A framework for nature conservation under future climates

Informing climate adaptation planning in the Adelaide and Mount Lofty Ranges region

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Executive Summary

There is now unequivocal evidence that the global climate is warming, and that this directional change is occurring as a result of human activity (particularly emissions of carbon dioxide, as well as land use change[1]. There is also increasing evidence that these directional changes in climate are impacting on global biodiversity [2, 3]. As with other fields of human endeavour, future conservation strategies will need to account for the predicted impacts of these directional changes in climate [4-6].

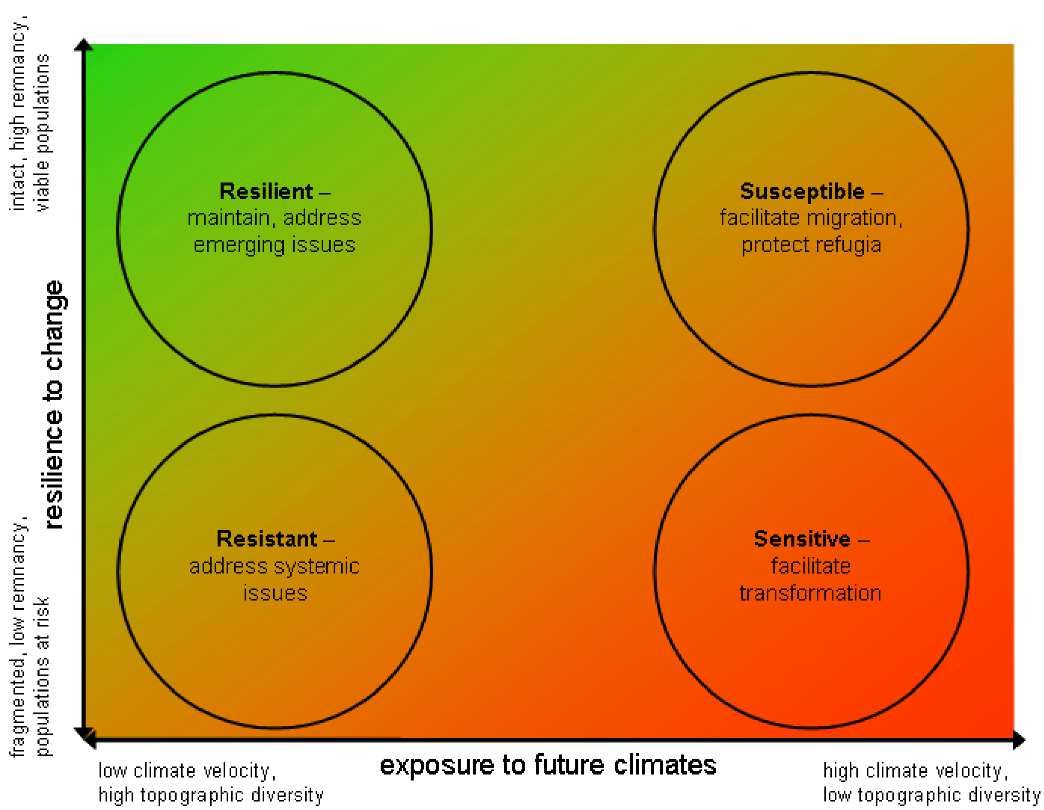
However, the nature and extent of these impacts will vary in complex ways that not only depend on the direct response of biota to climate variables, but on the capacity of the biota to respond to a changing climate. Rather than applying generic climate adaptation strategies to every situation, strategies should be designed that take account of the impacts that are likely to occur within the landscape of interest [4].

Building on the ideas and frameworks of Gillson *et al.* [5] and Prober *et al.* [6], here we apply a framework for identifying the relative risk, and adaptation options, of biodiversity in particular landscapes. For a given region, the risk to each asset is assessed against two parameters (see Figure below):

i) Climate exposure: The nature and extent of changes in the environmental conditions as a result of predicted changes in climate; this can be influenced by large-scale features such as latitude and ocean currents, as well as fine-scale features such as topographic variation [8, 10-12];

ii) Response capacity: The capacity for the asset to respond to changes in the biophysical environment; this capacity is related to the resilience of the asset [9, 13].

This framework for nature conservation under future climates can potentially be applied at multiple levels of biodiversity (species, ecosystem, landscape), noting that these levels interact [6]. Understanding these interactions among different hierarchical levels is important for planning, as the risks and adaptation options at lower levels (e.g. species) will be at least partly reflected by those risks and options at higher levels (e.g. landscapes) within which the lower levels are nested.



We have applied this framework to the Adelaide and Mount Lofty Ranges region, in order to assess the relative risk and adaptation options to the different ecological landscapes of the region. Four terrestrial landscapes were identified for the purposes of this process: i) Higher elevation ranges, that typically support stringybark forests and shrublands, along with the headwaters of streams and rivers; ii) Lower slopes of the ranges, that typically support open woodlands with grassy/herbaceous understoreys; iii) Plains, that typically support semi-arid shrublands and mallee woodlands; iv) Coastal landscapes, that typically support either coastal shrublands (in higher wave energy environments) or samphire shrublands and mangrove forests (in lower wave energy environments). When this framework was applied to these four landscapes, the following conclusions were drawn:

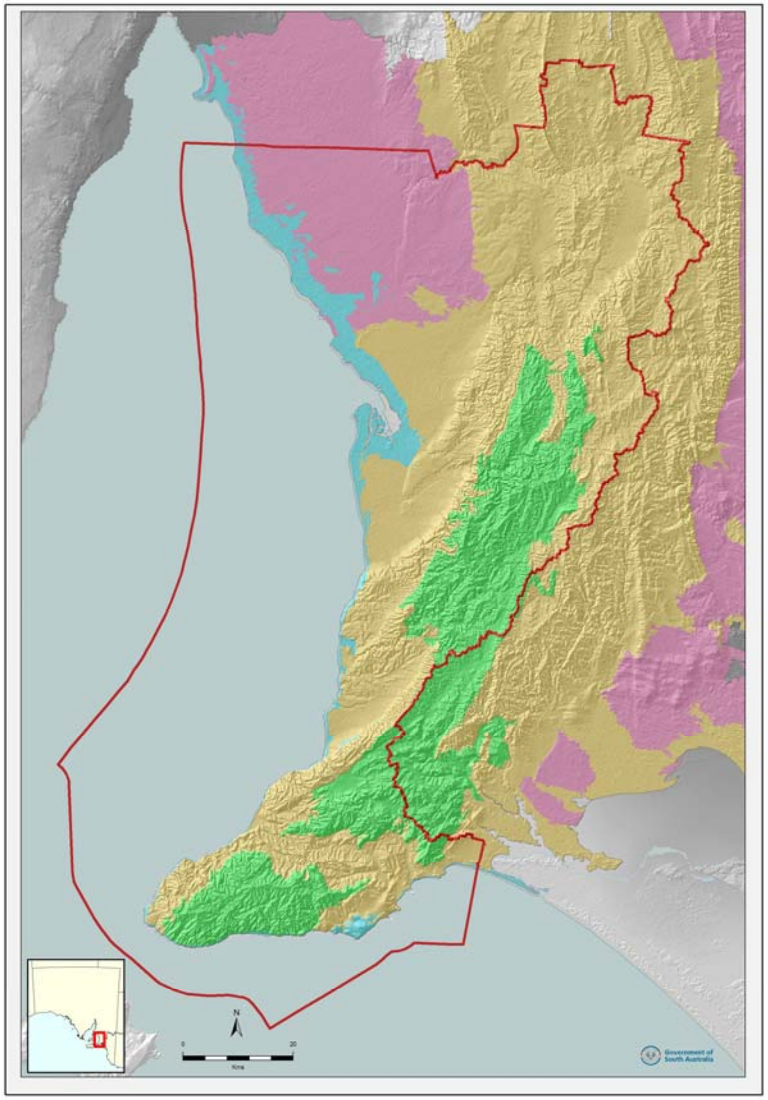
i) **Uplands:** The higher elevation landscape of the southern Mount Lofty Ranges are relatively intact (25.4% remnancy), and appear to be relatively stable and resilient [7]. In addition, this landscape is less exposed to rapid climate shifts when compared to other landscapes in the region [8], a pattern that is at least partly driven by the high topographic diversity of the landscape. As a result, the relative risk to biodiversity of future climates (in the context of other drivers) is low in comparison to other landscapes in the region. The recommended strategic response to climate change in this landscape is **Passive Adaptation**, whereby actions focus on the maintenance of current function, including identifying and addressing new (unknown) threats as they emerge.

ii) **Lower Slopes:** The lower elevation rolling hills of the southern Mount Lofty Ranges are strongly associated with declining function and resilience in the region. Mapped remnancy is low (8.4%), and dependent native biota are declining [7]. These areas are also considered to be more exposed to changing climate than the higher elevation ranges [8], although are likely to be less exposed than the surrounding plains (based on their topographic diversity). The key adaptation strategy in this landscape is **Active Adaptation**, which involves improving the resilience of native ecosystems in this landscape, through the restoration of grassy ecosystems. Under certain circumstances, however, **Transformation** may be required; this will potentially involve strategies including introducing species outside of their historic range such that they can provide important ecological functions under future climates.

iii) **Plains:** The semi-arid plains that flank the southern Mount Lofty Ranges have been subject to significant historic impacts (including urbanisation, industrialisation and intensive agriculture) since European settlement, and, as a result, no longer support much of the original dependent native biota (i.e. have entered an alternative stable state from the perspective of native biodiversity). This landscape is also likely to be highly exposed to changes in climate, largely due to the low topographic diversity of the landscape [5, 8]. From the perspective of nature conservation outcomes, the key management strategy for this landscape is **Passive Transformation**, which may include management of the matrix to maximise functional connectivity. This will help to ensure that the remaining biota of the landscape continue to provide the functions that currently support natural resources (including soil conservation, water management and sustainable agriculture).

iv) **Coastal landscapes:** The coastal landscapes of the Mount Lofty Ranges (particularly north of Adelaide) are relatively intact (41.6% remnancy), and continue to support unique flora and fauna in the region[9]. However, these landscapes are highly exposed to the impacts of future climates, particularly in relation to predicted changes in sea level. These changes in sea level will particularly impact the northern coastline environments that currently support samphire shrublands and mangroves [10], and continue to provide unique habitats in the region (e.g. for migratory shorebirds and regionally unique flora and fauna). For these lower energy coastlines, the key management strategy is **Transformation**, to facilitate landward migration of these systems (e.g. through appropriate land use planning and active intervention on these lands).

The recommendations presented here thus provide some strategic guidance for NRM planners to inform a nature conservation climate adaptation strategy. Given the inherent uncertainties within both climate models and in predictions of ecological response to future climates [11], the principles of adaptive management particularly need to be applied in the context of climate adaptation [12].



Uplands: Topographic diversity is high, and low sensitivity to climate change. Biota have high resilience, and capacity for change.

Recommended strategy: **Passive adaptation**. Identify and manage existing threats, and emerging threats as they arise.

Lower Slopes: Topographic diversity is high, but species turnover is more sensitive to climate. Biota has low resilience, and thus has little capacity to cope with change.

Recommended strategy: **Active adaptation to Transformation**, In addition to those strategies for passive adaptation, reconstruct habitats to increase resilience. In some cases, functional novel ecosystems may be encouraged.

Plains: Topographic diversity is low, and sensitive to climate. While major changes have occurred to biota since European colonisation, the extant biota is relatively stable (in a degraded state).

Recommended strategy: **Passive to active adaptation**, depending on the degree of modification. Aim is to maintain current ecological functions of the landscape. This may involve facilitated migration and buffering and restoring remnants.

Coastal: Topographic diversity is low, and sensitive to climate. In addition, this landscape is extremely sensitive to sea level rise, particularly in the northern low energy systems. Biota of this landscape is resilient and has some capacity to cope with change.

Recommended strategy: **Passive adaptation** (in intact areas that are less exposed to sea level rise), to **Transformation** where facilitation of landward migration is required

Biodiversity and climate change adaptation

The hierarchical nature of biodiversity

Biodiversity exists at a range of hierarchical levels of organisation (landscape, ecosystem, species, individual)[13]. Furthermore, these levels of organisation are at least partly nested, such that processes that influence one level of organisation will also have some influence on those levels above and below. For example, environmental drivers that impact a particular ecosystem will influence both how the broader landscape functions, and how populations of species (that depend on that ecosystem) function. From the perspective of conservation planning, the nested nature of biodiversity has been used as a way of nesting the range of management interventions required, using the analogy of 'coarse-filters' and 'fine-filters'[24-26]. In this case, the systemic conservation requirements at higher levels of organisation (ecosystems, landscapes) are thought to capture the requirements of at least some of the nested lower levels (species, individuals), such that the conservation 'coarse-filter' will capture much of the conservation requirements of a region. However, the 'coarse-filter' will not capture the complete range of requirements, particularly where species have specialised requirements, and so more specific management actions will be required in some cases (the conservation 'fine-filter')[14]. This conservation planning approach is currently being applied in the Adelaide and Mount Lofty Ranges region [7, 9], and has been used in other South Australian NRM regions to identify priorities for 'coarse-filter' conservation activity [15-17].

The response of biota to environmental change - including directional climate change - will depend on a range of biological attributes that differ among these hierarchical levels [6] (Table 1). Many of the attributes listed are less a function of the inherent sensitivity of biota to climatic change, but more a function of how biota are able to cope with change (i.e. *resilience*). These features of resilience are, in turn, mediated by a range of physical and biological drivers (including, but not limited to, climate drivers), and how these drivers interact. In the current global environment, these drivers are typically strongly influenced by human activity. For example, at the species level, capacity to disperse is not only influenced by the inherent dispersal mechanisms of a species, but also by the degree to which these dispersal mechanisms have been disrupted by human land-use (e.g. fragmentation of habitat by clearance for agriculture). At all levels in the biological hierarchy, therefore, the response of biota to future climates will be determined as much by the influence we have on non-climate drivers, as on the climate.

Table 1. Attributes of different levels in the biological hierarchy that mediate the response of these biota to climate change.
The response of biota to environmental change (including directional climate change) is generally related to the capacity of these systems to respond to change, which in turn is a function of a system's resilience. After Prober *et al.*[6].

Level of biodiversity	Attributes that mediate response to climate change
Individual	Physiological tolerance Phenotypic/behavioural plasticity
Species	Genetic diversity Population size Capacity to disperse Propagule availability
Ecosystem/Ecological community	Functional and response redundancy Potential for negative feedbacks (ecosystem complexity) Functional connectivity
Landscape	Environmental heterogeneity Functional connectivity Potential for negative feedbacks (ecosystem complexity)

The impact of climate change on biodiversity

There is now little doubt that increases in atmospheric CO_2 (primarily through fossil fuel emissions) are responsible for a significant, directional shift in global climate patterns. The recently released IPCC Fifth Assessment (Working Group I) Report[1] found the following:

- "Warming of the climate is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia"
- "CO_2 concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions, and secondarily from net land use change emissions"
- "It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century"

There is also increasing direct and indirect evidence that these climatic changes have, and will continue to have, significant impacts on the world's biodiversity[3, 31, 32]. These impacts will manifest in a range of ways, including range shifts, temporal changes to seasonal events (e.g. phenology, migration) and loss of habitat[18]. While the specific nature of these biological shifts contains a great deal of uncertainty, we can be reasonably confident that the biodiversity of a future climate will be different, in many respects, from that of the past.

While there is a consensus that biodiversity will be impacted by directional climate change, the particular nature of these impacts are mostly uncertain[19]. Predictions regarding future climates contain levels of uncertainty (that vary spatially and among the different climate variables)[1], while the direct response of even individual species to these predicted climates are also uncertain[20]. These biophysical uncertainties are then compounded by the additional complexities that stem from interactions among species (both current interactions, and new interactions where species range shifts occur). Furthermore there has been increasing commentary regarding the direct response of biota to future climates, relative to the impact that changes in human socio-economic behavior in response to climate change will have[21].

While uncertainty regarding the response of biota to future climates exists at a range of levels, predicting likely responses to particular climate scenarios can provide useful guidance for management under the likely range of future climates. For example, by highlighting where particular adaptation strategies are likely have benefits regardless of the exact nature of future climates (or the biotic response to these), we can implement these strategies with a degree of confidence that our actions will not lead to undesirable outcomes.

General approaches to climate adaptation for biodiversity conservation

In response to the predicted risks that global warming place on biodiversity, there have been a large number of recommendations regarding appropriate management responses to these changes. The adaptation strategies described can be placed into two categories[4]: strategies based on general principles, and those that are specific and actionable (if not relating to a specific location, these strategies at least provide specific guidance for how to determine the relevant actions to take at a specific location). Among the more common recommendations are those based on general principles[4]. These include:

- Increasing connectivity (e.g. remove barriers to dispersal, design corridors)[22]
- Increasing the area of land reserved for nature conservation (i.e. protected areas)
- Create buffer zones around reserves
- Create ecological networks
- Increase genetic diversity and gene flow[23]
- Protect current and future refugia[24]

One of the critical limitations of these generic adaptation strategies is their limited practical application, in that they often fail to guide the delivery of adaptation strategies in the particular context within which individual land managers operate. For example, recommendations that call for an increase in connectivity tend to do little more than provide guidance based on common sense[4], and don't provide adequate guidance to operationalise a strategy where the objective is to increase connectivity.

At the other end of the spectrum, an extensive literature exists[25, 26] regarding the predicted responses of individual species to future climates. The majority of this work correlates the current known distribution of species with the recent historic 'climate envelope' the latter which describes the range of climatic conditions under which the species is known to exist. These species distribution models rely on a number of critical assumptions[26]:

- SDMs tend to assume that correlation approximate causation, with regard to the relationship between a species distribution and particular climate parameters. These correlative relationships are only rarely described mechanistically, largely because these mechanistic relationships are often indirect, complex, and poorly understood. Furthermore, these correlative relationships can be used to make predictions about species distribution beyond the climatic extent on which the models are based.

- SDMs make the critical assumption that species are both in equilibrium, and fully occupy their climate niche. This assumption presents significant challenges, particularly in highly modified landscapes (where important anthropogenic drivers, such as habitat destruction, disrupt this equilibrium).

- SDMs assume that the observed climate niche approximates the potential niche, and that climate is the over-riding limiter of species distribution. Species may have physiological tolerances to climate beyond their known distribution (if, for example, their known distribution is limited by competition, non-climatic physical thresholds, or incomplete distribution data).

More broadly, SDMs in isolation are not particularly useful for informing the management of ecological systems under future climates. The use of the predictions drawn from SDMs needs to be placed in the context of appropriate management strategies at other levels in the biological hierarchy, and account for how these levels interact. Managers should be careful to avoid using SDMs to develop conservation strategies, unless this information has been integrated into a broader framework whose ultimate aim is to identify and address the systemic and specific ecological processes that result in undesirable change to native biodiversity[27-29]

Applying climate adaptation strategies based on general principles requires an understanding of where such strategies are the most appropriate for conserving biodiversity under future climates. This understanding is critical, given that:

- the climate will not, by nature, change in the same way everywhere. The inherently variable nature of landscapes means that different climate variables will change in different ways

- the extant biodiversity of a landscape will respond to these climatic changes in different ways that depend on both their inherent biology, but also (importantly) on the other drivers (particularly other human-induced drivers, such as land clearance, grazing, etc.) that determine their capacity to deal with these changes.

In the absence of this understanding, the application of such strategies runs the risk of being ineffective (and therefore wasting limited management resources that could have been applied elsewhere), or, worse, may have negative impacts. It is important to point out that, when applied to relevant ecological contexts, all of these recommendations are likely to be useful somewhere. The question we need to ask isn't 'Is an increase in ecological connectivity a good strategy for climate change?', but 'Given the predicted response of biodiversity to climate change in a particular context, where is increasing ecological connectivity an appropriate response?'

Here we present a framework that outlines the information required to determine appropriate adaptation strategies for particular ecological contexts, and how this information can be applied in the development of these strategies.

A framework for nature conservation under future climates

‘Axes of concern’: Exposure to climate change, and adaptive capacity to cope with change

While rapid climate change is an increasingly important driver of some ecological processes, climate does not act on biota in isolation of other drivers. Climate is but one of a number of drivers that impact on biodiversity. Furthermore, the impacts of changing climate patterns are likely to have important interactive effects with these other drivers[3]. Our adaptation strategies, then, need to account for the impact of a changing climate on the system of interest, *in the context of other important ecological drivers that act on these systems*[21]. Given the ubiquitous impact that humans have on ecological systems, these non-climate drivers often relate to human social and economic drivers, and these drivers vary both in their nature and extent, depending the social-ecological system of interest. For example, across the agricultural landscapes of South Australia, a key driver of ecological systems remains the historic clearance of native vegetation, and the ongoing effects this has on the resilience of native biota. However, the extent and impacts of vegetation clearance vary, depending, among other things, on agricultural potential and the local development history. In the context of these other drivers, the effect that future climates have on native biota will depend not only on the extent and rate of climate change, but on how native biota are able to respond to these changes in the context of the modified environments within which they currently operate (with the degree and nature of modification varying across landscapes).

Ecological responses to future climates, then, will be dependent on two features of a system[8, 9]:

1. the **exposure** (extent and rate of change) of the system to future climates
2. the **adaptive capacity** of the system (resilience) to adapt to these (and other) changes to the environment.

Exposure to climate change: The exposure of a system to future climates refers to the extent and rate over which relevant biophysical environments (that include climatic features) are likely to change. The exposure of a system will depend on the degree to which climate will change in the broad biogeographic region of interest (e.g. warming appears to be occurring faster near the poles than the tropics[30]), but also depends on local features, such as the influence of oceanic buffering of temperature. In particular, local or regional topographic diversity plays an important role in determining the exposure of systems to changing climates[10, 11, 31]. For example, a global analysis of climate velocity[31] showed that the velocity of climate change was strongest in large, relatively flat biomes, and slowest in mountainous biomes. However, the relative exposure of systems to changing climates also need to account for the distribution of other, non-climatic drivers of distribution, such as edaphic (soil-related) features that drive plant distribution[32].

In addition, the exposure of a system to a changing climate will depend on what climatic features are the primary drivers of a system. For example, many terrestrial systems primarily respond to aspects of climate that determine water balance (rainfall, evaporation), while aquatic systems also respond to the secondary climate impacts of flow regime, and near-coastal ecosystems also respond to changes in sea level. Understanding the important features of climate change for a system is thus an important step in understanding ecological responses to change, and our adaptation responses.

Adaptive capacity to change (including climate change): Even with an understanding of the exposure of a system to future climates, the response of that system to these changes will depend on the system’s capacity to adapt to future stresses, such as changing climate patterns. This adaptive capacity relates to ecological concepts of resistance and resilience.

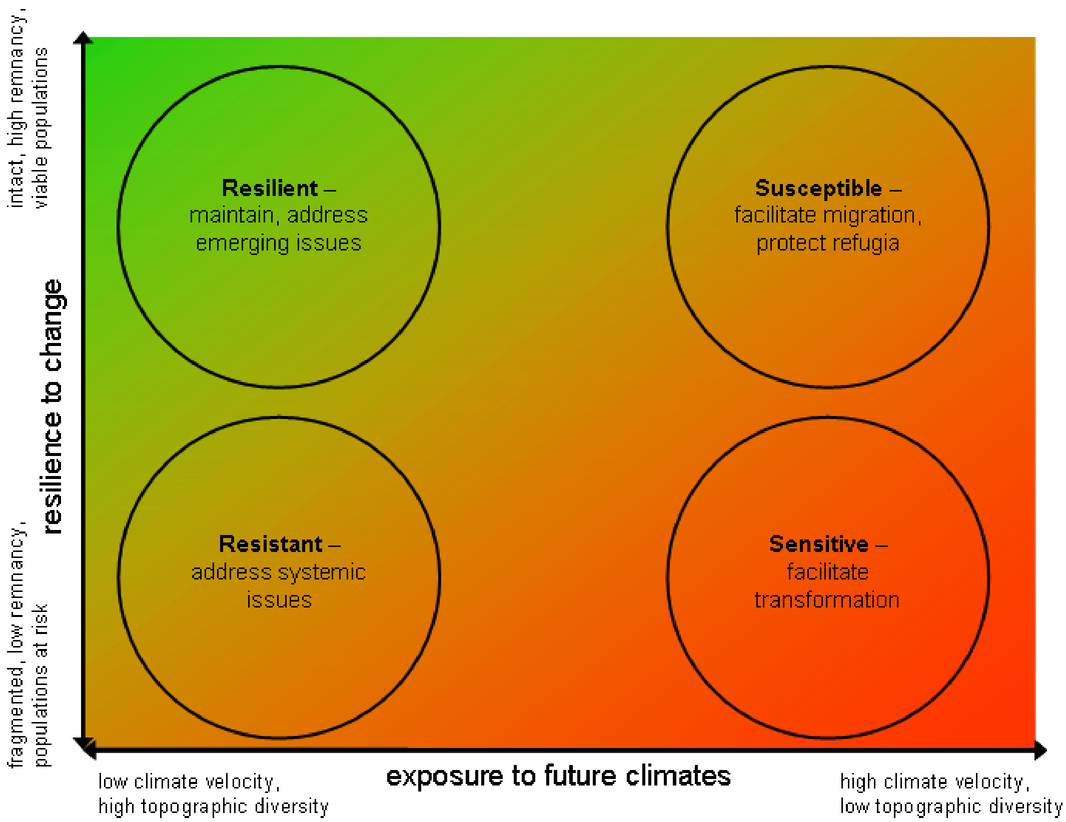


Figure 1. A classification matrix for the response of biota to climate change, based on two 'axes of concern'. **The risk of undesirable change to biota will depend on its exposure to future climates, and its capacity to adapt to these future climates (its resilience). Our subsequent adaptation responses to this risk will also depend on how different biota sit within this matrix. After Gillson *et al.* [5].**

The resilience of biological systems refers to the magnitude of a disturbance that a system can experience while maintaining its essential structure and function[33]. If a system has low resilience, even small disturbances will result in fundamental changes in the system's character and how it functions. In the context of climate change, then, a system's capacity to maintain function in the face of warming will depend on the resilience of this system.

In the current global context, the key determinants of a biota's resilience typically relate to drivers that are strongly influenced by human activity. In agricultural regions of South Australia, for example, a key driver of the resilience of ecosystems (and the species on which they depend) is the degree to which these systems have been converted to agricultural systems, and the extent and configuration of the remaining native vegetation within this agricultural matrix. Other important drivers of system resilience in South Australian systems are herbivory, fire regime, species interactions and hydrology, all of which have been significantly modified since European settlement. In the light of this relationship between system drivers of resilience and human activity, our management responses to climate change may, in some situations, be solely to reverse or restore those processes that have historically led to the degradation of system resilience, and thereby improve the capacity of these systems to cope with change (generally), and climate change (in particular)[6].

Context-specific adaptation responses for nature conservation

The risks posed by future climates to biodiversity will depend, then, on the exposure of a system to future climates, the adaptive capacity of that system, and the level of the system's organisation in the biological hierarchy (and how it interacts with other levels in that hierarchy). The identification of processes (including climate processes) that drive change thus provide a strong basis from which to identify where intervention is required, and the nature of these interventions[34]. It follows, therefore, that our adaptation responses for nature conservation will also depend on the nature of these features for any particular system. Gillson *et al.* [5] identified general adaptation strategies for landscapes, that account for these features of climate exposure and adaptive capacity. At this higher level of organisation, context-dependent adaptation responses can be classified as follows (Figure 1):

- *Resilient systems* (low climate exposure, high adaptive capacity): These systems are relatively intact, with functional ecological processes operating and adequate redundancy in response and function. They are also less likely to be exposed to large changes in relevant climate parameters (as they are found, for example, in topographically diverse areas). Our adaptation response for these systems largely involves **Passive Adaptation**. General passive adaptation responses include maintaining areas that currently support native biodiversity; ensuring that a diversity of functional environments are represented in the landscape; and addressing existing stressors.

- *Resistant systems* (low climate exposure, high adaptive capacity): While these systems are less likely to be exposed to large changes in relevant climate parameters, their resilience has already been compromised by other anthropogenic drivers (such as habitat destruction, inappropriate grazing regimes, inappropriate fire regimes or unsustainable extraction of water resources). For these ecosystems, non-climate drivers are of primary importance regarding the risk of irreversible, deleterious change. Our adaptation response for these systems involves **Active Adaptation**. General responses in this category include restoring habitats and ecological processes; identifying and protecting functional climatic refugia; are to identify the key drivers (such as those listed above) that are placing these systems at risk, and implement active management to address the impacts of these drivers.

- *Susceptible systems* (high climate exposure, high adaptive capacity): As in the case of resilient systems, susceptible systems are relatively intact. However, they are also relatively exposed to large changes in relevant climate parameters (as they are found, for example, in topographically homogenous areas). The biota of these landscapes are likely are more likely to have the capacity to respond to these shifts, such as through dispersal and migration to suitable environments, or through increased capacity for *in situ* adaptation. In these cases, our general strategy will overlap with that for Resistant Systems (**Active Adaptation**), particularly with regard to the protection of climate refugia and maximising the permeability of the matrix to ensure functional connectivity. In cases where opportunities for migration or refuge do not exist (e.g. if appropriate climate-edaphic settings no longer occur, or are unavailable due to other land-uses), our adaptation response may be similar to that for sensitive systems (see below).

- *Sensitive systems* (high climate exposure, low adaptive capacity): As with resistant systems (above), the resilience of sensitive systems has been compromised by (typically non-climatic) anthropogenic drivers, and are thus at risk of irreversible, deleterious change. Furthermore, these systems are exposed to large changes in relevant climate parameters. Because these systems are already compromised, they may not have the capacity to track changes in the distribution of suitable physical environments. The risk to these systems is that their composition changes in the future, such that they function in a way that is undesirable. The most appropriate adaptation response is **Transformation.** This may include species translocation, and designing systems that contain important structures and functions, while being compositionally novel[18, 19]. For example, if habitats for threatened species are likely to change due to a changing climate, we need to consider how to facilitate this change such that habitat attributes for these species are retained in the landscape [35]. A key step in these cases is to identify what these desirable functions are – how do we want future ecosystems to function, and why?[36]

While Gillson *et al.*[5] applied this framework specifically to the landscape level of organisation, a similar logic (with regard to the relationship that our adaptation responses have to climate exposure and resilience) can also be applied to lower levels of biological organisation[6]. At the species level, for example, Prober *et al.*[6] suggested that for species that were considered 'Susceptible' (using the terminology above, that is, high resilience, but high climate exposure), an appropriate management response would be to translocate intra-specific individuals from other populations (e.g. across the climate gradient of the species), while an appropriate response for species that are considered Sensitive (i.e. highly threatened species that are also sensitive to climate change) might be *ex situ* conservation as well as translocation[6]. However, the general principles apply at all levels of organisation; they key point of this framework is to identify where the most significant impacts of climate change are likely to be (with respect to both the velocity and magnitude of change, and to the system's capacity to respond), and implement management strategies that are designed to address the system-specific nature of these impacts in the context of the range of other drivers that are impacting on these systems[37, 38].

A case study using the Adelaide and Mount Lofty Ranges region

The foundational work of Prober *et al.*[6] demonstrated the application of a hierarchical climate response framework for biodiversity conservation, that was applied to a relatively intact landscape (the Great Western Woodlands of southern Western Australia). The landscapes of the Adelaide and Mount Lofty Ranges region provide an alternative context, with landscapes that largely range from variegated to relictual[39], while also containing some topographic diversity that suggests, in some cases, a range of different sensitivities to future climates. Applying the conceptual framework outlined above to the AMLR region will thus test the application of this framework under a more modified biotic environment, with a greater diversity of climatic sensitivity.

Landscape descriptions

For the purposes of this analysis, four broad landscapes were identified for the Adelaide and Mount Lofty Ranges region:

1. **Uplands.** These higher elevation areas (elevation range: 30 – 700mAHD) typically have higher than average rainfall for the region (mean annual rainfall ranges from 520 to 1,100 $mm.y^{-1}$, mean ± S.D. = 800 ± 91$mm.y^{-1}$). These areas also contain high local topographic relief, implying high microclimatic diversity. Native vegetation is dominated by sclerophyllous forests, woodlands and shrublands, with an overstorey that is typically dominated by *Eucalyptus baxteri*, *E. obliqua* and *E. goniocalyx*, and understoreys that are typically species-rich and dominated by shrubs. Native vegetation remnancy is relatively high (25.4%).

2. **Lower Slopes.** The lower elevation slopes of the southern Mount Lofty Ranges (elevation range: 0-600m AHD) have moderate average annual rainfall (mean annual rainfall ranges from 236 to 1020 $mm.y^{-1}$, mean ± S.D. = 530 ± 124$mm.y^{-1}$). This average annual rainfall varies geographically, particularly in the eastern slopes, where (for example) rainfall varies from 750$mm.y^{-1}$ at Mount Torrens, to 450$mm.y^{-1}$ at Palmer, over a distance of 19 km. The lower slopes of the southern Mount Lofty Ranges are thus a climatic transition region between the semi-arid Plains landscape, and the higher rainfall Upland landscape. Grassy woodlands and grasslands often dominate native vegetation. In the western slopes, these woodlands have overstoreys dominated by *Eucalyptus microcarpa*, *E. porosa* and *E. leucoxylon*, the latter two which are also common on the eastern slopes, along with *E. odorata* and *Allocasuarina verticillata*. Mapped native vegetation remnancy is low (8.4%), and remaining native vegetation is often degraded.

3. **Plains.** The plains surrounding the southern Mount Lofty Ranges have low elevation, and topographic heterogeneity is also low (elevation range: 0-450mAHD). Rainfall is relatively low compared with the landscapes of the ranges (mean annual rainfall ranges from 250 to 500 $mm.y^{-1}$, mean ± S.D. = 360 ± 44$mm.y^{-1}$). The native vegetation of the Plains landscape is typically dominated by semi-arid shrublands, grasslands and mallee woodlands. Mapped remnancy of native vegetation is low (8.4%), with the remaining vegetation concentrated in the eastern plains.

4. **Coastal.** The coastal landscapes of the Adelaide and Mount Lofty Ranges region range from high energy sandstone cliffs and sandy dunefields (principally along the south coast and southern Fleurieu), moderate energy sandy beaches (along the southern metropolitan beaches), and low energy mudflats, saltmarsh and mangroves (northern coastline). Mapped native vegetation is relatively high (41.6%), particularly on the northern, low energy coastlines.

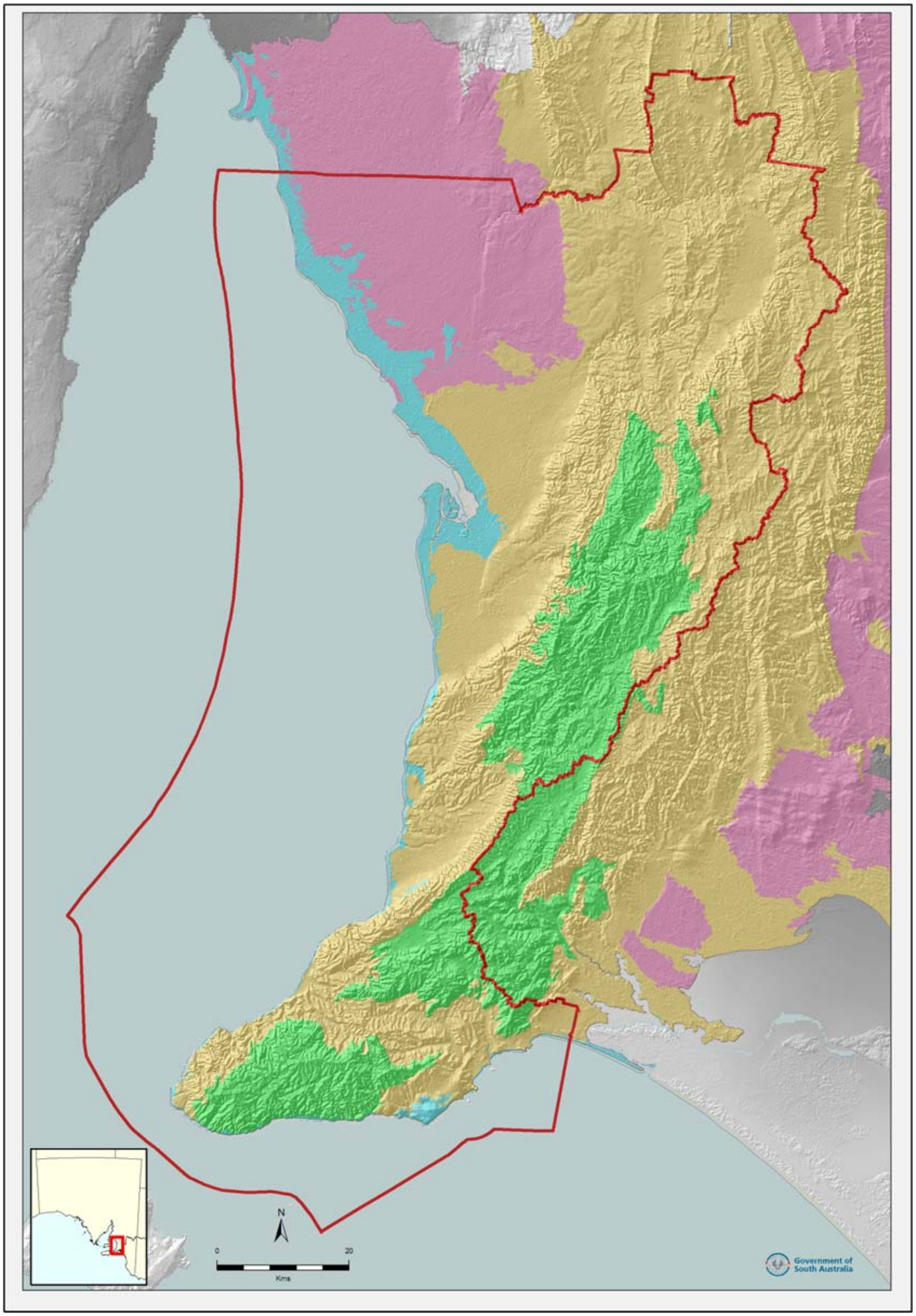


Figure 2. Distribution of the four terrestrial landscapes defined in this report. The four landscapes are: Uplands (green), Lower Slopes (orange), Plains (pink), and Coastal (blue). Detailed descriptions of these four landscapes are provided in the text.

Application of the framework to the landscapes of the AMLR region

As outlined above, the two broad information bases for determining the relative risk and appropriate response of biodiversity to future climates are the exposure of biota to future climate change, and the capacity of biota to cope with this change. Applied at the landscape level, this framework was populated using the following information:

1. Exposure to future climates. In the Adelaide and Mount Lofty Ranges region, the relative exposure of landscapes to future climates was determined from a number of sources:

   a. Topographic heterogeneity. By default, topographically diverse landscapes should be less exposed to future climates than topographically homogenous landscapes. Topographic diversity was measured by calculating the relief (elevation range) with each soil landscape unit of each landscape…

   b. Species turnover-climate relationships. Existing studies have investigated the relationship between climate and species turnover to identify which geographic areas are most likely to experience higher turnover under future climates. These results have been used here in the context of this framework.

2. Adaptive capacity. Landscape-scale adaptive capacity was determined using a number of lines of evidence:

   a. Proportion of the landscape with remnant native vegetation. This was calculated using the current version of floristic vegetation mapping [40], calculating the total area of native vegetation within a landscape as a proportion of the total area of the landscape. The proportion of native vegetation has often been used as a surrogate for the ability of a landscape to support extant native biodiversity [44-46]. However, landscape remnancy is an incomplete surrogate of function, as the nature and timing of modification, as well as the nature of the non-native matrix, are also important determinants of this functionality.

   b. Landscape Assessment. The state and trajectory of the landscapes of the southern Mount Lofty Ranges have been investigated in another study [7], to determine the priority landscapes for intervention (particularly restoration). This study combined information on:

      - the common ecological requirements of species, combined with information on their state and trajectory
      - The nature, timing and extent of land use change among different landscapes to identify systems that relatively resilient (compared with those that appear to be approaching critical thresholds).

1. Climate exposure

As expected, fine-scale topographic variation is higher for the Uplands and Lower Slopes landscapes, than the Plains and Coastal landscapes. For the Uplands landscape, the relief of 76.9% (n = 2,417) of soil landscape units was greater than 30m, while for the Lower Slopes landscape, 64.6% (n = 6,638) had a relief of greater than 30m. This compares with 23.6% for the Plains landscape (n = 2,208), and 25.8% for the Coastal landscape (n = 128). These data suggest that the Uplands, and to some extent, the Lower Slopes, will be less exposed to directional climate change than the surrounding Plains and Coastal landscapes (Figure 3).

In addition to being more likely to be sensitive to future changes in temperature and rainfall, the Coastal landscape is also highly exposed to another aspect of directional climate change – sea level rise. The risk of sea level rise are particularly relevant to the northern, low energy coastal systems, that both have extremely low slopes, and that contain biota whose composition is sensitive to changes in inundation regime.

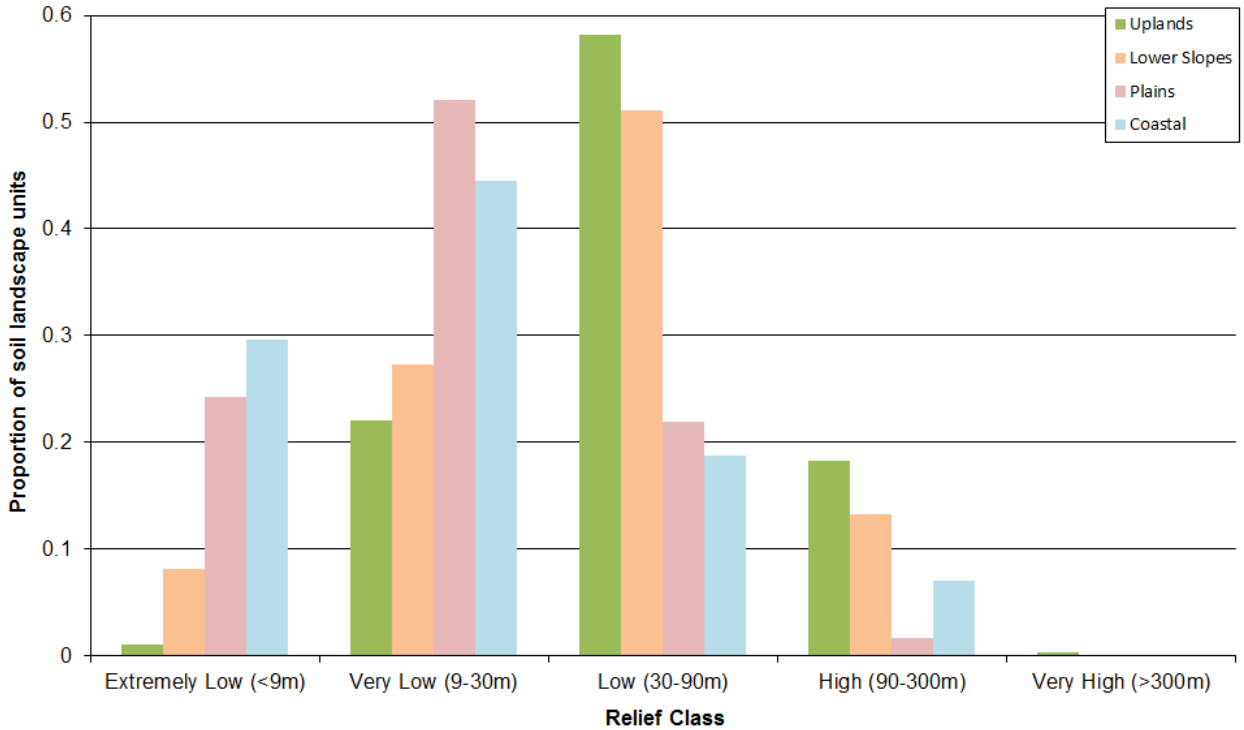


Figure 3. Distribution of relief classes among the soil landscape units for the four landscapes described in this report. Relief class for each soil landscape unit was determined by calculating the elevation range of each unit using the NASA S-Radar DEM (30 m horizontal resolution).

Guerin *et al.* [8] investigated the relationship between species turnover and climate in order to identify areas of the Mount Lofty Ranges where species composition is likely to change most rapidly under a changing climate. This study found that the areas that corresponded with temperature and rainfall ranges associated with more rapid species turnover were the lower slopes of the southern Mount Lofty Ranges (temperature and rainfall), and the plains adjacent to the Gulf St Vincent (temperature only). In contrast, the higher, more mesic upper slopes of the southern Mount Lofty Ranges were considered to be relatively stable with regard to rates of species turnover in relation to climate, suggesting that these higher rainfall areas are buffered to at least some degree of directional climate change [8].

2. Adaptive capacity

In addition to being relatively buffered from predicted future climates, the Uplands landscape continues to possess a relatively resilient biota that are likely to have an relatively good capacity to cope with change. The remnancy of mapped native vegetation is relatively high for the region (25.4%). Furthermore, using terrestrial birds as surrogates for system function, Rogers [7] found that these higher elevation/higher rainfall areas of the southern Mount Lofty Ranges are less strongly associated with decline than the lower elevation slopes of the Ranges.

In contrast, Rogers [7] found that the lower slopes of the southern Mount Lofty Ranges are strongly associated with decline, suggesting poor capacity to cope with future changes (including those driven by directional climate change). This is supported by the relatively low remnancy of mapped native vegetation (8.4%). A key determinant of whether this landscape can continue to support native biodiversity will be the extent to which the resilience of this landscape's biota can be improved.

As with the Lower Slopes landscape, the proportion of native vegetation remaining in the Plains landscape is low (8.4%). However, the longer history of land transformation in this landscape suggests that the biota of this landscape have already stabilised in response to these changes [9]. While this landscape is considered degraded relative to its pre-European condition, the biota currently associated with this landscape are stable. However patch scale management will be required in order to maintain the current functions that native biota provide in this landscape.

The northern coastal landscape is relatively intact (remnancy of native vegetation = 41.6%), and, while these coastal systems support state and nationally listed threatened species, they appear to be relatively resilient [9]. The rarity of these listed species may require additional, species-level risk management beyond the responses described here at the landscape level.

3. Synthesis and adaptation recommendations

Based on the evidence described above, the landscapes defined here for the Adelaide and Mount Lofty Ranges region were placed within the framework described above, and adaptation recommendations made accordingly. These recommendations are described in detail below.

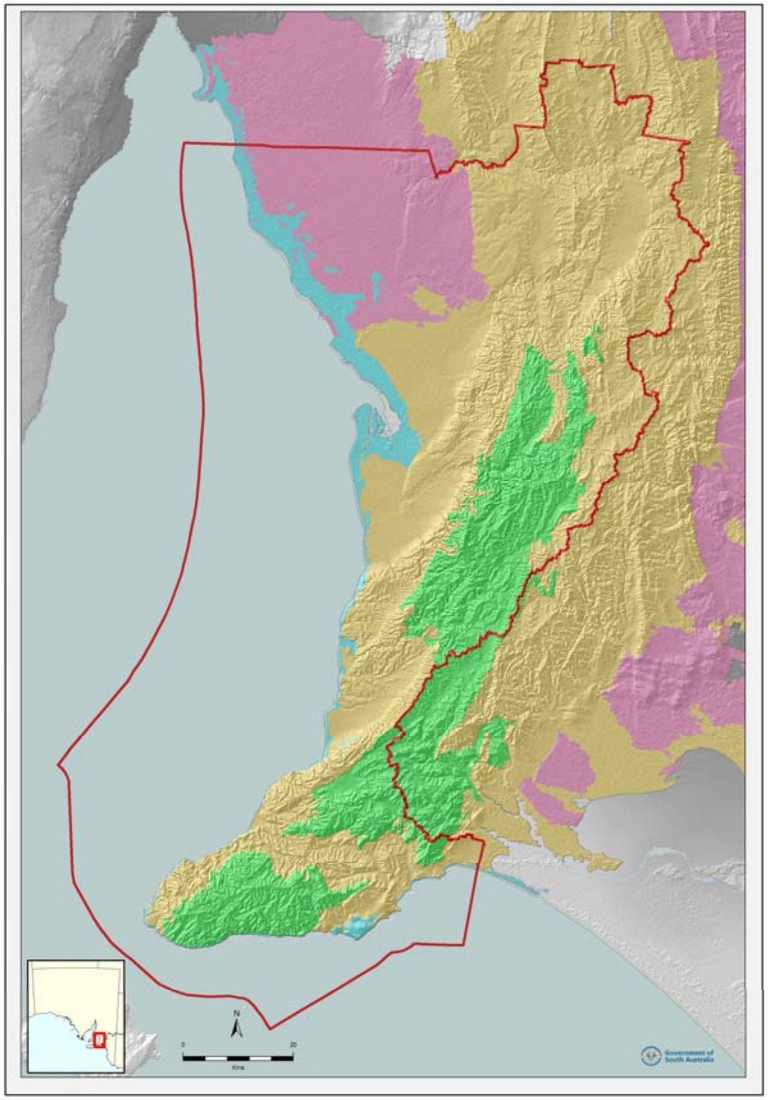
The **Uplands** landscape is Fragmented [39], with 25.4% of native vegetation remaining. However, relative to other landscapes in the region, this level of vegetation remnancy is high. Furthermore, the biota dependent on the habitats in this landscape suggest that the systems in this landscape are not at high risk of approaching undesirable thresholds[7]. In addition, the high topographic diversity of this landscape suggests the presence of climatic refugia that are likely to buffer changes in regional climate, a prediction reinforced by the predicted rates of species turnover for this landscape [8]. The recommended adaptation strategy for this landscape is **passive adaptation**. In this landscape, this can be translated as managing existing threats, such as invasive plants and animals, inappropriate fire regime and land use change, and new threats as they emerge.

The **Lower Slopes** landscape is considered Relictual [39], with 8.4% of native vegetation remaining. Furthermore the biota dependent the habitats of this landscape are showing strong evidence for decline [7], suggesting that this landscape is approaching an undesirable threshold (i.e. is not very resilient to change).

While the relatively high (compared with Plains and Coastal landscapes) topographic diversity suggests some buffering against climate change, the ecotonal nature of the landscape suggest that the biota of this landscape may be more sensitive to future climates than those of the Uplands landscape. The recommended adaptation strategy for this landscape is **active adaptation**. In addition to the actions required under passive adaptation strategies, this requires habitat reconstruction and restoration, to improve the resilience of declining biota such that they are better able to adapt to future climates. In some cases facilitated **transformation** may also be required. This would require identifying the critical functions that the ecosystems of this landscape play (e.g. as habitat for declining fauna), and to develop intervention (e.g. reconstruction) strategies that are able to maintain these functions under future climates.

The **Plains** landscape is also Relictual [39], with 8.4% of native vegetation remaining. However, the remaining biota dependent on this landscape are stable, with the biota dependent on the pre-European vegetation of this landscape having already undergone local extinction [9]. As the name suggests, topographic diversity in this landscape is low, with rates of species turnover expected to be high under future climates [8]. The recommended adaptation strategy for this landscape is **passive** to **active** adaptation, depending on the degree of modification.

The **Coastal** landscape is considered Variegated [39], with 41.6% of native vegetation remaining. The biota dependent on this landscape are also stable [9], although some have restricted global distributions and are thus threatened from national and global perspectives. However, many coastal systems – particularly the northern low energy coastlines, are highly sensitive to changes in sea level. In these cases, the recommended adaptation strategy is **transformation**, whereby facilitated landward migration may be required. This requires an understanding of where physical opportunities for migration exist, and ensuring that the land use of these migration areas allows for this migration. In the more intact coastlines that are less exposed to sea level rise (particularly the south coast cliff systems), **passive adaptation** is recommended.



Uplands

Topographic diversity is high, and low sensitivity to climate change. Biota have high resilience, and capacity for change.

Recommended strategy: **Passive adaptation**. Identify and manage existing threats, and emerging threats as they arise.

Lower Slopes

Topographic diversity is high, but species turnover is more sensitive to climate. Biota has low resilience, and thus has little capacity to cope with change.

Recommended strategy: **Active adaptation**, In addition to those strategies for passive adaptation, reconstruct and restore habitats to increase resilience.

Plains

Topographic diversity is low, and sensitive to climate. While major changes have occurred to biota since European colonisation, the extant biota is relatively stable (in a degraded state).

Recommended strategy: **Passive to active adaptation**, depending on the degree of modification. Aim is to maintain current ecological functions of the landscape. This may involve facilitated migration, and buffering and restoring patches of remnant vegetation.

Coastal

Topographic diversity is low, and sensitive to climate. In addition, this landscape is extremely sensitive to sea level rise, particularly in the northern low energy systems. Biota of this landscape is resilient and has some capacity to cope with change.

Recommended strategy: **Passive adaptation** (in intact areas that are less exposed to sea level rise), to **transformation** where facilitation of landward migration is required.

Conclusion and key recommendations

The analysis presented here provides recommendations regarding landscape-level strategies for managing native biodiversity under future climates, for the Adelaide and Mount Lofty Ranges region. This analysis highlights the fact that our response to directional climate change is not necessarily ubiquitous, and needs to account for the local impacts of climate change in the context of other important drivers of change. The key outcome of this analysis is that it allows natural resource managers to develop context-specific conservation strategies that account for climate change, in the context of other drivers of change.

In the Adelaide and Mount Lofty Ranges region, exposure to future climates and non-climate impacts (and, therefore, capacity to cope with future climate exposure) vary across the different biophysical landscapes. The risks posed to biodiversity in these landscapes by climate change (and the most appropriate strategic responses to these risks) vary across the region depending on:

- historic and ongoing non-climate impacts (e.g. total grazing pressure, historic clearance of native vegetation, changes in land use)
- ongoing responses of native biodiversity to historic impacts (i.e. disequilibrium between impacts and effects, such as extinction debt and patch-scale competition dynamics (weeds))
- sensitivity of native biota (community composition) to variation in climate
- high diversity of climatic environments at fine scales.

The broader biodiversity context

This report presents a framework for assessing the relative risk, and recommended adaptation strategies, for biodiversity in response to directional global warming. The focus of how this framework has been implemented for the Adelaide and Mount Lofty Ranges region has been on the landscape level of the biological hierarchy. There are good reasons for assessing risk and response at this level as a priority. First, evidence to inform adaptation strategies are often available at this level, as the required level of understanding is often coarse, and partly depends on the nature of the physical environments (with respect to climatic responses). This compares with the level of evidence required to inform adaptation strategies at, say, species or ecological community levels, where an understanding of the direct physiological impact of future climates, population demographics and interspecific interactions, will determine these responses to future climates. While attempts (some more successful than others) have been made to predict these responses in a way that is ecologically meaningful for particular species, a comprehensive assessment of species responses to climate is unachievable.

Second, an assessment of the responses of biota to future climates undertaken at these higher levels of organization allows us to take advantage of the nested nature of these levels of organization. Given our inadequate understanding and knowledge of how many and which kinds of species occur in an ecosystem, the best way to approach the problem of conserving the majority of them is to ensure that the system continues to have the same overall structure and function[41]. This requires an understanding of which species' conservation requirements are met by addressing issues at higher levels (and which species' requirements are not met, and require species-level attention)[42].

While adaptation strategies at the landscape level will provide benefits at lower levels in the face of future climates, there will still be a need for targeted, species-specific strategies. This will be particularly important for those species whose requirements are not met by landscape-level adaptation strategies, including species with idiosyncratic requirements, or those that are highly threatened and whose populations are at risk through secondary drivers associated with small populations[14]. In these cases, comparable information (regarding climate sensitivity and adaptive capacity) will inform conservation strategies for these species. However the application of this information in developing adaptation strategies at the species level may be different, such as the coupling of stochastic population models with dynamic habitat models that incorporate climate-mediated drivers [43]. These population-climate models have been applied to a number of threatened species [49, 50], including Pygmy Blue-tongue *Tiliqua adelaidensis* [44]. The value of these studies is that they make predictions regarding the implications of future climates on extinction risk, in the context of other historic and current drivers. By incorporating the response of threatened species to multiple drivers (including climate-mediated drivers), predictions regarding the responses to alternative management strategies can also be made and thereby directly inform the development of adaptation strategies for these species.

Climate change, biodiversity and the rise of a new conservation paradigm

Historically, the relatively new field of conservation biology has had a primary focus that referred to the state of biodiversity at some historic time-point (e.g. pre-European), with the presumption that human (or European) activity was operating on an otherwise static system. Climate change, and its impacts on biodiversity, have forced a broad re-think of this conservation paradigm, by reinforcing the dynamic nature of biological systems: essentially we need to acknowledge that the future will not be the same as the past, and "give the impression that ways can be found to either hold or turn back the clock and preserve or recreate imagined Edens" (Hobbs *et al.*[36] p442). By acknowledging this dynamic nature, natural resource managers need to then ask – what are we trying to conserve? This then requires managers to explicit about their goals for management, beyond the protection or restoration of historic biological systems[45], including a clear expression of the functions and services that we want a biological system to provide. From the perspective of nature conservation, one of these functions may be to support the maintenance of a diversity of native organisms (such that, for example, we can continue to meet our national and international obligations), that both have inherent value, and support a range of services in their own right[36].

The acknowledgement that systems are inherently dynamic (and may be more so under future climates) provides opportunities for natural resource managers that are not provided by a static historic view of nature conservation[46]. By being explicit about the functions that we want biological systems to provide, we can design management strategies that are designed to maintain these functions. Under future climates, we may expect that the historic composition of biological systems will change, through processes such as shifting bioclimatic envelopes for different species[38]. However, if we are clear about what functions we want to maintain, we can facilitate system transformation under these changes, such that these functions can continue to be maintained, even if the composition of these systems has no historic precedent[18, 56]. This new way of thinking about nature conservation requires a dramatic philosophical shift[36]. However, by making this shift we will be prepared to manage our natural resources under what will inevitably be an environment that is quite different from the one which we have experienced to date.

Accepting that we may be managing systems for transformation, however, carries its own risks, and as such we need to be judicious in how we facilitate such transformation. Given the level of uncertainty regarding the nature of future climates (let alone ecological responses to these), actively managing systems for a particular outcome – when that outcome is unprecedented – means that ecological responses to the management strategy itself are highly uncertain[38]. This uncertainty needs to be acknowledged in the design of intervention strategies. Broadly, the information presented here is useful for discriminating where such high uncertainty needs to be accounted for (i.e. where transformative strategies are likely to be relevant), and where we can avoid such high risk strategies (i.e. where the risk of transformation is relatively low, and strategies with an historic precedent are likely to be the most appropriate course of action). More specifically, the need to account for high uncertainty reinforces the need to implement conservation activities in an adaptive manner. The use of adaptive management in natural resource management is, therefore, most relevant in those systems where transformation is most appropriate.

The role of adaptive management under climate change

Fundamental to the management of social-ecological systems is an acknowledgement that natural resource managers have limited control over these systems, and that our understanding of system responses to management typically contains high levels of uncertainty. This means that natural resource management needs to be implemented within an adaptive framework, a key outcome of which is to improve our understanding of system responses through appropriate planning, delivery, and monitoring and analysis. In addition, this uncertainty and relative lack of system control means that we need to be managing these systems as inherently dynamic, where the goal of management is to support a system's capacity to cope with change (which we can't predict), rather than to optimise for a particular outcome.

The fact that natural resources are now being managed within the context of directional climate change only reinforces the need to manage these systems within an adaptive framework. Our certainty in the nature future climates, and the ecological responses to these, is variable, as is our ability to manage these systems with confidence in the outcomes. The uncertainties regarding our predictions of what future climates will look like, and the ecological (and social) responses to these changes, mean that we should be delivering management programs on the basis of a range of plausible future scenarios, and, importantly, test the predicted responses to these management responses through appropriate monitoring and evaluation design[47]. There are now a number of studies that demonstrate the practical application of adaptive management as a framework for natural resource management (see, for example, Allan and George [48]), that can provide practical guidance for how adaptive management can be applied in the context of a changing climate[47].

There is some debate regarding the range of plausible scenarios within which adaptive management should operate, ranging from more prescriptive responses based on the most likely future climates, management responses that are relevant across all plausible scenarios, or management responses that relate to the most extreme (but not necessarily most likely) scenarios. Given the uncertainty around future climates[11], more prescriptive responses may not be the most appropriate, if the management response reduces future management flexibility (in an attempt to optimise a particular management solution) [49]. Conversely, management strategies that are likely to contribute to a desired outcome under a wide range of likely future climates may be considered low-risk, and may be more appropriate to pursue.

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