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# Informing climate adaptation pathways in multi-use woodland landscapes using the values-rules-knowledge framework

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A B S T R A C T

An emerging planning framework for climate adaptation focuses on interactions among societal *values*, institutional *rules* and scientific and experiential *knowledge* about biophysical impacts of climate change and adaptation options. These interactions shape the decision context that can enable or constrain effective adaptation. To illustrate the operationalisation of this 'values-rules-knowledge' (VRK) framework we developed biophysical adaptation pathways for agricultural landscapes of south-eastern Australia, which are expected to become warmer and drier under climate change. We used the VRK framework to identify potential constraints to implementing the pathways. Drawing on expert knowledge, published literature, biodiversity modelling and stakeholder workshops we identified potential adaptation pathways for (1) the production matrix, (2) high conservation value remnant eucalypt woodlands, and (3) woodland trees. Adaptation options included shifts from mixed cropping-grazing to rangeland grazing or biomass enterprises; promoting re-assembly of native ecological communities; and maintaining ecosystem services and habitat that trees provide. Across all pathways, applying the VRK framework elucidated fifteen key implementation constraints, including limits to farm viability, decreasing effectiveness of environmental legislation and conflicting values about exotic plants. Most of the constraints involved interactions among VRK; 13 involved rules, eight involved values, and seven involved knowledge. Value constraints appeared most difficult to address, whereas those based on rules or knowledge were more tangible. The lower number of knowledge constraints may reflect the scale of our analysis (which focused on decision points in pre-defined pathways); new knowledge and participatory approaches would likely yield a richer set of scenarios. We conclude that the VRK framework helps connect the biophysical knowledge-based view of adaptation with a perspective on the need for changes in social systems, enabling targeting of constraints to adaptation. Our focus on pathways and decision points in different sectors of the multi-use landscape highlighted the importance of group and higher level planning and policy for balancing the collective outcomes of multiple decisions by many land managers.



## 1. Introduction

Climate change is one of the greatest incipient threats to the Earth's social-ecological systems. Irrespective of efforts to mitigate greenhouse gas emissions, global mean surface temperatures are

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expected to continue rising into the next century, and extreme weather events are expected to become more frequent and severe (IPCC, 2013). Policy makers and natural resource managers face the complex task of managing the ensuing pressures on societies, ecosystems and biodiversity, commensurate with likely transformations in their structure, function and composition (Wise et al., 2014). However, pro-active approaches to ensure the development and adoption of best practices in climate adaptation management are still in their infancy.

The 'values-rules-knowledge' (VRK) framework (Gorddard et al., 2016) is an emerging framework to facilitate planning for climate adaptation, which focuses on addressing the social context in which adaptation decisions are made. It emphasises that effective decisions and actions are enabled or constrained by the 'decision context', defined as the interactions among societal *values* (e.g. outlooks and goals shaped by basic human values and preferences, O'Brien and Wolf, 2010; Schwartz, 2012), societal *rules*, including rules-in-use (e.g. social norms, practices and heuristics) and rules-in-form (laws, regulations and governance structures; Ostrom, 2011), and the body of *knowledge* (scientific information and lived experience leading to beliefs about the world) regarding possible biophysical impacts and adaptation options (Colloff et al., 2017; Gorddard et al., 2016; Pelling, 2011; Wise et al., 2014). For example, transformative adaptation in land management is likely to require shifts in values and aspirations, which in turn may facilitate shifts in industry practice and government regulations (e.g. Pelling, 2011). While offering fresh perspectives on climate adaptation planning, ways of operationalising the VRK framework are yet to be established.

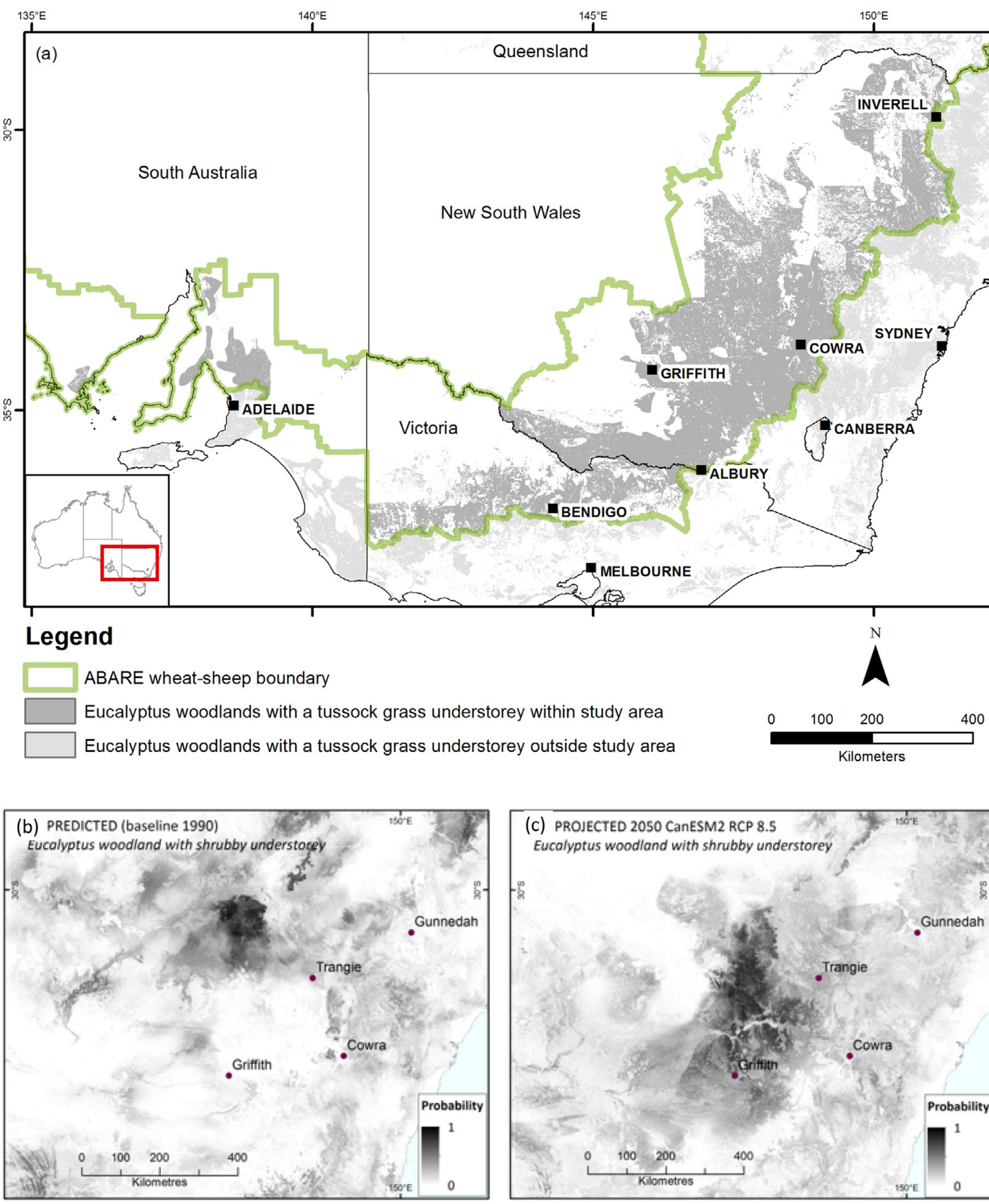



**Fig. 1.** (a) The study area (dark grey) as defined by the intersect of 'Eucalyptus woodlands with a tussock grass understorey' (light and dark grey, Department of the Environment, 2012) in NSW, Victoria and South Australia; and the wheat-sheep belt (as mapped by ABARE, Australian Bureau of Agricultural and Resource Economics and Sciences). (b and c) Projected shifts in the spatial locations of environments currently supporting shrubby eucalypt woodlands for central NSW (indicating probability of occurrence; Department of the Environment, 2012, Major Vegetation Subgroups) under the CanESM2, RCP 8.5 climate scenario (derived from Prober et al., 2015a).

The ‘adaptation pathways’ concept is also increasingly applied to climate adaptation planning. The pathways approach moves planners away from a focus on short-term solutions, and emphasizes that adaptation is a dynamic and long-term process involving multiple sequential decisions (Haasnoot et al., 2013; Maru and Stafford Smith, 2014; Wise et al., 2014). It incorporates flexibility within long timeframes by identifying decision points (i.e. social or environmental indicators that trigger a re-evaluation of the best course of action), and helps identify social-ecological constraints to implementation (Fazey et al., 2015; Stafford Smith et al., 2011). In so doing, the pathways approach helps people embrace potential for different futures, and avoid maladaptive choices that increase the risk of adverse climate-related outcomes or the foreclosure of future options (Barnett and O'Neill, 2013).

Our study aimed to demonstrate how the VRK framework can be operationalised, through a case study in temperate grassy eucalypt woodland landscapes of the wheat-sheep zone of sub-humid south-eastern Australia (Fig. 1). The study landscapes are characterised by a social context involving multiple stakeholders and decision-makers, including graziers, farmers, community organisations, natural resource management bodies, local councils, state and federal agencies and Indigenous traditional owners. Their highly productive soils support extensive dryland cropping and livestock production, in turn supporting vibrant rural communities.

The high productivity of these landscapes has led to trade-offs between agriculture and environmental conservation (Lavorel et al., 2015; Smith et al., 2012). Commonly, >90% of native vegetation has been cleared and many constituent woodland communities are listed as nationally threatened. Native species persist in remnant vegetation fragments on public and private lands, native pastures, paddock trees and other landscape elements. Nevertheless, many woodland birds, mammals and herbaceous plants are in significant decline and are particularly vulnerable to the additional pressures of climate change (McIntyre and Lavorel, 2007; Prober et al., 2012).

To operationalise the VRK framework, we constructed adaptation pathways for the study landscapes by synthesising existing knowledge of potential climate change impacts and adaptation options, focusing on biophysical actions and goals. We then examined each decision point in the proposed biophysical pathways through the lens of the VRK framework, aiming to identify mismatches in values, rules and/or knowledge that could represent key constraints to effective implementation of adaptation options. We predicted this approach would reveal actions that could enhance the likelihood of successful adaptation, and that these would include a mix of options addressing societal values, societal norms and rules, and social-ecological and technical knowledge gaps.

## 2. Methods

The study region was defined as the intersection of the wheat-sheep belt of NSW, Victoria and South Australia, and ‘*Eucalyptus* woodlands with a tussock grass understorey’ as mapped by Department of the Environment (2012; Fig. 1a). Climate change projections (Table 1) indicate a high confidence of increasing temperature and decreasing cool season rainfall across the region. Changes in warm season rainfall are uncertain, but some increases may occur in the north-east of the study region. The period between rainfall events is likely to lengthen and more extreme rainfall and drought events are expected (www.climatechangeinaustralia.gov.au).

To broadly envision potential climate change impacts and adaptation options for terrestrial biodiversity and dryland agriculture in the study landscapes, we drew on a wide range of existing resources as well as new biodiversity modelling (Appendix 1). Key resources included:

- prior modelling of climate change impacts and adaptation options for biodiversity (Prober et al., 2012; Williams et al., 2014; Prober et al., 2015a) and agriculture (e.g. Ghahramani and Moore, 2013, 2015; Moore and Ghahramani, 2013, 2014; Potgieter et al., 2013; Yang et al., 2014; Anwar et al., 2015) in the region;
- prior expert and stakeholder workshops and analyses focusing on climate adaptation in the region (Prober et al., 2012; Lavorel et al., 2015; Dunlop et al., 2016), including involvement of stakeholders from more than seven NRM regions;
- expert knowledge among co-authors with substantial collective experience working with stakeholders and researching biodiversity and agriculture in the region;
- the wider scientific literature on biodiversity and agriculture in the region, including other targeted analyses of climate change impacts and adaptation options for the region (e.g. Hayman et al., 2012; Lunt et al., 2012; Daryanto et al., 2013; Eldridge and Soliveres, 2014; Lavorel et al., 2015).

Literature was sourced using Web of Science™ searches, initially for publications that included a search term from each of the following three groups: (1) temperate eucalypt woodland*, box-gum woodland*, temperate grassy, Murray-Darling, south-eastern Australia, southern Australia, New South Wales, South Australia or Victoria; and (2) crop*, graz*, farm, wheat, livestock, grass, biodiversity, conservation, or native; and (3) climate change, warming, climate variability, or rainfall variability. This resulted in 869 publications, which we screened for relevance based on title and abstract. Further publications were identified from reference lists and targeted searches were undertaken for specific topics on an as needs basis (e.g. Buffel grass invasion).

Models to project climate change impacts on biodiversity in the study landscapes by 2050 were derived from 250 m-resolution national-scale spatial modelling products provided at http://adaptnrm.csiro.au/ (Prober et al., 2015a; Williams et al., 2014). These were generated using a Generalised Dissimilarity Model (GDM) to link environmental data layers and herbarium-derived data on plant community composition. We combined the GDM model with kernel regression to project the 2050 distributions of three woodland eucalypt dominants (Fig. 2, Appendix 1); and used the modelling products to show projected changes in the distribution of grassy and shrubby eucalypt woodlands (Fig. 1b and c; Prober et al., 2015a). These used the RCP8.5 emissions scenario, and a relatively mild and a relatively hot climate scenario with moderate rainfall change (using the global climate models MIROC5 and CanESM2 respectively; Williams et al., 2014) to

**Table 1**
Indicative expectations for changes in annual mean maximum temperature and mean annual rainfall in regions currently supporting temperate grassy eucalypt woodlands, based on Maximum Consensus of eight CMIP5 models selected for use in Australia (climatechangeinaustralia.com.au). Projections used include a high emissions (RCP8.5) scenario for 2050 and 2090, and a medium emissions (RCP4.5) scenario for 2090.

| | 2050 high/2090 medium | 2090 high |
|---|---|---|
| Annual mean maximum temperature | +1.5 to +3 °C | +3 to +4.5 °C |
| Mean annual rainfall | −15 to +5% | −25 to +5% |

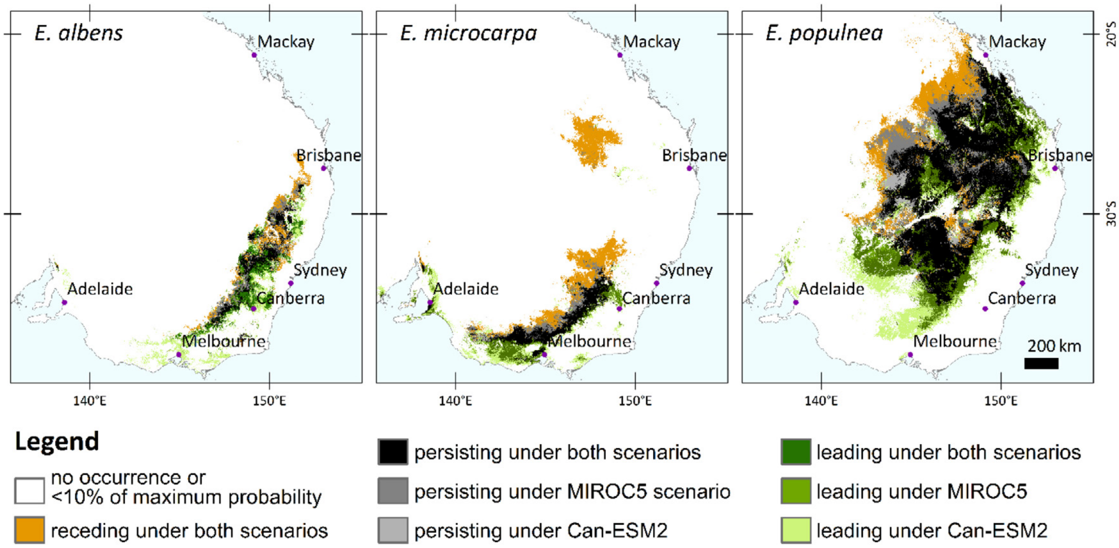



**Fig. 2.** Generalised dissimilarity modelling projections of the distribution of three dominant woodland *Eucalyptus* spp. by 2050, under high (RCP8.5 W m$^{-2}$) emissions scenarios, using two climate scenarios (Can-ESM2 and MIROC5, see Appendix 1). The composite maps indicate areas of potential advance (leading edges), areas of potential persistence, and areas of likely mortality (trailing edges) for each scenario.

represent the spectrum of 'Maximum Consensus' futures for Australia (climatechangeinaustralia.com.au). We developed a state-and-transition model to characterise processes underlying transitions between grassy and shrubby woodlands based on documented ecosystem dynamics (Fig. 3).

Owing to heterogeneity within the study landscapes, we constructed adaptation pathways for three key landscape

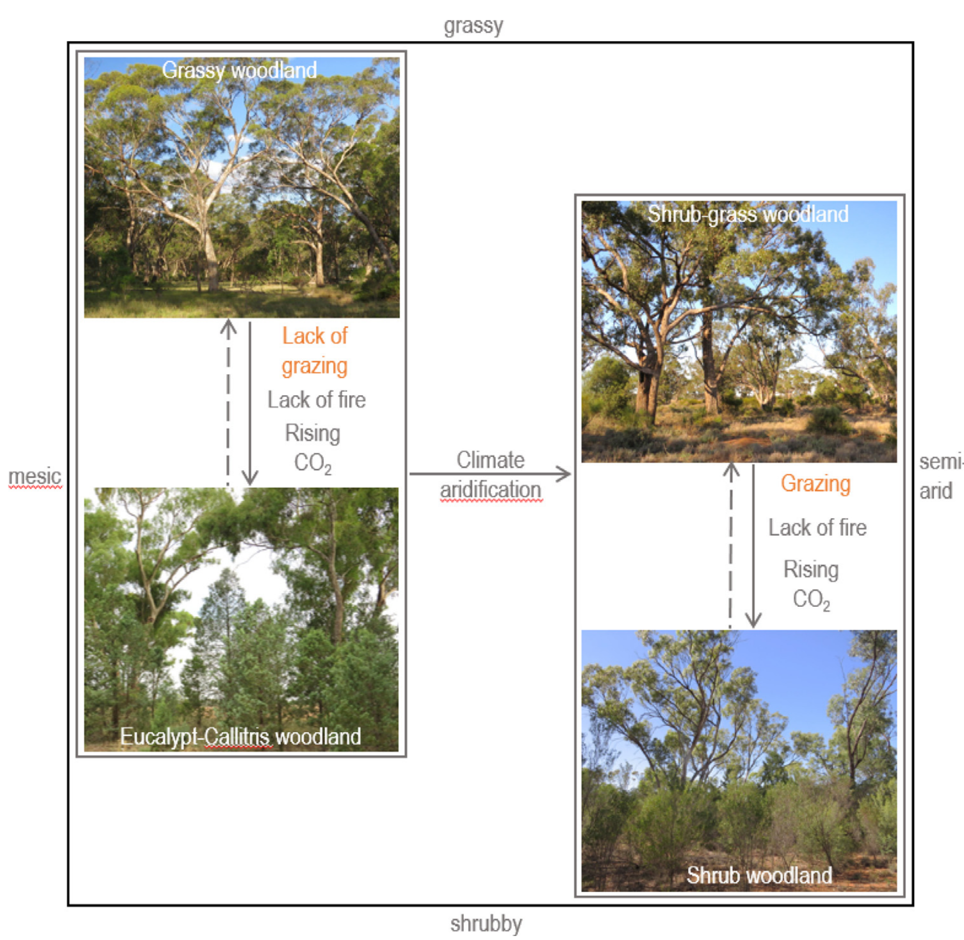



**Fig. 3.** State-and-transition model highlighting expected shift towards shrub woodland with increasing aridification, manageable to some extent using fire and grazing. Note the shift with aridification in the role of grazing from one of maintaining grassy systems (mesic) to promoting woody systems (semi-arid), relating to shifts from palatable (e.g. *Callitris*) to unpalatable (e.g. *Eremophila*) woody species.

elements. Two of these represent sites with different degrees of historical modification of the ground-layer (production matrix and high conservation value ground-layers), consequently with different (although interlinked) values, management needs and goals. The third represents a significant structural element (trees) common to both of these but involving values and management independent of the ground-layer:

1. The production matrix. This includes improved and native pastures and cropland, forming the dominant part of the landscape. Component sites have moderate to high production values and low to moderate biodiversity values (Lavorel et al., 2015).
2. High conservation value native ground-layers. These typically involve sites that for historical reasons have not been fertilised and have had little or intermittent livestock grazing, resulting in high values for ground-layer fauna and plants. Such sites include little-grazed roadsides and paddocks, little-used country cemeteries, and travelling stock reserves and routes (i.e. linear reserves where grazing is restricted to herds being driven from a place of origin to another destination). These sites also have historical and cultural values, but only occasional production uses (e.g. intermittent grazing in stock routes). They are small in total area (typically $<$10% of the landscape) but widely dispersed across the region (Prober et al., 2012; Lavorel et al., 2015).
3. Trees and tree-dependent fauna. Mature, regenerating and planted trees occur in small to large patches and as scattered individuals throughout the production matrix and with high conservation value native ground-layers. They have high aesthetic, production (e.g. livestock shelter, preventing salinisation and erosion; Lavorel et al., 2015) and habitat values (e.g. bark, canopies and hollows provide for vertebrate and invertebrate fauna; Lindenmayer et al., 2016).

Plausible biophysical adaptation pathways were developed for each of the three landscape elements based on projected changes and adaptation options drawn from our synthesis, focusing on maintaining values similar to the initial values of each element (see above). For each pathway we identified decision points (i.e. junctures when management choices need to be made) and associated cues indicating arrival at such a juncture; and potentially adaptive and maladaptive management alternatives once decision points are reached. While we indicate this may occur over an approximate 30–100 year timeframe, we emphasise that the rate and degree of change at any location will depend on the initial climate and rate of climate change, with areas that are currently more arid being more likely to reach the more extreme transitions, and more mesic areas perhaps only progressing part way along the pathways. We also identified options for enhancing resilience of ecosystems and businesses to climate change.

We then examined the biophysical adaptation pathways using the VRK framework. At each decision point and for each resilience option, we asked what factors from the domains of values, rules or knowledge could limit favoured outcomes or promote maladaptive choices (Appendix 2), acknowledging that classification and prioritisation of constraints was subjective (see Introduction for definitions). We assumed ongoing stability of Australia's liberal democracy and mixed economy, although globalisation, technological change and mass migration linked to climate change are among the drivers that could in time transform this overarching decision-making environment (Klein, 2014). Held or intrinsic values, such as the desire to maintain the viability of rural communities, are strongly linked to ascribed or instrumental values (*sensu* Abson and Termansen, 2010) relating to economic benefits of land use in these landscapes. In this study we presume 'production (or instrumental) values' reflect economic benefits from agricultural and pastoral production, and their roles in supporting agricultural communities.

## 3. Results and discussion

### 3.1. Expected biophysical change

Synthesis of scientific and stakeholder knowledge (Dunlop et al., 2016; Lavorel et al., 2015; Prober et al., 2012) suggests that key impacts of climate change in the region are likely to include pressures on agricultural systems, risks of accelerated aridification, reduced tree cover, altered shrub-grass balance, declines in native forbs, and invasion by arid-adapted exotic plants. We summarise these below.

#### 3.1.1. Pressures on agricultural systems

Mixed cropping (particularly cereals and canola) and livestock grazing characterise the region's agriculture. At farm scales, high inter-annual climatic variability is managed by adjusting stocking rates and area planted to crops (Crimp et al., 2010), although the financial viability of farming enterprises can be challenged by long or repeated droughts.

Projections for the ongoing productivity of cereal crops as the climate changes vary among studies and locations (e.g. +6% to −30% change in yield by 2030–2050; Anwar et al., 2015; Potgieter et al., 2013; Yang et al., 2014). However, sustained increases in aridity, and frequency and duration of drought, are expected to increase the likelihood of crop failure and reduce profitability in drier areas. Profitability of pastoral enterprises is expected to decline, particularly at the drier margins of the case study region although less so than cropping enterprises (Crimp et al., 2010; Moore and Ghahramani, 2013).

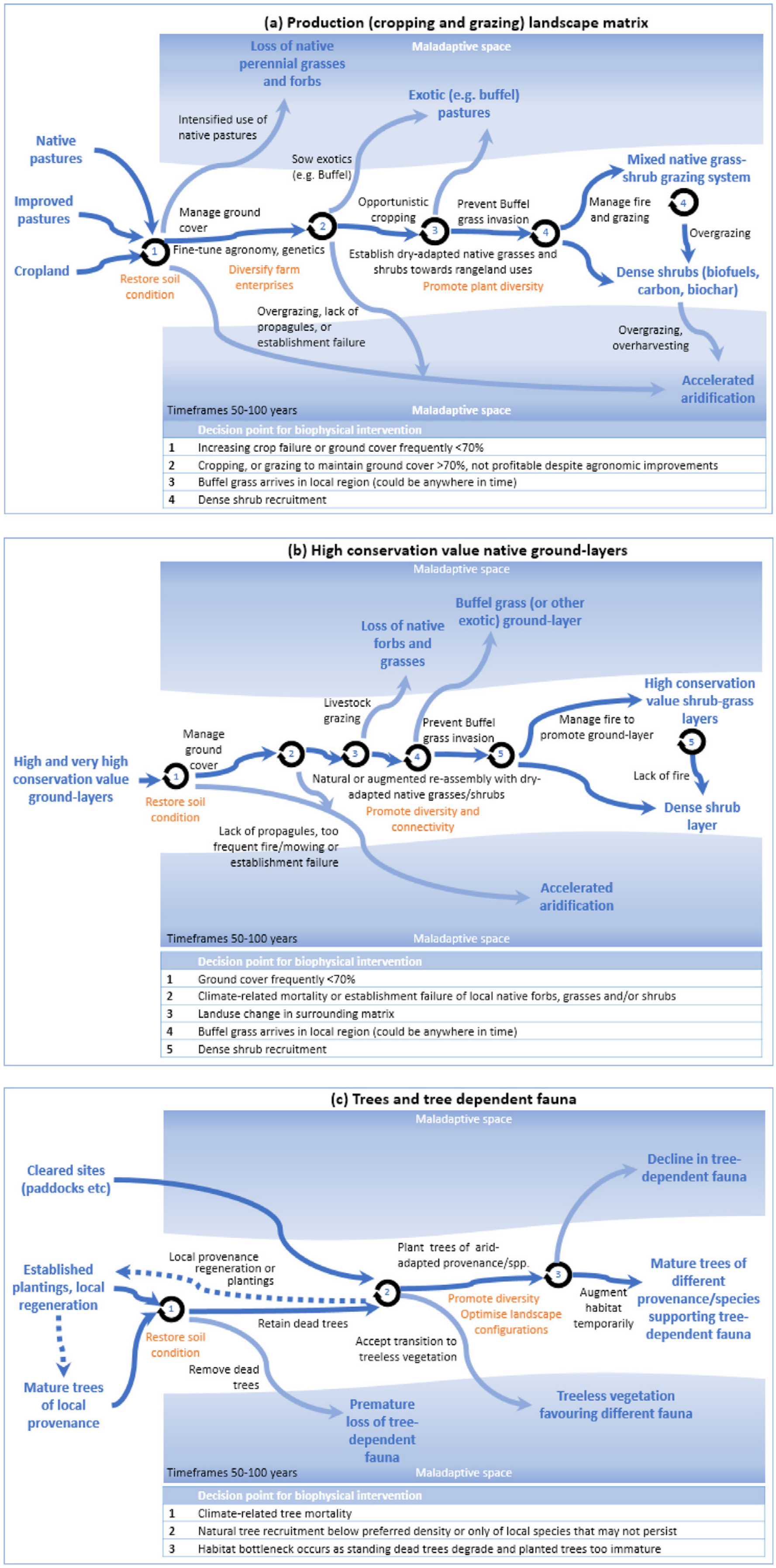
#### 3.1.2. Accelerated aridification

Inadequate reduction of grazing pressure and slow recolonisation of abandoned cropland are likely to accelerate declines in production and biodiversity initiated by the aridifying climate, through interactions between vegetation cover and soil processes (Ghahramani and Moore, 2013; Ludwig et al., 1996). Perennial vegetation limits soil erosion, prevents surface-crusting due to raindrop and light exposure, enhances soil structure, and retards evaporation. Ground cover thresholds of less than ~70% disrupt these processes (Lang and McCaffrey, 1984), leading to soil loss and reduced soil functioning. For example, prolonged reduction in ground cover is associated with 30% lower topsoil water-holding capacity in temperate grassy eucalypt woodlands (Prober et al., 2014), and in semi-arid landscapes can lead to desertification (Ludwig et al., 1996).

#### 3.1.3. Changing tree cover

Declining rainfall and increasing temperature are likely to reduce the life expectancies of mature trees, potentially via drought or wildfire events, and alter recruitment success. In turn, tree densities and the spatial distribution of individual species are expected to change (Prober et al., 2012). The latter is illustrated by projected southerly shifts by 2050 of suitable environments for three dominant woodland eucalypts (Fig. 2, Appendix 1).

These expectations could be offset by improved water use efficiency associated with rising atmospheric $CO_2$, or within-species capacity to adjust to changing climates (Hovenden and Williams, 2010). However, substantial tree mortality potentially related to aridification is already evident in other temperate eucalypt woodlands (e.g. *Eucalyptus viminalis* in New South Wales and Tasmania; Ross and Brack, 2015). Widespread premature tree mortality would have significant implications for ecosystem services, including shade and shelter for livestock, landscape


(a) Production (cropping and grazing) landscape matrix
Maladaptive space
Loss of native perennial grasses and forbs
Exotic (e.g. buffel) pastures
Native pastures
Improved pastures
Cropland
Intensified use of native pastures
Sow exotics (e.g. Buffel)
Manage ground cover
Opportunistic cropping
Prevent Buffel grass invasion
Manage fire and grazing
Mixed native grass-shrub grazing system
Overgrazing
Fine-tune agronomy, genetics
Establish dry-adapted native grasses and shrubs towards rangeland uses
Restore soil condition
Diversify farm enterprises
Promote plant diversity
Dense shrubs (biofuels, carbon, biochar)
Overgrazing, lack of propagules, or establishment failure
Overgrazing, overharvesting
Accelerated aridification
Timeframes 50-100 years
Maladaptive space
Decision point for biophysical intervention
1 Increasing crop failure or ground cover frequently <70%
2 Cropping, or grazing to maintain ground cover >70%, not profitable despite agronomic improvements
3 Buffel grass arrives in local region (could be anywhere in time)
4 Dense shrub recruitment
(b) High conservation value native ground-layers
Maladaptive space
Buffel grass (or other exotic) ground-layer
Loss of native forbs and grasses
High conservation value shrub-grass layers
Livestock grazing
Manage ground cover
Prevent Buffel grass invasion
Manage fire to promote ground-layer
High and very high conservation value ground-layers
Natural or augmented re-assembly with dry-adapted native grasses/shrubs
Lack of fire
Restore soil condition
Promote diversity and connectivity
Dense shrub layer
Lack of propagules, too frequent fire/mowing or establishment failure
Accelerated aridification
Timeframes 50-100 years
Maladaptive space
Decision point for biophysical intervention
1 Ground cover frequently <70%
2 Climate-related mortality or establishment failure of local native forbs, grasses and/or shrubs
3 Landuse change in surrounding matrix
4 Buffel grass arrives in local region (could be anywhere in time)
5 Dense shrub recruitment
(c) Trees and tree dependent fauna
Maladaptive space
Cleared sites (paddocks etc)
Decline in tree-dependent fauna
Local provenance regeneration or plantings
Plant trees of arid-adapted provenance/spp.
Established plantings, local regeneration
Mature trees of different provenance/species supporting tree-dependent fauna
Retain dead trees
Promote diversity
Optimise landscape configurations
Augment habitat temporarily
Restore soil condition
Accept transition to treeless vegetation
Remove dead trees
Mature trees of local provenance
Premature loss of tree-dependent fauna
Treeless vegetation favouring different fauna
Timeframes 50-100 years
Maladaptive space
Decision point for biophysical intervention
1 Climate-related tree mortality
2 Natural tree recruitment below preferred density or only of local species that may not persist
3 Habitat bottleneck occurs as standing dead trees degrade and planted trees too immature

hydrological processes, erosion mitigation, and scenic and cultural values of these iconic Australian landscapes (Eldridge and Freudenberger, 2005; Lavorel et al., 2015). Habitat for tree-dependent fauna would similarly decline (Gibbons and Lindenmayer, 2002; Lindenmayer et al., 2016).

#### 3.1.4. Change in shrub-grass balance

Several lines of evidence suggest shrub densities could increase in temperate grassy woodlands as the climate changes (Lavorel et al., 2015; Prober et al., 2012): shrub densities already increase with aridity in these woodlands (Prober and Thiele, 2004), increasing atmospheric $CO_2$ can favour woody over herbaceous species (Hovenden and Williams, 2010), and increasing bare ground may assist shrub recruitment. These predictions are consistent with projected incursions of shrub woodlands into grassy woodlands by 2050 based on Generalised Dissimilarity Modelling (Fig. 1c).

Further, altered disturbance dynamics could exacerbate woody thickening (Fig. 3, Lunt et al., 2012). Pre-European fire regimes are thought to have promoted an open, grassy structure in mesic eucalypt woodlands, later replaced by livestock and rabbit grazing that limit dense establishment of palatable woody species of *Eucalyptus* and *Callitris* (Lunt et al., 2012). Unlike prominent woody species in mesic woodlands however, semi-arid woodland shrubs (e.g. *Dodonaea, Eremophila* and *Senna*) are typically unpalatable (Eldridge and Soliveres, 2014). Rather than suppressing shrubs, overgrazing depletes grass fuels, limiting wildfires and permitting widespread shrub recruitment after high rainfall events (Eldridge and Soliveres, 2014; Lunt et al., 2012). Grazing by livestock and rabbits could thus indirectly promote, rather than limit, transitions to stable, shrub-dominated understoreys as the climate aridifies (Fig. 3; Lunt et al., 2012).

Increasing cover of unpalatable shrubs is likely to reduce the profitability of livestock grazing enterprises (Crimp et al., 2010), and the abundance and diversity of ground-layer dependent species (e.g. native forbs). On the other hand, shrubs would favour shrub-dependent native biota, help limit invasion by exotic species during vegetation transitions, and provide alternative ecosystem services including options for carbon farming and extensive pastoralism (Eldridge and Soliveres, 2014; Lavorel et al., 2015; Prober et al., 2012, 2015a).

#### 3.1.5. Further pressure on declining native perennial forbs

Native perennial forbs of temperate grassy eucalypt woodlands have already declined immensely due to clearing, grazing, nutrient enrichment and weed invasion (Dorrough and Scroggie, 2008; McIntyre and Lavorel, 2007; Prober and Thiele, 2004). Native perennial forbs also decrease in abundance and diversity with increasing aridity (Prober and Thiele, 2004), suggesting forbs will decline further with climate change, concurring with projections for replacement of grassy with shrubby woodlands in some regions (Figs. 1 and 3). Climate-driven changes in land management, such as fertilising native pastures (Ghahramani and Moore, 2015) or grazing high conservation value sites (McIntyre and Lavorel, 2007), could similarly exacerbate loss of native forbs.

#### 3.1.6. Changing invasion risks

Crop abandonment and mortality of ground-layer plants due to aridification are likely to increase opportunities for exotic plant invasions (Prober et al., 2012). Although currently-pervasive exotics (e.g. annuals such as *Avena, Bromus* and *Echium*) may decline (Prober et al., 2012, 2013), models suggest conditions may become more suitable for semi-arid invasive grasses such as Buffel Grass (*Cenchrus ciliaris*; Martin et al., 2015; Scott et al., 2014).

Exotic grasses such as Buffel Grass are already known to reduce native plant diversity and threaten native fauna elsewhere, and can be extremely difficult to control once established (Marshall et al., 2012). In addition to direct effects on biodiversity, robust invasive grasses can increase the quantity and connectivity of fuels, promoting more intense and frequent fires. Elsewhere this is already transforming ecosystems, driving the loss of long-lived *Acacia* spp. (Miller et al., 2010).

### 3.2. Plausible adaptation pathways in the production matrix

Goals for adaptation in the production matrix are likely to focus on maintaining the viability of agricultural enterprises and thereby sustaining rural communities (Hayman et al., 2012). Shifts towards lifestyle-focused land uses are also likely near urban centres, but these were outside the scope of our analysis.

A potential adaptation pathway (Fig. 4a) could involve a transition from mixed cropping-grazing systems towards extensive grazing and/or biomass-based enterprises (Lavorel et al., 2015). In intermediate phases, frequent declines in ground cover beyond thresholds of 70% (Lang and McCaffrey, 1984; **decision point 1** in Fig. 4a) and declining profitability of grazing systems can potentially be ameliorated by improving livestock genetics, applying fertiliser, growing Lucerne (*Medicago sativa*) pastures and supplementary feeding (Ghahramani and Moore, 2015). Focusing grazing intensification in abandoned cropland or improved pastures, rather than biodiversity-rich native pastures, would minimise loss of native plants (Dorrough and Scroggie, 2008; McIntyre and Lavorel, 2007).

The viability of cropping (**decision point 1**, Fig. 4a) may similarly be prolonged through improved varieties and advances in precision agriculture and weather forecasting (Potgieter et al., 2013; Anwar et al., 2015; Dunlop et al., 2016). Nevertheless, an increasing proportion of pastoral land uses would be expected in the longer term, especially in more arid areas (Dunlop et al., 2016; Howden et al., 2008; Lavorel et al., 2015; Potgieter et al., 2013).

Extensive pastoral land uses such as light grazing of dry-adapted native grasses and palatable shrubs (Revell et al., 2013) may become necessary if ground cover thresholds (>70%) cannot be sustained despite agronomic advances (**decision point 2** in Fig. 4a, Hayman et al., 2012; Lavorel et al., 2015). These options offer environmental benefits, but even if opportunistic cropping continued, farm incomes would likely decline.

Sowing dry-adapted exotic grasses may be another attractive option for graziers if native forage species are slow to recruit or less productive (**decision point 2**, Fig. 4a). However this could amplify biodiversity losses in the short and long term, foreclosing options for active or passive re-assembly of diverse native ecological communities across much of the landscape (Marshall et al., 2012). A similar outcome is likely if such exotics spread naturally (**decision point 3**, Fig. 4a), but could be averted by establishing strict monitoring and control protocols *prior to* this decision point.

Finally, dense shrub recruitment (**decision point 4**, Fig. 4a) may occur after high rainfall events as the climate dries (Fig. 3; Prober et al., 2012). Monitoring to detect recruitment events would allow open native grass-shrub grazing systems to be maintained by

**Fig. 4.** Plausible adaptation pathways for (a) the production matrix, (b) high conservation value ground-layers and (c) trees and tree-dependent fauna, indicating starting states, potentially maladaptive and desirable outcomes (blue text), decision points (numbered circular arrows indicating cues for when choices need to be made, see Appendix 2), management options (black text), and potential actions to increase resilience (red text). The white path represents adaptive space and blue represents maladaptive space. The order of some events may vary, e.g. exotics could appear at any stage in the pathway, and the degree of change at any location will depend on the initial climate and rate of climate change. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

managing fire and grazing (Fig. 3). Alternatively, woody ecosystems could be promoted for carbon, biofuels or biochar (Daryanto et al., 2013; Dunlop et al., 2016; Hayman et al., 2012).

### *3.3. Plausible adaptation pathways for high conservation value ground-layers*

Adaptation goals for high conservation value ground-layers are likely to focus on promoting a diversity of locally and regionally native species, and maintaining some open grassy woodlands to facilitate persistence of otherwise poorly-conserved native ground-layer species.

A plausible adaptation pathway (Fig. 4b) is superficially similar to that for the production matrix, with greater emphasis on helping biodiversity adapt whilst limiting exotic invasion. Significant ground cover declines (**decision point 1**, Fig. 4b) could be ameliorated by reducing total grazing pressure (livestock, native and feral herbivores) or adjusting fire or mowing regimes (Prober et al., 2013) to avoid accelerated aridification. Replacement of locally indigenous plants (e.g. *Themeda, Poa)* by dry-adapted species (e.g. *Rytidosperma, Austrostipa*) may occur naturally (Prober and Thiele, 2004) or may need to be facilitated to balance mortality or recruitment failure (**decision point 2**, Fig. 4b). Invasives such as Buffel Grass (**decision point 4**, Fig. 4b) would need to be monitored and controlled.

Another risk involves potential for rapid land use change (**decision point 3**, Fig. 4b) to compromise the integrity of high conservation value biota that has persisted in sites with low grazing intensity. For example, allocating travelling stock reserves

**Table 2**
Values-rules-knowledge constraints identified in three inter-related adaptation pathways in temperate grassy eucalypt woodlands, consolidated from Tables A2.1–A2.3. Pathways relevant to each set of constraints (rows) are shown as Ag. matrix (Production matrix), Ground-layer (High conservation value ground-layers) and Trees (trees and tree dependent fauna), with the relevant decision points (from Fig. 4) in parentheses. The second left hand column indicates the suggested leading constraint (bold) that limits removal of subsequent constraints. Numbering commensurate with Section 3.6.

| | | Values | Rules | Knowledge | Pathway (decision point) |
|---|---|---|---|---|---|
| 1 | **R** V | Value placed on maintaining farm viability could override value placed on environmental sustainability, favouring overgrazing and accelerated aridification | Risk of farm business failure may increase pressure to overgraze. | | *Ag. matrix (1)* |
| 2 | **R** V | Value placed on maintaining viability may override value placed on biodiversity in native pastures, favouring intensified production and loss of biodiversity | Reduced farm income or viability could favour decisions to intensify use of native pastures | | *Ag. matrix (1)* |
| 3 | **K** | | | Inadequate knowledge (e.g. improved genetics) could limit capacity to fine-tune current farming systems | *Ag. matrix (1)* |
| 4 | **V** K R | Lack of value placed on native-based production systems may constrain their development as future options | Lack of industry infrastructure could limit capacity to establish native-based production systems at scale | Lack of knowledge could limit capacity to establish native-based production systems at scale | *Ag. matrix (2)* |
| 5 | **V** R | Lack of consensus to keep out transformer exotics could limit establishment of legislation and monitoring to prevent introductions | Lack of legislation to keep out transformer exotics could favour their introduction, and subsequent biodiversity loss | | *Ag. matrix (2,3) Ground-layer (4)* |
| 6 | **R** K V | Perceptions that fire is undesirable could lead to excessive fire control | Lack of information dissemination about the role of fire limits understanding of its potential benefits | Lack of community understanding about potential benefits of fire could lead to perceptions that fire is undesirable | *Ag. matrix (4) Ground-layer (5)* |
| 7 | **R** | | Lack of infrastructure and capacity to monitor and control shrubs (using burning) could promote widespread woody thickening | | *Ag. matrix (4) Ground-layer (5)* |
| 8 | **R** K | | Inadequate information dissemination could limit knowledge of contrasting fire-grazing interactions in semi-arid vs. mesic woodlands | Lack of community knowledge about difference in fire-grazing interactions could promote overgrazing and shrubs | *Ag. matrix (4) Ground-layer (5)* |
| 9 | **V** | Conflicting values about culling native fauna could lead to overgrazing and accelerated aridification | | | *Ground-layer (1)* |
| 10 | **R** | | Legal protection for high quality sites may become ambiguous in a changing climate | | *Ground-layer (3)* |
| 11 | **K** V R | Local provenance concepts may constrain use of better adapted spp. or genotypes; | Rules (Guidelines) constrain use of non-local species or provenances that may be better adapted to future climates | Lack of knowledge may lead to maladaptive beliefs and choices of species and provenances to replant | *Ground-layer (2) Trees (2)* |
| 12 | **V** R | Values about dead trees may be a pressure to allow their removal | Rules may be pressured to allow removal of dead trees | | *Trees (1)* |
| 13 | **R** | | Logistic challenges may limit capacity to augment fauna habitat at scale | | *Trees (3)* |
| 14 | **K** R | | New production alternatives may require market development | Limited knowledge of viable production alternatives | *Ag. matrix (resilience)* |
| 15 | **V** K R | Insufficient demand to develop affordable resilient restoration methodologies and invest at scale | Limited capacity to restore resilience at scale | Inadequate knowledge to restore resilience | *Ag. matrix Ground-layer Trees (resilience)* |
| | | 9 (5 leading) | 13 (7 leading) | 7 (3 leading) | |

to neighbouring properties could accelerate the loss of high conservation value native forbs.

Finally, dense shrub recruitment (**decision point 5**, Fig. 4b) can be managed with fire, either to maintain open grass-shrub ecosystems or to promote shrubs. Managing for grassy ecosystems would enhance persistence of declining perennial forbs, and maintain the option to manage for shrubs and associated biodiversity. Removing shrubs once established is more difficult (Eldridge and Soliveres, 2015).

### 3.4. Plausible adaptation pathways for trees and tree-dependent fauna

Important goals regarding trees include maintaining the ecosystem services they provide, minimising the loss of tree-dependent native fauna, and avoiding replacement by arid-adapted exotic trees such as *Vachellia nilotica* (Prickly Acacia; Kriticos et al., 2003). Climate-related tree mortality, for example during heatwaves or prolonged droughts (Fig. 4c, **decision point 1**), could result in management decisions to remove dead trees for firewood or aesthetic reasons. Dead trees retain critical habitat features (Gibbons and Lindenmayer, 2002) so their removal would be maladaptive.

Climate-related tree mortality indicates that current provenances or species may not persist under increasing climate change (e.g. Ross and Brack, 2015). Inadequate natural regeneration of more climate-resilient (local) tree species, or regeneration of local provenances that may not persist through future droughts or heatwaves (**decision point 2**, Fig. 4c), would require managers to choose among various intervention options or letting nature take its course.

If local provenances showing evidence of climate-related mortality recruit successfully or are planted, natural selection of arid-adapted individuals could improve population persistence, permitting natural processes to drive change. However, the risk of premature mortality of the next generation of trees would be high during droughts or heatwaves, resulting in reversion to the beginning of the adaptation pathway (dashed arrow, Fig. 4c). Assisted selection, e.g. using emerging genomic approaches to cull poorly adapted genotypes (Prober et al., 2015b), could improve the success of local provenances. Alternatively, managers could plant a diversity of arid-adapted provenances and species from a wider local region, preferably informed by modelling tools (e.g. Fig. 3, Prober et al., 2015b; Dunlop et al., 2016). These plantings would be more likely to persist in the longer term, but represent a shift from the contemporary paradigm that favours local provenances and species (Broadhurst et al., 2008). For revegetation in cleared sites, these decisions need to be made at planting (**decision point 2**, Fig. 4c) even where evidence of mortality of local provenances (**decision point 1**, Fig. 4c) is not available.

Finally, dead trees can stand for 50–100 years, which may not be long enough for a new generation of climate-resilient trees to develop critical habitat features (**decision point 3** in Fig. 4b, Gibbons and Lindenmayer, 2002). If such bottlenecks occur over broad scales, strategic provision of artificial habitat (e.g. nest boxes) may be the only option for supporting at least some hollow-dependent species (those that use nest boxes and that are able to withstand the changing climate) (Lindenmayer et al., 2016). Other services are expected to return more readily as new generations of trees mature.

### 3.5. Augmenting resilience

Pathways described so far have assumed ideal ecological functioning of current agronomic and ecological systems. However, soils and vegetation in temperate woodland landscapes are frequently degraded, and a range of restoration options offer means for increasing ecological resistance and resilience (hereafter resilience) to climate change (Pelling, 2011; Walker et al., 2012), potentially slowing or avoiding progression towards points at which change is necessary (Fig. 4a–c, Prober et al., 2012, 2014). Options include restoring soil-water infiltration and water holding capacity (Prober et al., 2014), attention to spatial landscape configurations to benefit native fauna, and augmenting the diversity of plant species in native pastures and remnant woodlands that can maintain ecosystem functions and services (Prober et al., 2012). Similarly, maintaining a diversity of enterprises and markets, possibly combined with off-farm income, could help farmers to maintain economic stability (Abson et al., 2013). Resilience options are often relevant at multiple points in our adaptation pathways, so are treated independently of decision points.

### 3.6. Addressing the decision context for adaptation

The pathways we constructed focus on biophysical aspects of adaptation, assuming that if an option is available, it can be implemented. Examining each decision point and associated choices using the values-rules-knowledge framework revealed a suite of potential constraints to achieving adaptation goals and avoiding maladaptation (detailed for each pathway in Appendix 2, Tables A2.1–A2.3). As some constraints overlapped among pathways, we consolidate them in Table 2 to fifteen key sets of interacting constraints, each set relevant to one or more of our adaptation pathways and associated decision points (as listed in Table 2). We describe each set below using numbering concordant with Table 2, allocating constraints to values (V), rules (R), and/or knowledge (K) based on reasoned judgement, discussion and consensus among co-authors; and where possible suggesting potential solutions drawn from our literature review.

1. Farm viability constraints could promote accelerated aridification (RV)

Avoiding accelerated aridification due to soil degradation as the climate aridifies would require timely management of ground cover (Crimp et al., 2010; Moore and Ghahramani, 2013). Considerable financial stress on farm businesses, including risk of bank foreclosure (R), could lead to preferences (V) to maintain rather than reduce grazing pressure, based on the expression of interests and values for sustaining short-term viability and profitability at the expense of minimising environmental damage and maximising future options. In terms of reframing the decision context to allow for such options, Australia has a long history of rural reconstruction schemes (Cockfield and Botterill, 2006) that could facilitate property amalgamations or other transitions to help avoid the deleterious effects of such preferences (e.g. Howden et al., 2008). Similarly, better mechanisms to incorporate the environmental costs of agriculture into markets and business accounting frameworks (Elkington, 1997), and potential application of technologies such as remote sensing to assess land condition and value, could help shift values and interests in order to develop approaches to minimise pressures on soils and biota.

2. Pressure to maintain profitability may promote loss of native pastures (RV)

Native pastures offer dual services, supporting low-input production from livestock grazing, and conserving environmental values. Similar to (1), the imperative to maintain farm profitability (i.e. to avoid business failure, R) under increased aridity could lead to a preference (V) for adding fertilisers to maintain or increase grazing pressure in native pastures (rather than reducing grazing pressures to maintain ground cover) (Ghahramani and Moore, 2015). Increased nutrients and grazing pressure implemented as a result of values-based preferences for increasing profitability would be detrimental to woodland forbs and other native ground-layer species, and could negatively impact soil and hydrological processes by encouraging dominance by shallow-rooted exotic annuals (V; McIntyre and Lavorel, 2007). Again, rural reconstruction schemes and marketplace adjustments could help reframe values and interests away from such decisions, by providing alternative pathways for failing businesses and incorporating environmental costs in accounting frameworks (e.g. property values).

3. Inadequate research and development could constrain incremental improvements in cropping and grazing systems (K)

Genetic and agronomic improvements are a likely early response to decreasing profitability of current farm enterprises under climate change. Many of these improvements would require research and development (K) and thus early investment; for example, genetic improvement of crops and livestock is generally achieved gradually over time (Moore and Ghahramani, 2014). The costs of investing in potentially short-term incremental change need to be balanced against the potential need for transformational options (see 4).

4. Values limit development of knowledge and infrastructure that would enable native production systems (VKR)

Palatable native grasses and shrubs offer opportunities to adapt grazing systems to aridifying climates (Revell et al., 2013), and benefit biodiversity and soil condition. Cropland and pastures may transition naturally where native seed sources are adequate, but it is likely that vast areas would benefit from sowing or planting to improve pastoral values and avoid prolonged reductions in ground cover and profitability.

Agronomic techniques and resources to establish native-based production systems have progressed in recent decades (e.g. Walters et al., 2000), but investment in technical advances has been relatively low. We suggest this reflects limited recognition of current and potential future values of native-based production systems (V), and the resulting limited knowledge (K) and infrastructure (R) is likely to constrain the rapid establishment of native pastures at broad scales if needed in the future. Reframing the decision context would require timely investments to decrease the cost and scarcity of seed supplies and advance agronomic technologies such as seed harvesting and sowing protocols. Overcoming a lack of impetus to support these developments is challenging, and exacerbated by uncertainties related to the timing and degree of climate change. Nevertheless, industry grant schemes and best practice demonstrations could facilitate change where options can be shown to be beneficial (e.g. Pannell et al., 2006).

5. Conflicting values and inadequate rules could result in high social and environmental costs of exotic plants (VR)

With pressures to maintain productivity in aridifying environments, attention will undoubtedly turn to exotic perennial forage plants, which often threaten native biota and are costly to control (Driscoll et al., 2014). This classic values conflict between production and biodiversity (V), has resulted in inadequate rule systems (R) to prevent introductions or invasions. Economic models currently fail to accommodate the social and environmental costs of such species (Driscoll et al., 2014), and legislation to control them is only now emerging. For example, recent (2013) listing of the threatening process 'Novel biota and their impact on biodiversity' under the federal *Environment Protection and Biodiversity Conservation Act 1999* has resulted in specific threat abatement advice for Buffel grass, including calls for restrictions on further development for agriculture, surveillance, and research into native alternatives. However, these recommendations are non-binding. Whether their implementation is timely and adequately supported depends on the challenge of addressing values conflicts between production and biodiversity (V). Even then, monitoring, eradicating or containing these exotics would require concerted community effort, investment, consensus and support (R) (Marshall et al., 2016).

6–8. Values-rules-knowledge interactions could limit potential to manage for open shrub-grass ecosystems (RKV, VR, RK)

Scientific knowledge of fire and grazing is adequate to manage the shrub-grass balance as the climate warms and dries, potentially benefiting both production and biodiversity (Fig. 3, Eldridge and Soliveres, 2014). However, this knowledge may not be readily available to local communities (interpreted as a rules-knowledge interaction); in turn influencing values such that local land managers potentially perceive fire as dangerous or undesirable for its short-term impacts on forage availability (RKV, e.g. Harr et al., 2014). Conflict could thus arise between the desire to suppress fire (e.g. by grazing to reduce fuels loads) and the need for fire to control woody plants. Additionally, in production landscapes, misunderstandings about shrub-grazing interactions (e.g. beliefs that grazing suppresses shrubs in semi-arid woodlands when evidence indicates it promotes shrubs; Fig. 3) may unintentionally promote high shrub densities (again seen as a rules-knowledge interaction, RK).

Even where fire is accepted as a management tool, there may be insufficient capacity and infrastructure (R) to manage fire across broad landscapes, or detect shrub recruitment events that require fire management. Indeed, implementing planned fires is increasingly difficult due to multiple permit systems and inadequately-targeted regulations. For example, legislation in New South Wales currently permits hazard-reduction burning, but not burning for ecological management.

Reframing the decision context to manage for open shrub-grass ecosystems would thus require the freeing up of the VRK constraints to the use of fire management at landscape scales. Community learning opportunities about shrub-grass dynamics (e.g. Harr et al., 2014; Howden et al., 2008; Pannell et al., 2006; Pelling, 2011), and modified regulations to permit safe ecological burns, are tangible options. Regarding logistical constraints, ecological burns to promote grassy ground-layers are likely to benefit declining native forbs of cultural significance to Aboriginal people, e.g. the Yam Daisy (*Microseris lanceolata*). Supporting local Aboriginal people to undertake fire management through employment and training in natural resource management offers one potential way to achieve ecological burning in such sites.

9. Values could constrain capacity to manage native grazing pressure (V)

Managing total grazing pressure to avoid accelerated aridification may require culling of native herbivores such as kangaroos. The potential for kangaroos to contribute to land degradation under climate change has not been widely assessed, but even in current climates kangaroo culling is often required to control population explosions and avoid degradation (e.g. Mowska, 2015 and references therein). Kangaroos are protected by law, with routine culling controlled by licensing, so regulations do not in themselves limit kangaroo control. However, kangaroo culling is typically unpopular, potentially limiting effective kangaroo control (V), especially in high conservation value woodlands which are more likely to attract public scrutiny. Mowska (2015) showed that education may only partly modify such views. Reframing the decision context to manage total grazing pressure is thus likely to be unsuccessful without concerted effort to shift societal values on culling as a more humane option than starvation.

10. Inadequate rules could jeopardise high conservation value sites (R)

Threatened ecological community legislation currently protects high conservation value temperate grassy eucalypt woodlands and derived grasslands. Remnants need to meet specific criteria to qualify for protection, for example <30% shrub cover, presence of >8–12 native perennial forb species or a specified dominant tree species (e.g. Department of the Environment, 2015).

As ecosystems adjust to climate change, sites currently qualifying as threatened ecological communities are likely to retain high conservation values because they represent the least-invaded and least nutrient-enriched sites. They therefore offer the best opportunities for conserving existing species and for community re-assembly by regionally native (rather than exotic) species (Prober et al., 2012). However, with tree mortality, changing species composition or increasing shrub cover, these sites may no longer meet definitions for legislative protection (R), making them vulnerable to introduction of livestock grazing, fertilisation or other management that would reduce their biodiversity values. Similarly, existing guidelines or legislation (R) may constrain adaptive management (e.g. introduction of non-local provenances). These challenges indicate an imperative to update legislation to allow for the impacts of climate change on threatened ecological communities (e.g. using lists of important sites).

11. Inadequate knowledge underpinning values and rules could lead to ineffective revegetation choices (KVR/KRV)

Evidence that local populations are best adapted to local conditions has led to a strong focus on using local provenances (including local species and genotypes) for environmental plantings (Broadhurst et al., 2008). In a changing climate, principles of local provenancing may no longer apply. The longevity of many of the species being planted, and delay to establish tree hollows (100+ years, Gibbons and Lindenmayer, 2002), makes it crucial to select provenances with a high likelihood of persisting through climate change. However, provenancing strategies that consider adaptation potential under uncertain rates and magnitudes of climate change are as yet untested (e.g. Prober et al., 2015b). Similarly, the degree to which preferred local provenances could adapt through natural or assisted selection, potentially reducing the need to introduce non-local provenances, is poorly known. The absence of adequate knowledge (K) to underpin alternative guidelines (R) and modify values (V) could thus constrain the appropriate adjustment of provenancing practices.

Nevertheless, local communities have begun the process of reframing the decision context for revegetation by already proposing the planting of non-local provenances as a way to address a drying future (Dunlop et al., 2016). This suggests a shift in community values, based on a shift in knowledge, is feasible. To

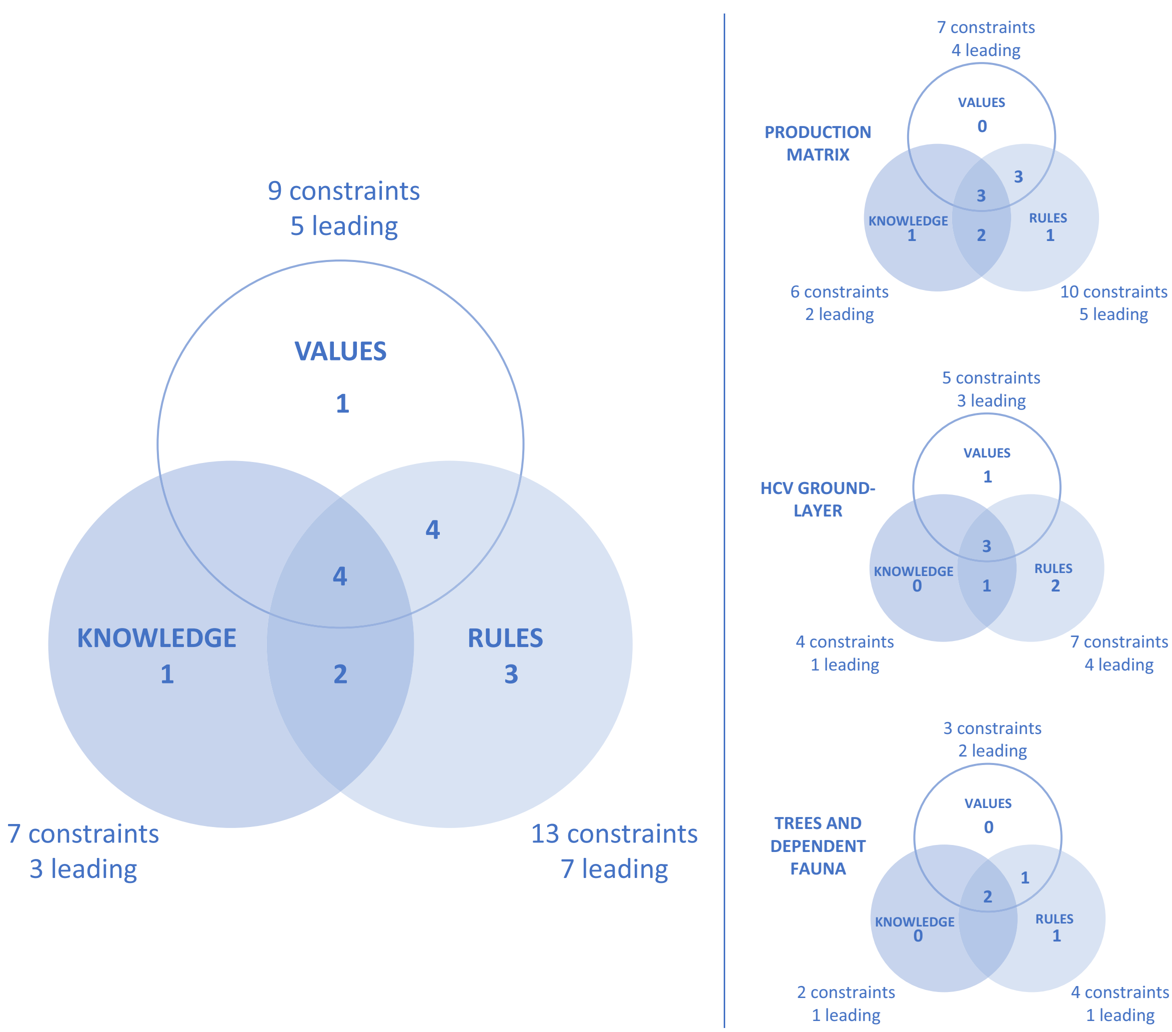



**Fig. 5.** Combinations of values, rules and knowledge constraints recognised through our analysis as limiting climate adaptation in temperate grassy woodlands, consolidated across the three adaptation pathways (left) and for individual adaptation pathways (right). Leading constraints are those that likely need to be addressed first within an interacting set of constraints.

reduce and manage uncertainties (K) and influence associated values and guidelines about provenancing (VR), it would be valuable to develop a testable framework to guide the choice of species and provenances for restoration.

12–13. Values and rules constrain capacity to maintain tree-dependent fauna (VR, R)

Decline of woodland trees already threatens tree-dependent fauna across temperate grassy eucalypt woodlands (Lindenmayer et al., 2016). Even dead trees are variously protected under state legislation owing to their significant habitat values (Department of the Environment and Heritage, 2005), but if tree mortality becomes widespread, pressures may arise to modify legislation to allow their removal (interpreted as a values-rules interaction, VR). These pressures could be difficult to alleviate. Further, dead trees will decline in habitat value over time, and efforts to manage revegetation and provide artificial habitat are likely to be logistically constrained across broad scales (R). Strategically locating artificial habitat in connected networks of refugia across landscapes would be more achievable.

14. Diversification of farm businesses may be constrained by paucity of viable alternatives (KR)

Established and emerging production alternatives offer farm businesses some options to increase their financial resilience through diversification, but diversification and adaptation could be limited by availability of new, climate-appropriate enterprises and markets (inadequate knowledge and institutions, KR). Reframing the decision context could be expedited by industry grant schemes facilitating investment in research; again, trade-offs between investments in transformational options need to be balanced against investment in incremental enhancements of current enterprises.

15. Insufficient demand to develop cost-effective soil, vegetation and landscape restoration methodologies limits knowledge and capacity to optimise resilience (VKR)

Tree planting, fencing of remnant vegetation and conservation farming methods (e.g. stubble retention) are widely used to restore aspects of ecological resilience in temperate eucalypt woodland landscapes, but soil, vegetation and hydrological degradation remain prevalent (Prober et al., 2012; Scott et al., 2010). Greater effectiveness is limited by insufficient support (V) to seek and implement novel solutions (KR), exacerbated by the sheer complexity and extent of the ecological degradation. Increasing

**Table 3**
Setting the scene for adaptation. A summary of VRK preparatory actions, resilience building options and biophysical management tools to facilitate adaptation in temperate eucalypt woodland multi-use landscapes.

| Options | Purpose | Timing |
|---|---|---|
| **Address value-related constraints** | | |
| Typically challenging, likely to require diverse and novel approaches | Potential contribution of native production systems recognised, environmental risks of transformer exotics considered, kangaroo culling/harvesting socially acceptable, dead trees valued, ecological restoration valued for capacity to build resilience | Early |
| **Address rule-related constraints** | | |
| Markets | Environmental costs of production accounted for by markets to minimise land degradation and costly invasions by transformer exotics; new markets developed for novel enterprises | Early |
| Incentives | Adjustment of rural economies facilitated with minimum environmental cost | As required |
| Legislation | Legal protection for threatened communities updated to account for climate change; introduction of transformer exotics prevented; ecological burning enabled | Early |
| Monitoring | Woody thickening and invasions by transformer exotics identified early | As becoming relevant locally |
| Infrastructure | Production systems in place for native forage species and alternative (e.g. carbon) enterprises | Early |
| Capacity | Aboriginal and other community capacity increased to facilitate increased need for burning, restoration, monitoring, seed collecting and habitat augmentation | Early |
| Extension | Local managers understand fire, grazing and shrub interactions, facilitating application to management | As becoming relevant locally |
| **Address knowledge constraints** | | |
| Research and development | Fine tuning of agronomy and genetics prolongs viability of current enterprises, agronomic advances enable viable native production systems; new provenancing strategies promote long-term viability of plantings; new climate resilient enterprises developed to encourage enterprise diversity; new restoration approaches refined to enhance ecological resilience | Early |
| **Build resilience** | | |
| Restore degraded lands and vegetation to increase resilience | Degraded lands restored to optimise soil condition; plant diversity increases resilience of native pastures, remnants and plantings; configurations (connectivity, larger patch sizes) enhance resilience of native fauna | Early |
| Diversify on and off farm enterprises | Farm input and market diversity buffers farm viability | Early |
| **Manage biophysical change** | | |
| Manage ground cover | Total grazing pressure reduced (livestock, kangaroos, feral herbivores) to prevent degradation | As required |
| Incorporate climate-resilient crop and livestock genetics | E.g. increased crop drought tolerance or improved livestock prolong viability of enterprises | As required |
| Fine-tune crop and pasture agronomy | E.g. lot feeding, intensification in grazing systems already based on exotics; precision agriculture prolong viability of enterprises | As required |
| Establish native forage species | E.g. native grasses, saltbush provide alternative production options | As required |
| Control transformer exotics such as buffel grass | Eradication or containment facilitated by rapid response to invasion | As required |
| Manage shrub densities through fire and grazing | Preferred balance of shrubs and groundlayer species maintained | As required |
| Plant native grasses, trees and shrubs for biodiversity | Provenances and species planted offer higher climate resilience | As required |
| Augment fauna habitat | A network of habitat refugia facilitate persistence of tree-dependent fauna | As required |

support for innovation is challenging when solutions are elusive, but it may grow as the impacts of climate change intensify.

### 3.7. Perspectives on application of the values-rules-knowledge framework to adaptation pathways

Our analysis illustrates how applying a values-rules-knowledge perspective to biophysical adaptation pathways can elucidate constraints to planning and implementing climate adaptation. This paves the way for identifying solutions, and reflects increasing recognition that adaptation options are constrained by governance arrangements and human behaviour (Maru and Stafford Smith, 2014; O'Brien and Wolf, 2010; Ostrom, 2011; Wise et al., 2014).

Of the 15 sets of constraints we identified across the three adaptation pathways we examined, most (13) involved rules, nine involved values and seven involved knowledge (Fig. 5). Similar ratios were observed for individual pathways (Fig. 5). Gorddard et al. (2016) argue that consideration needs to be given not only to independent values, rules or knowledge constraints, but to interactions among them. Consistent with this, ten of the 15 constraints included two or three way interactions (Fig. 5).

Notably, we found that where constraints interacted, a 'leading' constraint (that underpins or drives subsequent constraints) could often be identified. For example, to maintain a region free of invaders such as Buffel Grass would require both strong community support (V) and legislation (R); however, legislation is likely to be dependent on first gaining community support. Similarly, lack of knowledge (K) currently underpins conflicting values (V) and guidelines (R) regarding appropriate provenancing strategies for revegetation under climate change. These interactions align with the concept that changes in one element of the values-rules-knowledge triad, or among a suite of leverage points, may drive responses in one or more of the others (Abson et al., 2017; Gorddard et al., 2016).

In our analysis, seven of the 15 sets of constraints were led by rules-related constraints, consistent with the increasingly recognised importance of governance and institutions in the dynamics of change (Colloff et al., 2017; Fazey et al., 2015; Gorddard et al., 2016; Wise et al., 2014). Unlike substantial power imbalances or need for deep institutional reform that can be difficult to address (e.g. Abson et al., 2017; Fazey et al., 2015), most of these had tangible solutions such as updating legislation on threatened ecological communities or transferring knowledge to land managers (Table 3). An exception was for logistic constraints (which we classed as rules-related if they were dominated by an overwhelming lack of capacity). Some of these, such as landscape-wide monitoring and burning to control shrubs, or provision of interim faunal habitat, could become feasible if resource and capacity deficits were rectified strategically across a region.

Five sets of constraints were led by values (in the sense of Schwartz, 2012; O'Brien and Wolf, 2010), and these appeared the most difficult to overcome (Table 3). For example, views on culling native animals can involve deep-set ethical beliefs, that education may only partly modify (Mowska, 2015). Similarly, trade-offs between production and biodiversity benefits lead to conflicting interests and views regarding introduction of exotic plants, and this conflict remains unresolved in other Australian ecosystems (Driscoll et al., 2014). This apparent challenge is consistent with the argument that values represent 'slow' variables that are difficult to change (Pannell et al., 2006; Fazey et al., 2015; Walker et al., 2012), requiring attention to deep leverage points such as promoting connections between humans and nature (Abson et al., 2017).

Nevertheless, O'Brien and Wolf (2010) argue that, while conflicts over differing values and world views are difficult to resolve, ethics dictate that adaptation responses benefiting the broader community and environment should be prioritised over responses motivated more by self-interest or personally-held values. The expression of values through group and higher level interests, aided by decision support tools that facilitate exploration of the consequences of different scenarios, are thus likely to make achieving consensus and balanced outcomes more tractable (Brandt et al., 2017; Pretty and Smith, 2004). Further, we found that when led by knowledge-related constraints, values-related constraints appear more tangible, consistent with Pannell et al. (2006) who suggest that enhancing learning can accelerate adoption of new methods. For example, controlled use of fire may become acceptable if its benefits are well-demonstrated and fears around risk are appropriately addressed (Harr et al., 2014).

It is notable that we identified fewer knowledge-related (7) constraints than other categories, including only three leading constraints, and two that were related to poor knowledge transfer (RK, Pelling, 2011) rather than poor underpinning knowledge. This highlights the power of the VRK approach for moving beyond a 'we just need more information' mentality (Brunk, 2006) to a more pro-active approach to change. Investment in research could address the remaining knowledge-related constraints (Table 3), although for two we suggest more intangible limits to public demand (V) could constrain such investment. The latter is supported by already limited investment in native-based production systems (e.g. Revell et al., 2013) and the challenge of solving complex ecological problems to restore resilience in Australian agricultural landscapes (e.g. salinisation, biodiversity decline; Prober et al., 2012).

The lower prominence of knowledge constraints also highlights a particular feature of our operationalisation of the VRK framework. Focusing on decision points within biophysical adaptation pathways effectively identified constraints to predefined steps, but these pathways were created within the limits of existing knowledge. As illustrated by the resilience options (which both included knowledge constraints, 14 and 15 in Table 2), new knowledge could reveal new potential solutions. Thus the operationalisation of the VRK framework needs to be iterative and to take account of changes in knowledge. Uncertainty about the rate and magnitude of climate change also underpins all pathways. 'Lack of knowledge' can thus operate at a larger scale than the decision point, consistent with the broader adaptive planning approach (Haasnoot et al., 2013; Maru and Stafford Smith, 2014; Wise et al., 2014), and requiring research and innovation contexts that lead to richer sets of scenarios (e.g. Castree et al., 2014).

Our study comprised multi-use landscapes with multiple stakeholders and decision-makers in a liberal decision-making environment: our focus on pathways and decision points for three different landscape elements highlighted several conclusions dependent on this context (and hence likely relevant to similar social–ecological landscapes). On the one hand, we propose that a diversity of local-scale, within-sector decision-makers (e.g. individual farmers) would help maintain diversity in the landscape and expedite the refinement of efficient solutions (e.g. the most profitable land uses, win-win solutions). This is unlike the more contentious emergence of multiple pathways driven by social or historical inequities, such as differing opportunities for individuals of different socio-ethnic origin in Transylvanian communities (Fazey et al., 2015).

On the other hand, cross-sectoral trade-offs between biodiversity and production (e.g. Smith et al., 2012) are likely to become more pressing. As noted above, differences in values and influence among stakeholders (O'Brien and Wolf, 2010) emphasise the importance of group and higher-level planning and policy (rules) to achieve an adequate balance of biodiversity and production outcomes (Fazey et al., 2015; O'Farrell and Anderson, 2010; Pannell et al., 2006; Smith et al., 2012). Nevertheless, the need for higher-level solutions to solve within- or among-sector challenges (e.g. potential farm business failure or preventing exotic invasions) could disempower local people and action (e.g. Pannell et al., 2006).

The application of the VRK framework in conjunction with decision points also offers guidance on the sequencing of climate adaptation actions and helps indicate where path dependencies may arise (synthesised in Table 3; Gorddard et al., 2016). Some of the actions we generated require early intervention, before a decision point is even reached (e.g. establishment of monitoring programmes). On the other hand, investing too early in change could lead to wasted resources and loss of trust. This emphasises the importance of strategies such as choosing no-regrets options early, but being more strategic about high investment or higher-risk decisions (Haasnoot et al., 2013). For example, the use of native grasses is of increasing interest even under the current climate, so investment to improve agronomic knowledge is likely to be beneficial regardless (Revell et al., 2013). Similarly, trade-offs between invasive pasture species and biodiversity conservation already occur across Australia, and it would be beneficial to hasten adoption of solutions to this issue at the national scale (Driscoll et al., 2014). More challenging are decisions that are difficult to reverse, such as introducing non-local native species and provenances for revegetation.

Finally, Abson et al. (2017) propose that interventions to engender transformational change towards sustainability are centred on 'deep leverage points' in a complex system (where small shifts may lead to large system changes): reconnecting people to nature, restructuring institutions and rethinking how knowledge is created and used in pursuit of sustainability. We consider the VRK perspective represents a powerful heuristic for intervening at these deep leverage points of system *design*, including how changing rules provides incentives, frees constraints and increases capacity for change, and *intent*, which include goals, paradigms and the power to transcend them.

### 3.8. Concluding remarks

We conclude that potential futures for temperate eucalypt woodland landscapes in a changing climate are characterised by a variety of opportunities, and that application of the values-rules-knowledge framework helps to identify and hence overcome constraints to achieving effective outcomes. This case study illustrates how the framework provides a link between a biophysical, knowledge-based view of adaptation, and a perspective focusing on responses and adjustments in social systems. Our focus on multiple pathways and decision points across the production and biodiversity sectors also revealed the importance of group and higher-level planning for shaping the collective outcomes of individual decisions by many land managers across multi-use landscapes.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2017.02.021.

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