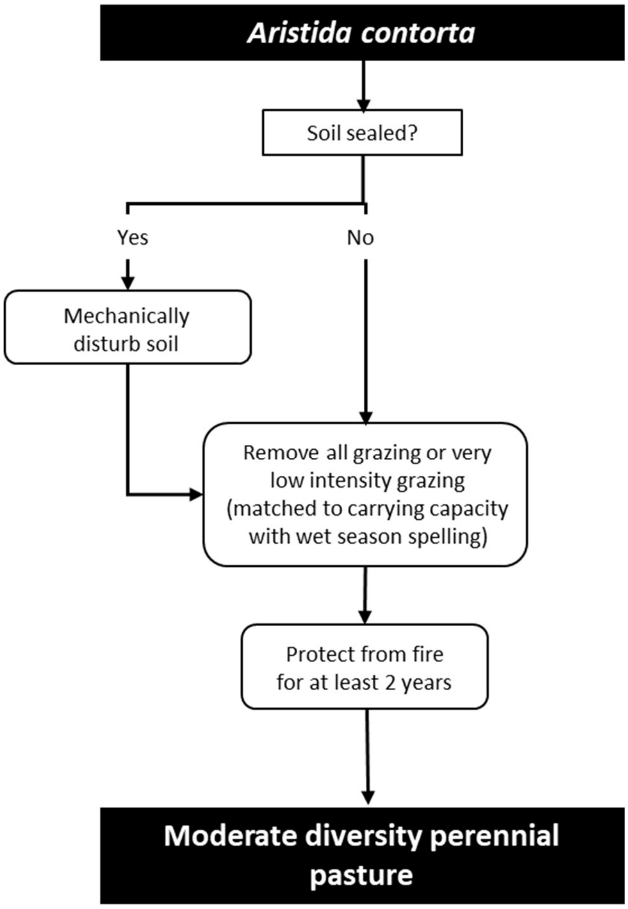


Figure 51. Example of management actions required to enact a transition from '*Aristida contorta*' to the 'moderate diversity perennial pasture' ecosystem state in the Wet-dry tropical eucalypt woodlands (red soil) ecosystem type.

6.3 Knowledge gaps, lessons learned and conclusions

Lessons learned from the process of developing S&TMs for tussock grasslands and woodlands of the Kimberley include:

1. *How to include grazing management effects in conjunction with variability between expressions driven by endogenous disturbances.* This required specification of general grazing management principles for each state that interact with expression change e.g. during drought years grazing is minimized or pasture is spelled when a state is in a low cover expression. If grazing management for a particular state is not applied as specified, then a transition is likely.

2. *Linking pasture types and condition to different ecosystem states.* In most cases multiple pasture types were represented by a single state (but their condition scores tended to vary across states). To explain this, we had to be explicit about environmental gradients within a state that cause variation in dominant grass species (and hence pasture type) across the landscape.

3. *Grouping pasture types into two broad ecosystem types (black soils and red soils) was useful for organising information that related to high level disturbance drivers.*

Several knowledge gaps in the S&TMs remain and these could inform the next steps needed to operationalise the models. They include:

- Uncertainty about the likelihood of certain recovery transitions (those from undesirable to desirable states) occurring. This was particularly the case for those transitions that required revegetation because sourcing native grass seed in sufficient quantities would be challenging. However, evidence from the Ord River regeneration project (Payne et al. 2004) suggests that recovery may be possible. Further monitoring of different intervention actions for improving pasture condition (and driving transitions between ecosystem states) is needed to improve understanding of the likelihood of recovery under different circumstances. This could occur through experimental testing of management interventions, further analysis of WARMS data and/or by finding pastoralists who already champion best practice and undertaking post-hoc assessment of change using historical remote sensing data from these leases.
- Two novel states were described in the S&TMs: 'Indian couch' (red soils) and 'Indian couch' (black soils), however, further novel states are likely to occur in the future and a challenge remains in articulating these states. This is particularly needed if the information in S&TMs is used for predicting future landscape change in the Kimberley under different climate and land management scenarios.
- As identified in section 6.1, detection of some ecosystem states might require identification of grass species, which isn't currently possible with existing remote sensing technologies, although suggestions were given on how this might be done.
- There are several ways different ecosystem states can be characterised, including in terms of condition (ecological integrity) and pasture condition (capacity to support livestock grazing). Other values that could be ascribed to ecosystem states in the future might be the potential for carbon storage and sequestration and persistence of biological groups or threatened species. Adding these additional values to the S&TM could be achieved through habitat-based biodiversity assessment tools (Mokany et al. 2022) and the Full Carbon Accounting Model (FullCAM) (Richards and Evans 2004).
- During the workshops and team discussions a knowledge gap was identified around understanding of spinifex dynamics within tussock grasslands which abut hard spinifex pastures in more arid regions of the Kimberley. A 'spinifex dominant' state was included in the model, but there was substantial uncertainty around the drivers of this state.
- For the 'Indian couch' state on red and black soils, and the 'buffel grass' state, nutrient run-down was highlighted as a potential driver of change in these states, possibly leading to a future transition to a new state that may only support a low biomass and basal area of these introduced grass species. There is substantial uncertainty about whether the nutrient run-down effect could drive this transition.

In conclusion, the development of S&TMs for tussock grasslands and woodlands of the Kimberley has provided a framework for organising information about ecosystem dynamics across the region that can speak to existing classifications of pasture type and condition. It has provided a basis for interpretation of landscape change and classification into two types of change (1) change driven by a transition between ecosystem states that impacts on values that flow from the landscape (e.g. cattle production and ecological integrity), versus (2) natural variability in landscapes driven by endogenous disturbances (fire, drought, and flood). The models provide a structured way to assess pasture condition, especially

where dominant grass species that define pasture types may be rare or absent and provide guidance for management actions that might be implemented to reverse undesirable changes. Lastly, the process of guiding and engaging experts and articulating the model structure is easily transferable to other regions of the rangelands, providing a unique method for capturing and synthesising deep, experiential knowledge of land management that could otherwise be lost in the future.

Several knowledge gaps remain, and next steps should focus on better defining the key characteristics of the ecosystem states and mapping the spatial location of ecosystem states (section 6.1) using the extensive WARMS dataset as a guide for articulating the threshold values for ecosystem states (see examples provided in section 4.3.11 and section 4.4.8). Additional suggestions around shaping the S&TMs into decision trees and making these publicly available for informing practical land management, monitoring and evaluation have also been described (section 6.2). Lastly, for many of the management actions identified to reverse undesirable transitions and improve pasture condition, there is limited or no on-ground evidence of their effectiveness. An important validation of the S&TMs described here would be testing of these uncertain transitions with experimental on-ground interventions.

Appendix A State and transition modelling workshop agenda

Workshop agenda: State & Transition Models for tussock grasslands and woodlands of the Kimberley

Date: 18th & 19th May 2022

Location: Aloft Perth Hotel, 27 Rowe Avenue, The Springs, Riverdale, Perth

Organisers: Anna Richards (CSIRO, facilitator), Suzanne Prober (CSIRO, facilitator), Brett Abbott (CSIRO, facilitator), Matthew Fletcher (DPIRD, facilitator), Kath Ryan (DPIRD, facilitator), Chris Hetherington (DPIRD, facilitator), Jodie Hayward (CSIRO, logistics support), Anita Dean (DPIRD, logistics support)

Objectives:

1. identify common ecosystem states associated with red and black soil pasture types in the Kimberley region,
2. determine drivers (e.g. fire, grazing) of transitions between ecosystem states,
3. quantify characteristics and their variability (e.g. dominant species, ground cover etc.) associated with each state.

DAY 1: Wednesday 18th MAY 2022

Time (WST)	Item	Facilitated by
8:30 am	Tea and coffee	
8:45 am	**Acknowledgement of Country, general introductions, housekeeping & workshop objectives**	Anna Richards
9:15 am	**Introduction to the project: problem context**	Rick Fletcher (DPIRD)
9:30 am	**Pasture types of the Kimberley and the WARMS project explainer video**	Matthew Fletcher, Kath Ryan & Chris Hetherington
10:00 am	Short stretch break	
10:05 am	**The Australian ecosystem models framework and State and Transition models** • Capturing reference and modified ecosystem states • What is in and what is out • Reference model templates for tussock grasslands and savanna woodlands *Plenary discussion* – Where might state and transition models be useful and what other information might be needed to address the problem? Are there systems or disturbances missing? Are the connections with different pasture types clear or are some missing?	Anna Richards & Suzanne Prober
10:45 am	Morning tea	
11:15 am	**Review reference models** Introduce exercise *Small group session* ('Red soil' & 'Black soil' groups) • Critique reference disturbance dynamics and expressions • Quantify reference ecosystem attributes • Quantify disturbance regimes *Report back at 12:00 pm*	CSIRO & DPIRD facilitators, Workshop participants
12:10 pm	**Introduction to the WARMS dataset**	Karyn Reeves & Matthew Fletcher
12:30 pm	Lunch	

1:30 pm	**Video 1 & 2:** *Transitioning pastures & Introduction to frontage grass pastures*	Chris Hetherington
1:40 pm	**Developing state and transition models** *(group discussion)* 1. List of common threatening processes and management actions in the Kimberley 2. Introduction to state & transition model templates, and straw-person states 3. Qualitative list of major Kimberley tussock grassland states	Anna Richards, Matthew Fletcher & Brett Abbott
2:25 pm	**Video 3:** *Is it Mitchell grass or Blue grass pasture?*	Chris Hetherington
2:30 pm	**State and transition model – state descriptions** *Small group session* Complete attribute tables for each state in small groups	CSIRO & DPIRD facilitators & Workshop participants
3:20 pm	Afternoon tea	
3:40 pm	**State and transition model – state descriptions** *Group work cont'd:* report back at end of session, 4:40 pm	Workshop participants
4:50 pm	**Video 4:** *Ribbon grass or Arid Short grass pasture?*	Chris Hetherington
5:00 pm	**Wrap-up of Day 1**	Anna Richards
6:30 pm	Workshop Dinner (The Empire Bar)	

DAY 2: Thursday 19th MAY 2022

Time (WST)	Item	Facilitated by
8:30 am	Tea and coffee	
8:45 am	**Re-cap of previous day and introduction to day 2**	Anna Richards
8:50 am	**Video 5:** *Drivers of change: fire, buffel grass*	Chris Hetherington
8:55 am	**State and transition model – state descriptions** *Group work cont'd from Day 1:* report back at end of session	Workshop participants
9:55 am	**State descriptions – plenary session** *(group discussion)* Collation of state descriptions developed on previous day and first thing, and their refinement with the whole group, including: • Review of state descriptions • Identify key indicators of each state • Note knowledge gaps and how to fill these	Anna Richards, Brett Abbott & Matt Fletcher
10:20 am	**Video 6:** *Drivers of change: the exclosure effect*	Chris Hetherington
10:30 am	Morning tea	
11:00 am	**State descriptions – plenary session** *Review and feedback on state descriptions continued*	Workshop participants
11:30 am	**Transition descriptions** *Plenary session* - Introduction to transition exercise, then outline plausible transitions as a group *Group work:* • Separate into state groups and develop transition descriptions for plausible transitions • include drivers, timeframes, probabilities and conditions for transitions to occur	Anna Richards & Suzanne Prober
12:30 pm	Lunch	
1:30 pm	**Transition descriptions** *Group work continued*	Workshop participants
3:30 pm	Afternoon tea	
3:50 pm	**Transition descriptions** *Group work continued*	Workshop participants

4:15 pm	**Transition descriptions** Report back to whole group on transitions, knowledge gaps and summarise uncertainty and probability	Workshop participants
4:30 pm	**Wrap up, next steps & workshop evaluation**	Anna Richards
4:45 pm	**Finish**	

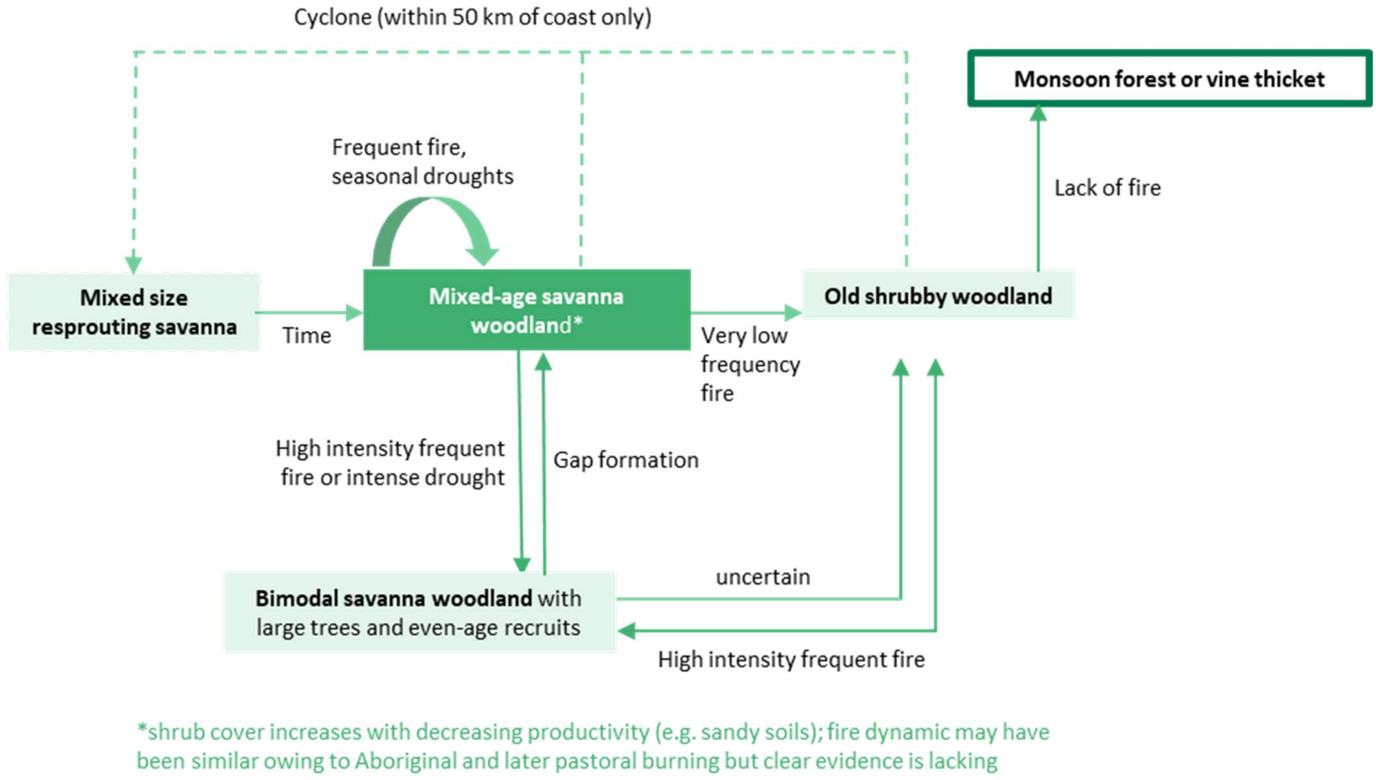
Appendix B Wet-dry tropical eucalypt woodlands archetype

Most *Wet-dry tropical eucalypt woodlands* comprise mixed-age tree stands dominated by various eucalypts (*Eucalyptus* spp. and *Corymbia* spp.) over a grassy understorey. These woodlands can grade into open and tall open eucalypt forests in areas of high, but still strongly seasonal rainfall, and the use of the term 'woodlands' here encompasses these taller wet-dry tropical eucalypt forests.

The tropical eucalypt species in these woodlands are highly tolerant of the frequent, relatively low intensity of fires that dominate the wet-dry tropical landscapes, including Indigenous fire management that has been practised for millennia. If top-killed, these species generally resprout from their lignotuberous bases or root suckers (Williams et al. 1999). Other associated tropical genera contribute many midstorey species and co-dominants. They may be less fire-tolerant, but are also generally strong resprouters.

Many of these ecosystems are called savannas in Australian literature. In savannas elsewhere on the globe, fire can cause a bottleneck limiting tree recruitment into the canopy, but in these Australian ecosystems, eucalypts are much less affected by the fire-induced bottleneck.

These woodlands do not release seeds after fire but typically have a large bank of lignotuberous resprouts. Recruitment of these resprouts into the canopy is slow, but continuous at a landscape scale so that most of these woodlands have mixed-age stand structures (Cook et al. 2016).



Ecosystem dynamics

Two main disturbance processes drive the ecosystem dynamics of the Wet-dry tropical eucalypt woodlands. These are frequent (typically several per decade), relatively low intensity fires (usually < 15 MW m-1) and both seasonal (late dry season) and major multi-year droughts with return periods of many decades (Murphy et al. 2015). Seasonal drought is a major factor that sets the carrying capacity of a landscape for trees, as evidenced by observations of juvenile tree death in the late dry season and the decline in the total basal area with decreasing rainfall.

In these ecosystems tropical C4 (warm season) grasses and forbs thrive on frequent fires of intervals < 5 years, as long as those fires are not implemented in the driest months (August to November) where they can be damaging to grass tussocks. Having regular fires every two to five years, especially during times when there is higher soil moisture, promotes a patchily burnt landscape with a mosaic of patches of different ages.

Mixed-age tropical woodland

Mixed-age *Eucalyptus miniata* (Darwin woollybutt) woodland. Litchfield NP, NT. (Image: S. Prober)

The most familiar expression of *Wet-dry tropical eucalypt woodlands* is *Mixed-age tropical woodland*. This is characterised by mixed-age eucalypt stands over a grassy understorey. This expression is maintained by frequent, relatively low intensity fires as described above. Decreases or increases in fire intensity or cyclones (within 50 km of the coast) can drive this towards a range of other expressions described in the model.

Bimodal woodland with large trees and even-age recruits

Modelling and observational studies indicate that in some circumstances fire regimes can lead to ecosystems dominated by larger trees, with relatively few small to intermediate trees (Cook et al. 2015). Large-scale disturbances such as regional droughts and hot fires can subsequently lead to pulsed recruitment and the development of stands with a bimodal size class distribution. Such ecosystems would be unstable, with the death of older trees creating gaps that could be colonised by juveniles, leading to the redevelopment of mixed-age stands.

Bimodal woodland with a young and an old age class evident. East Arnhem land, NT. (Image: G. Cook)

Large overstorey trees can suppress the growth of juveniles, causing top-kill late in the dry season. Evidence of woodland thickening in savannas of north-eastern Australia – both of increasing size of existing trees and recruitment of saplings have been interpreted as a consequence of reduced use of fire associated with the advent of commercial grazing (Burrows et al. 1998, Burrows et al. 2002), but is more likely to be a response to historic droughts (Fensham and Holman 1999, Murphy et al. 2015).

Old shrubby woodland

The eucalypt-dominant tropical woodlands typically have an understorey of perennial tussock grasses or annual sorghums in high rainfall areas (Williams et al. 2017). However, there is also a wide range of shrubs which may be obligate-seeders e.g. many species of Acacia, or strong resprouters. Long periods without intense fires can lead to a transition of these shrubs into trees. Longer fire-free intervals promote shrub growth in many ecosystems, especially those with sandy soils. Under these circumstances, grass growth may be suppressed (Scott et al. 2012).

Long-unburnt shrubby woodland with shrub and liana understorey, Berrimah, NT. (Image: S.Prober)

Mixed-size resprouting woodland

Northern Australian woodlands, unlike those of most of the world's tropics, are affected by tropical cyclones and the effects of these are strongest within 50 km of the coast. Cyclonic winds cause savanna trees to be uprooted or snapped and the subsequent fires can then kill damaged trees (Hutley et al. 2013). Such disturbances lead to pulsed recruitment that can be seen in stand age structures.

Mixed-size resprouting eucalypt woodland, showing resprouting, recruiting or dead trees after cyclone then fire, Lockhart River, Qld. (Image: S. Prober)

Transition to Marine-influenced and Non-marine influenced rainforest

Eucalypt-dominant tropical woodlands are rarely observed to transition to other vegetation types. Long fire-free periods (decades to centuries) can lead to conversion to monsoon forest or vine thicket (captured in the archetype models: *Marine-influenced rainforest* and *Non-marine influenced rainforest*) and the probability of this conversion is greater in higher rainfall regions.

Experts consulted

Garry Cook, Anna Richards

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Appendix C Rainfall-pulse disturbed arid and semi-arid tussock grasslands archetype

These grasslands occur on clay rich soils:

(a) across northern Australia (> 500 mm rainfall) with summer dominant rainfall.

(b) in arid and semi-arid (< 500 mm) Australia with winter to summer dominant rainfall,

Many of these grasslands are commonly known as Mitchell grasslands after the common perennial grasses *Astrebla* spp. Other common perennial grasses include *Chrysopogon fallax* and *Heteropogon contortus*. Annual grasses such as *Iseilema* spp. *Sorghum stipoideum* and *Aristida* spp. can also be dominant. A wide range of forbs co-occur with the grasses.

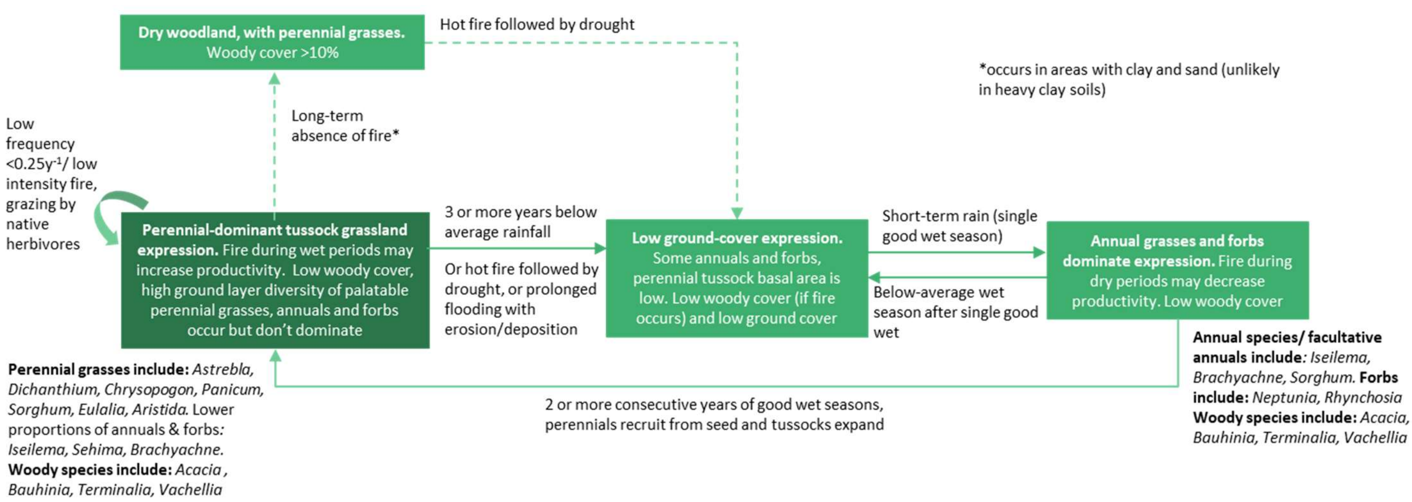
Variations in precipitation and fire drive this system's dynamics. The dominant perennial tussock grasses increase in productivity during rainfall pulses and decrease during dry periods. Fire can kill perennial grasses and, if followed by low rainfall, can lead to a greater dominance of annual species. Inter-tussock species can establish and grow in most circumstances where inter-tussock gaps remain open. In subtropical and tropical grasslands, the decomposition rates are sufficient to prevent dead grass from closing inter-tussock gaps.

In arid and semi-arid systems, tussock growth is limited by water availability, but longevity appears to be an adaptation to survive extended droughts (Morgan et al. 2017).

Recruitment of Astrebla spp. is likely to be greater if two successive wet summers occur – the first to produce a larger seedbank and the second to facilitate its germination and establishment (Orr 1991).

The driest habitats for Mitchell grasses are in the Gibber Plains with less than 200 mm mean annual rainfall. Here, tussock grasslands exist within closed depressions known as gilgai that collect run-off water and have cracking clay soils. In the gilgai, Mitchell grasses co-occur with Eragrostis spp., Chloris spp. and Rytidosperma caespitosa and other minor grasses and forbs (Wilson and Leigh 1964; Ollier 1966; Brandle 1998). On the Nullarbor Plain, run-on areas called Dongas are characterised by heavy-textured soils and C3 dominated grasslands.

Many of these grasslands abut chenopod shrublands and there may be some ecotonal dynamics between the grasses and the chenopods driven by long term variations in rainfall. Although fires in chenopod shrublands are rare or absent, they can affect the ecotones with other more fire prone ecosystems (Ladbrook 2015). Native grasses and forbs can invade and establish a grass-fire cycle leading to a replacement of the shrubland by a grassland in such areas (van Etten and Burrows 2018).



Ecotonal dynamics may also be associated with geomorphological dynamics with long-term changes in clay contents of soils, hydrology and salinity favouring or disfavouring tussock grasslands.

Analyses of emu egg shells indicates that the advent of commercial grazing in at least western NSW and arid South Australia appears to have led to a loss of C4 grasses and a relative increase in C3 chenopods (Johnson et al. 2005). For the Kati Thanda–Lake Eyre basin, this loss of grass cover was probably the result of overgrazing, drought, and a decrease in fire frequency. The finding suggests that grasses were a more common component of chenopod shrublands than has been observed over the past century. Thus, an ecotonal dynamic may have been more common in the past.

Diverse tussock grassland on cracking clay soils, Victoria River region, NT (Image: A. Richards)

Ecosystem dynamics

Arid and semi-arid grasslands dominated by annual grasses and forbs

During times of below average rainfall, perennial grasses and forbs and any woody plants may suffer greatly reduced productivity or die in extreme cases. These responses will be particularly strong in the run-off zones of the landscape. Annual grasses can take advantage of small rainfall events and reduced perennial grass cover, while winter forbs can grow if sufficient winter rains occur (Orr 1981). The growth of these annuals is more likely in run-on areas which may be in gilgai areas in arid environments and the lower part of the grassland band in banded mulga communities. In tropical grasslands of northern Australia, the annual genus *Iseilema* may replace perennials such as *Astrebla* and *Chrysopogon*. A return to higher rainfall will lead to high productivity of the *Iseilema*, but also the gradual expansion of perennial grasses that will eventually outcompete annual grasses.

Arid and semi-arid grasslands dominated by perennial tussock grasses and forbs

Perennial grasses typically recruit during pulses associated with very wet years. These systems often occur on floodouts which accentuate the wet pulses (Morton, Stafford Smith et al. 2011). Summer rainfall will support the recruitment of C4 grasses. The dominant grasses in the southern extent are Chloridoids (e.g., Enteropogon spp.) and Pooids (e.g., Austrostipa spp. and Rytidosperma spp.).

In the north, Cloridoids dominate, particularly species of Astrebla. Winter rainfall will favour C3 grasses and forb growth. It is hypothesised that the decomposition rate is sufficiently high in the northern Mitchell grasslands that markedly less biomass can accumulate in long unburnt systems than in temperate mesic grasslands (Fensham, Butler et al. 2017). Thus, these systems maintain inter-tussock spaces and may be able to maintain their diversity of forbs in the inter-tussock spaces in the absence of fire and other disturbances. Fire can alter grass species dominance but should not alter vegetation structure and fires when soil moisture is high can increase productivity, while fires when soils are dry can decrease productivity (Scanlan 1980). A long-term absence of fire may lead to increased recruitment of woody species (Hunt 2014) and a transition to Dry woodland but not on cracking clay soils.

Transition to dryland chenopod shrublands

Dryland chenopod shrublands may expand and displace tussock grasslands when seed is available through wind or water wash processes and follow-up rains support establishment. Over a period of decades, the growth of chenopod shrubs can displace grasses (Hunt 1992). Such dynamics may be restricted to ecotones but has been reported for the riverine plains of NSW (see *Dryland chenopod shrublands* archetype).

Transition to dry woodlands

In the absence of fires, coupled with pulses of recruitment from basal resprouts or seedling recruitment, these grasslands may transition to various woodlands. For example, in banded mulga during wetter periods, the mulga groves may expand on the upslope edge of the groves and displace tussock grasslands. A return to normal or drier periods would see mulga dying on the downslope edge of the groves and being replaced by grasses.

Knowledge gaps

- The historic role of native herbivores on the dynamics of tussock grasslands is mostly unknown in Australia (Morgan et al. 2017: p. 447). This question has two parts with the first being the impact of now-extinct megafauna on both the dynamics and evolution of these grasslands. The second concerns the role of extant native herbivores under practices of Indigenous hunting and use of fire.
- Morgan et al (2017) p447. "… it remains unclear how frequent fire may have historically influenced the structure and composition of tussock grasslands, especially where traditional burning has long ceased."
- Little is known about the dynamics of tree populations in tussock grasslands on clay soils prior to commercial grazing.
- The drivers of transitions of rainfall pulse driven arid and semi-arid tussock grasslands to and from other systems such as woodlands and dryland chenopod shrublands are poorly understood.

Experts consulted

Jennifer Firn, Ian Watson, Andrew Ash, Robyn Cowley

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List of report attachments

1. Common pasture types and grasses of the Kimberley (provided as pre-workshop reading)
2. Excel spreadsheet describing attributes for each state/expression in the red soil pasture group
3. Excel spreadsheet describing attributes for each state/expression in the black soil pasture group

Glossary

TERM	DEFINITION
Abundance	the total number of individuals of a species in an area, population or plant community.
Annual	a plant which grows from seed and completes its life cycle, including flowering and seeding, within 1 year or less; some annuals can live longer than 1 year when growing conditions are favourable (https://www.agric.wa.gov.au/rangelands/rangelands-glossary#rangeglossP)
Archetype model	conceptual model that describes the endogenous disturbance dynamics and ecosystem expressions that characterise ecosystems with integrity. These models are not operational and cannot be directly or solely used for measurement or mapping but provide a template for reference and modified states in state and transition models (Richards et al. 2020).
Australian Ecosystem Models Framework	a standardised approach to collate, synthesise and summarise scientific knowledge on ecosystem dynamics in a set of conceptual models. These models describe the dynamic characteristics and drivers of Australian ecosystems in reference and modified states, as defined by (Richards et al. 2020).
Basal area	in the rangelands, this term is used for the percent of ground covered by the base or butts of perennial tussock grasses. Basal area of tussocks is a consistent way of measuring the health of a tussock grassland from year to year. Tussock bases persist in both drought and good seasons and can be measured (basal cover %) despite being hidden by stems and leaves in good seasons. Foliar cover % varies with seasonal and grazing effects (https://www.agric.wa.gov.au/rangelands/rangelands-glossary#rangeglossP).
Canopy cover	the percentage of ground covered by a vertical projection of the outermost perimeter of the natural spread of plant foliage (https://www.agric.wa.gov.au/rangelands/rangelands-glossary#rangeglossP).
Carrying capacity	the number of livestock units a paddock or management area can carry over the long term while maintaining or improving land condition. Carrying capacities provide long-term guides to the potential productivity of the rangeland but should not be considered absolute values. The actual grazing value and forage availability of a particular paddock or station at any time will vary with seasonal conditions, rangeland condition, watering points and the degree of recent utilisation (https://www.agric.wa.gov.au/rangelands/rangelands-glossary#rangeglossP).
Cattle unit	this unit was used in Western Australia, and is based on observations of feed intake relative to a DSE (dry sheep equivalent). In general, 1 CU = 7 DSE, and was based on a 400 or a 450 kg steer. Western Australia is now adopting the well researched AE unit, which has an equivalent of 1 AE = 8.4 DSE (https://www.agric.wa.gov.au/rangelands/rangelands-glossary#rangeglossP).
Conceptual model	abstraction of reality that uses descriptions of system parts and their interactions to condense complex systems and processes into a format that allows more general understanding (Tilden et al. 2012, BoM 2016). In ecology, they offer a flexible and simple way to summarise and communicate current understanding of ecosystem behaviour and enable identification of knowledge gaps. Conceptual models can also be used to explain historical ecosystem changes and help to predict future changes (Vankat 2013). By removing complex details, conceptual models may assist in the discovery of patterns and the development of generalised characterisations of systems.
Continuous grazing	Continuous grazing is a management system where livestock run in a paddock continuously over time with no, or only infrequent, spells from grazing (https://www.agric.wa.gov.au/rangelands/rangelands-glossary#rangeglossP).
Disturbance	discrete event (in both space and time) that resets an ecosystem; that is, it disrupts ecosystem, community or population structure and changes resources, substrate availability or the physical environment (White and Pickett 1985, Hobbs and Huenneke 1992). Disturbances are described by a regime, including frequency, intensity, duration, extent and timing. In contrast, a perturbation is 'any change in a parameter (state variable) that defines a system; that is, a departure (explicitly defined) from a normal state, behaviour, or trajectory (also explicitly defined)' (White and Pickett 1985). While the terms 'disturbance' and 'perturbation' are sometimes used interchangeably, we will use the term 'disturbance' to denote a causal event that is temporary and localised, while terms like 'perturbation' or 'stress' are restricted to describing an effect or response of an ecosystem to a disturbance event or other ecological process (Rykiel 1985 p.5). Thus, climate change may be a stress to

	biodiversity, but droughts, which are predicted to increase in frequency and duration under climate change in many regions (Trenberth et al. 2014, Lemoine et al. 2016), are the potential sources of disturbance (Dornelas 2010).
Driver	a factor that causes a particular phenomenon to happen or develop. In the case of the Australian Ecosystem Models Framework (Richards et al. 2020), a driver may be a management action or a threatening process that results in a transition between ecosystem states.
Ecological integrity	an ecosystem's capacity to maintain composition, structure, functioning and self-organisation over time using processes and elements characteristic for its ecoregion and within a natural range of variability (UNCEEA 2021). Alternatively, the level of intactness, completeness and integration in the structure, composition and function of an ecosystem with respect to the persistence of biodiversity. If a system is able to maintain its organisation (function and structure) over time in response to environmental disturbance cycles then it is said to have integrity (Kay 1991, Kandziora et al. 2013).
Ecosystem	a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit (CBD 1992).
Ecosystem attributes	the biotic and abiotic properties and functions of an ecosystem (grouped into physical conditions, species composition, community structure, ecosystem function and external exchanges) (McDonald et al. 2016).
Ecosystem condition	the quality of an ecosystem measured in terms of its abiotic and biotic characteristics (UNCEEA 2021). In the AusEcoModels Framework (Richards et al. 2020) ecosystem condition is a measure of ecosystem integrity including the capacity of ecosystem states to maintain biodiversity and ecosystem flows and connections. In the context of state and transition models it is defined as the departure of each ecosystem state from the reference state.
Ecosystem dynamics	ecosystem patterns and processes that are driven by disturbance and recovery (Battisti et al. 2016). Different stages of ecosystems along pathways of disturbance and recovery are termed 'ecosystem expressions'.
Ecosystem expression	a distinct, recognisable, but transient phase within both the reference state and modified states of ecosystems. Each ecosystem state is dynamic and contains one to several ecosystem expressions, which have different ecosystem characteristics resulting from disturbance and biomass recovery processes.
Ecosystem state	the manifestation of an ecosystem at a particular point in space and time
Ecosystem type	a unit of an ecosystem classification defined by the ecosystem characteristics (for example, facets of structure, function, composition) that characterise the reference state for a given scale of organisation, for example defined by its discrete disturbance and recovery dynamic (Kay 1991, Richards et al. 2020). An ecosystem type, once defined, may be spatially identified and mapped.
Endogenous disturbance	a disturbance internal to an ecosystem (Rogers 1996) that maintains ecosystem integrity. They include fire, drought, floods, cyclones, storms, erosive and depositional processes, heatwaves, cold snaps, chemical intrusion and biotic outbreaks. They characterise ecosystems in the Australian environment prior to processes that have driven the homogenisation of ecosystems (an era termed the 'Homogenocene') and may be driven by anthropogenic (for example, ecological fire management) or non-anthropogenic (climate) processes.
Ephemeral	a plant that goes through its entire life cycle in a very short time. In the rangelands, this usually refers to a very short-lived annual (https://www.agric.wa.gov.au/rangelands/rangelands-glossary#rangeglossP).
Exogenous disturbance	a disturbance external to an ecosystem (Rogers 1996) that can trigger transitions from the reference to modified states (with lower ecosystem integrity) by transforming transient disturbances into persistent disturbances (for example, switching from macropod grazing regimes to continuous cattle grazing), introducing new disturbances that result in chronic stress on an ecosystem (for example, habitat fragmentation from land clearing) or suppressing important disturbance events (for example, fire suppression near urban areas) (Suding and Hobbs 2009). Exogenous disturbances are driven by anthropogenic actions associated with the Homogenocene.
Forbs	any herbaceous plant that is not a grass or grass-like. Forbs can be annual or perennial (https://www.agric.wa.gov.au/rangelands/rangelands-glossary#rangeglossP).
Frequency	Plant frequency is defined as the number of times a plant species is present within a given number of sample quadrats of uniform size placed repeatedly across a stand of vegetation (Daubenmire 1968, Mueller-Dombois and Ellenberg 1974).
Management action	deliberate action undertaken by people to alter aspects of an ecosystem, often resulting in the transition from one ecosystem state to another. One or more management actions may be part of an exogenous disturbance.

Modified state	an ecosystem state that is not in reference condition, due to exogenous disturbances. Modified states are dynamic and change between ecosystem expressions resulting from interactions between endogenous and exogenous disturbances (for example, natural flood events may shift expressions within a modified state in conjunction with managed environmental watering events).
Palatability	the degree to which a grazing animal finds a plant attractive to eat; this can vary with the age of the plant or the type of soil it is growing on (https://www.agric.wa.gov.au/rangelands/rangelands-glossary#rangeglossP).
Pasture condition	describes the current condition of the vegetation compared with the optimal condition which could be expected considering the potential of the area for grazing (pastoralism) (https://www.agric.wa.gov.au/rangelands/rangelands-glossary#rangeglossP). It can range from excellent through to very poor.
Pasture type	a distinctive mix of plant species, soil type and landscape position (Ryan et al. 2013)(Ryan et al. 2013; (Payne and Mitchell 2002).
Perennial	a plant which lives for 3 or more years; plants that complete their life cycle over 2 years are biennial (https://www.agric.wa.gov.au/rangelands/rangelands-glossary#rangeglossP).
Rangeland condition	the state of a rangeland ecological community in relation to its ability to conserve water, soil and nutrients compared to an optimal state unaltered by grazing or physical disturbance; usually expressed as good, fair or poor. DPIRD's rangelands officers use the matrix of soil erosion extent and pasture condition ratings to arrive at the range condition score (good, fair or poor) for each monitoring site or lease inspection point during assessments (https://www.agric.wa.gov.au/rangelands/rangelands-glossary#rangeglossP).
Reference condition	the condition against which past, present and future ecosystem condition is compared to in order to measure relative change over time (UNCEEA 2021).
Reference disturbance	see 'endogenous disturbance'
Reference state	the dynamic state of an ecosystem that has ecosystem integrity and is in reference condition. Archetype models are used as templates for the description of a reference state for a particular ecosystem type. Usually reference states refer to a local example of an ecosystem and contain more detailed quantitative information on ecosystem attributes and endogenous disturbance regimes, compared to the archetype model.
Spelling	removal of all grazing animals for a period, to allow recovery of leaf area and root energy reserves of mature desirable plants, germination of other plants in addition to desirable plants, and to allow seed production and release (https://www.agric.wa.gov.au/rangelands/rangelands-glossary#rangeglossP).
State and transition model	conceptual tool that describes the state of a particular ecosystem (which may vary, for example, from reference to degraded, in terms of ecosystem integrity), and the drivers or agents that cause transitions between states (Westoby et al. 1989, Stringham et al. 2003, Bestelmeyer et al. 2017). Transitions between states occur as a result of the introduction of new exogenous disturbance regimes, the transformation of transient disturbances into persistent disturbances, and/or changes to reference disturbance regimes (resulting in a shift to an exogenous disturbance), altering environmental conditions and resources available to constituent species. These changes may be directly caused by recent anthropogenic modification of local habitats (for example, vegetation thinning or clearing, stock grazing, introduction of native or alien invasive species), or may result from recent and rapid climate change (i.e. an indirect anthropogenic driver). Transitions in state and transition models are difficult to reverse without application of intensive management, an extreme event or long timeframe (Bestelmeyer et al. 2009, Rumpff et al. 2011), and are distinguished from pathways between different ecosystem expressions within a state, which often result from slow-acting but incremental successional processes (Richards et al. 2020).
Threatening process	a process that causes or may cause a transition from one ecosystem state to another, resulting in reduced ecosystem condition
Transition	change between ecosystem states. A transition is not reversible without active management intervention, an extreme event or an unacceptably long time frame (Bestelmeyer et al. 2009).
Umbrella class	group of archetype models in the AusEcoModels Framework (Richards et al. 2020) that is compatible with Major Vegetation Groups in the National Vegetation Information System (NVIS) (NVIS Technical Working Group 2017).
Utilisation (of pasture)	the most common use is the percentage of pasture production by weight that is consumed or destroyed by livestock. Rangeland pasture utilisation to maintain the perennials and optimise livestock production is usually 15 to 40%, and commonly less than 30% (https://www.agric.wa.gov.au/rangelands/rangelands-glossary#rangeglossP).

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