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Designing landscapes for biodiversity under climate change: A validation

Supplementary Report

Veronica Doerr, Kristen Williams, Michael Drielsma, Erik Doerr, Micah Davies, Jamie Love, Art Langston, Samantha Low Choy, Glenn Manion, E. Margaret Cawsey, Heather McGinness, Tom Jovanovic, Debbie Crawford, Mike Austin and Simon Ferrier

DESIGNING LANDSCAPES FOR BIODIVERSITY UNDER CLIMATE CHANGE: A VALIDATION

The architecture of resilient landscapes: scenario modelling to reveal best-practice landscape design principles

Supplementary report

Commonwealth Scientific and Industrial Research Organisation

Authors

Veronica Doerr – CSIRO
Kristen Williams – CSIRO
Michael Drielsma – NSW Office of Environment and Heritage
Erik Doerr – CSIRO
Micah Davies – CSIRO
Jamie Love – NSW Office of Environment and Heritage
Art Langston – CSIRO
Samantha Low Choy – Queensland University of Technology
Glenn Manion – NSW Office of Environment and Heritage
E. Margaret Cawsey – CSIRO
Heather McGinness – CSIRO
Tom Jovanovic – CSIRO
Debbie Crawford – CSIRO
Mike Austin – CSIRO
Simon Ferrier – CSIRO

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The role of NCCARF is to lead the research community in a national interdisciplinary effort to generate the information needed by decision-makers in government, business and in vulnerable sectors and communities to manage the risk of climate change impacts.

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Abstract

Landscape design – the particular placement of areas devoted to restoration of native vegetation at landscape scales – is a primary approach to climate adaptation for biodiversity. It may facilitate the maintenance of larger populations and shifts in species distributions, both of which should help native species adjust to changing climates. However, it is unclear exactly how to design landscapes to best achieve these goals, particularly because future landscapes will involve changed land uses and distributions of native communities which may interact with landscape designs.

We investigated whether one or more current approaches to landscape design would be robust to future climates – would tend to improve the likelihood of persistence for native species (and decrease the likelihood of persistence for key invasive species) across a range of plausible futures. In the previous final report for this project (Doerr et al. 2013), we selected two case study landscapes in New South Wales and modelled 48 future landscapes for each which differed in future land uses and distributions of native vegetation communities. We applied three current approaches to landscape design plus controls for spatial planning and total amount of restoration to each of these future landscapes. We then used a metapopulation capacity model to evaluate the change in each landscape's capacity to support viable populations of four native species groups and two invasive species. Finally, we analysed whether the change in metapopulation capacity across all future landscapes for all species was influenced by landscape design principles. We found no effect of detailed spatial placement of restoration projects on the change in metapopulation capacity of our future landscapes. Only our positive control – restoring landscapes to ~30% native vegetation cover – improved future landscapes relative to current landscapes. However, the invasive peppercorn tree (*Schinus molle*) showed the opposite pattern, becoming more problematic with landscape improvements for native species.

For this supplementary report, we performed additional analyses to validate these results using a third case study landscape, the area managed by the Wimmera Catchment Management Authority in Victoria. The Wimmera was selected because it has an overall drier climate, somewhat different vegetation types, smaller total area, and slightly different vegetation types. These differences allowed us to evaluate whether our conclusions from the previous two case study landscapes were potentially dependent on local factors and specific model inputs, or whether they are truly generally applicable.

We found that our original conclusions are still valid – that only our positive control (restoring landscapes to ~30% native vegetation cover) improved future landscapes relative to current landscapes. The only difference was that the results for the Wimmera study landscape showed weaker patterns. We suggest this was due to the specific vegetation types present in the Wimmera but also the fact that land-use changes projected for the Wimmera involved less loss of native vegetation, particularly in the form of scattered trees. This strengthens our suggestion that spatial planning of changes in productive land uses may provide an additional management lever for biodiversity that is currently underutilised.

Executive summary

Climate change is expected to result in significant changes in temperature, rainfall and evaporation, with the degree of change projected to accelerate. As a result, Australia's native species will experience different local environments than they do now and will need to adjust to those environmental changes, move to live elsewhere, or go extinct. Large populations and well connected natural areas may be required for species to make these adjustments, but both of these have been impacted by alteration of land uses and fragmentation of natural areas. Thus, landscape design and management is one of the primary ways in which land managers can assist biodiversity under climate change. Under landscape design and management, areas to be managed and/or restored for biodiversity are planned in very specific locations over relatively large scales with the aim of achieving large populations, spread over multiple patches of native ecosystems in the landscape and intermingled with other necessary land uses.

Many landscape design and management initiatives are underway in Australia and they differ in their specific details. Unfortunately, it is not clear whether one set of these 'landscape design principles' is better than another as a climate adaptation action. This is because design principles are developed based on current landscapes rather than future, climate-affected landscapes. Yet future landscapes may be very different in terms of where we might find particular native species and in terms of land uses, including the amount of intensive agricultural production and plantings for carbon sequestration. All these potential changes could affect where native species live and the degree to which the landscape is connected to allow species movements. Thus, we need to evaluate how well different landscape design principles perform in future landscapes. Because we can't predict exactly what future landscapes will be like, we need to consider a broad range of possible futures and try to identify landscape design approaches that are likely to benefit native species across all of them.

To accomplish these goals, we modelled a range of plausible future landscapes and applied the most common current landscape design principles to these landscapes (as well as an aspirational design principle). We then evaluated the degree to which the design principles might improve the capacity of the landscapes to support populations of native species in the long term, and decrease their capacity to support two key invasive species. Our goal was to find one or more landscape design principles that improved all future landscapes for native species, as such an outcome would allow us to plan for the future without having to know precisely what the future will look like.

In the initial final report for this project, we worked with two case study landscapes: South-East New South Wales (the Southern Rivers, Murray and Murrumbidgee Catchment Management Authority areas) and North-East New South Wales (the Border Rivers/Gwydir, Namoi and Northern Rivers Catchment Management Authority areas). We modelled 48 future versions of each of these landscapes based on:

- Four 'storylines' of land-use change linked to different potential future climates as well as social and economic drivers and barriers of land-use change (defined with a group of experts across disciplines including agriculture and forestry)
- Two global climate models which project differing rainfall patterns and were used to model where native vegetation communities will be in the future
- Six landscape design principles based on the amount and placement of new areas of native vegetation in the landscape (three based on where Australian landscape managers currently place restoration projects in their landscapes,

one with random placement of restoration, one with no restoration, and one with a much more restoration than currently considered achievable)

We then evaluated our 96 future landscapes using a 'metapopulation capacity' model, which uses data on species' habitat preferences and movement abilities to estimate a landscape's ability to support populations that are large enough to persist long into the future. We ran the model for four groups of native species (native orchids, animals that specialise on wet forest environments, and two groups of animals that specialise on grassy woodland and dry forest environments) as well as two invasive species (red fox and peppercorn tree).

In the supplement to the final report, we worked with a third case study landscape (the area managed by the Wimmera Catchment Management Authority) to provide a validation of the results derived from the New South Wales landscapes. We used a subset of the original land-use change 'storylines' and landscape design principles and compared the results from analysing all three study landscapes as well as the Wimmera by itself to the results presented in the original final report for the two NSW landscapes. Across all three study landscapes and all futures, we were hoping to find that one or more of the current, implementable design principles tended to improve the metapopulation capacity of landscapes (increase it for native species groups and decrease it for invasive species) better than the other principles.

Instead, we found that only our aspirational design principle – restoring landscapes to ~30% native vegetation cover – reliably improved future landscapes relative to current landscapes. None of the currently used design principles was better than another and none of them arrested declines in the capacity of landscapes to support native species, on average. However, there were some differences between species. The capacity to support wet forest specialist fauna declined regardless of design principles, and the invasive peppercorn tree increased with landscape improvements for native species. Improvement in the capacity to support populations into the future also depended on land-use change storyline, so spatial planning of changes in land use may provide an additional management approach to climate adaptation for biodiversity management. These conclusions applied across all three study landscapes, though the patterns were weaker in the Wimmera, where climate-related changes in land uses and native vegetation may not have as dramatic an impact on persistence of native species.

Collectively, these results suggest that current approaches to landscape design and management may not be sufficient to serve as climate adaptation strategies for biodiversity. The total amount of restoration is more important than detailed spatial configuration to counteract declines in biodiversity from climate-related changes in land use and suitable habitat, at least at very large landscape scales. While sobering, these results suggest several useful and even positive key messages for how best to manage landscapes for terrestrial biodiversity under climate change:

- Act locally, and empower local managers to make decisions based on local goals, but coordinate local efforts to manage a larger landscape
- Restoration should be accompanied by targeted alien invasive species management, focussing on the subset of invasive species likely to benefit from landscape improvements for native species
- We need much more restoration (to achieve ~30% native vegetation cover), but there will still be 'climate losers' who may not persist into the future regardless of landscape design and management
- Focus restoration efforts in priority areas to achieve 30% cover in smaller areas
- Consider spatial planning of all types of land-use change, not just restoration

1 Introduction

1.1 Context for the Validation – Objectives of the Project

It may be impossible to prevent climate change from impacting biodiversity, and indeed a range of impacts are already being observed (Doerr et al. 2011b; Dunlop et al. 2012). Yet it should be possible for species and ecosystems to respond to environmental change to some degree via existing ecological and evolutionary processes. These processes include genetic adaptation but also phenotypic and behavioural plasticity, including changes in dispersal patterns that result in shifts in species' distributions (Donnelly et al. 2012; Hughes et al. 2010; Lande 2009; Lawler 2009). Our understanding of how to support these processes is limited, but they all require variability (genetic, phenotypic or behavioural) and variability is usually greater in larger populations (Hartl and Clark 2007; Lacy 1997). In addition, changes in dispersal patterns will only be possible if the broader landscape between populations is sufficiently permeable to allow movements of native species (Doerr et al. 2011a). Thus, the most common approach to climate adaptation for terrestrial biodiversity is to scale up from traditional site-based management to planning and managing at landscape scales (Alexandra 2012; Pettorelli 2012). In landscape design and management, larger population sizes and greater permeability may both be achieved through functionally linking smaller patches of native vegetation, reducing threats from the 'matrix' (the wider landscape between patches), and increasing the nativeness of the matrix itself (Bennett 2004; Hilty et al. 2006; Mackey et al. 2010).

However, philosophies and approaches to landscape design and management differ widely, influenced by different ideas in the fields of landscape ecology and metapopulation theory as well as by different local experiences of the practicality of achieving landscape-scale biodiversity goals. Furthermore, current planning approaches to determine where and how to improve landscapes for biodiversity are usually conducted using information about current native community compositions and surrounding land uses (e.g., Barrett et al. 2011; Barrett and Love 2012; MCMA 2012). Yet climate change is projected to significantly impact both of these (Ferrier et al. 2010; Olesen and Bindi 2002; Stokes and Howden 2010), so it's difficult to know which of the many approaches to landscape management are likely to be robust into a climate-affected future. Thus, the aim of this project was to compare the performance of some of the most commonly used approaches to designing landscapes for biodiversity under a range of plausible climate-affected futures, focusing on the spatial placement of revegetation and restoration areas. Our ultimate goal was to find some useful general principles – approaches to spatial restoration planning that are likely to have a positive effect on terrestrial biodiversity regardless of exactly which future climates, land uses, and native vegetation community types eventuate.

We did this by considering a range of plausible climate-affected future landscapes, including the results of climate adaptation in other sectors such as agriculture. We also wanted to compare approaches to landscape design and management as they are currently practiced, to ensure we were comparing approaches that land managers believe can be implemented and would consider adopting into the future. Thus, our detailed objectives were to:

- Model a range of future landscapes in multiple parts of Australia that incorporate a broad set of plausible changes in climate, vegetation communities, and land uses

- Apply several of the most common principles of landscape design (i.e. spatial placement of restoration works) to these landscapes, along with a random spatial control and positive and negative controls for amount of restoration
- Analyse future landscapes, with design principles applied, using a metapopulation capacity model (Drielsma and Ferrier 2009) to evaluate their future capacity to support long-term viable populations of key native species groups

While landscape design and management have become common approaches to biodiversity conservation, there is still a question about whether these approaches may be somewhat counter-productive because they could encourage the spread of invasive species (Rahel 2007; Vila and Ibanez 2011; With 2004). Thus, we also aimed to use the metapopulation capacity model to evaluate the degree to which design principles in future landscapes might influence the long-term viability of some key invasive species.

1.2 Conclusions from the Final Report

In our final report (Doerr et al. 2013), we analysed the results for two study landscapes in New South Wales (NSW) that each covered three Catchment Management Authority boundaries. We found no effect of detailed spatial placement of restoration projects on the change in metapopulation capacity of our future landscapes. Only our positive control – restoring landscapes to ~30% native vegetation cover – improved future landscapes relative to current landscapes. All currently-used design approaches failed to fully compensate for losses in metapopulation capacity resulting from climate-related changes in land use and native vegetation communities. However, the effect of design principles differed across species. The capacity of landscapes to support wet forest specialist fauna declined regardless of landscape design, and the invasive peppercorn tree increased with landscape improvements for native species. Improvement in metapopulation capacity also depended on land-use change storyline, so spatial planning of changes in land use may provide an additional management lever that is currently underutilised. Based on these conclusions, we put forward the following key messages:

- **Enable local planners and managers**: As details of the spatial placement of restoration projects may not have a strong influence on landscape-scale outcomes, local managers can still make local decisions that suit their goals and opportunities without compromising goals at larger scales.
- **Simply align boundaries to create large corridors for climate change**: We may need to manage large landscapes to facilitate species' range shifts under climate change, but the amount of restoration within those landscapes is more important than the details of what is done where. Thus, achieving cross-boundary collaboration in establishing these corridors could be as simple as agreeing on cross-jurisdictional boundaries of large corridors, then letting different landscape managers within different jurisdictions within those boundaries make their own individual decisions.
- **Only some invasive species will need special management**: Some (but not all) invasive species will likely benefit from increasing the amount of native vegetation and landscape connectivity. These are most likely to be those that co-occur with native vegetation (those that are specifically environmental invasives rather than problematic on agricultural or urban lands) and that may be somewhat dispersal-limited, or rely on native species as dispersal agents. Thus, landscape design and management initiatives should include coordinated plans to manage the risk of spread of these particular species.

- **There may be little we can do to help the 'climate losers'**: Some species will likely lose so much suitable area purely due to changes in climate that there may be little landscape managers can do to prevent declines in these species' chances of persisting into the future.
- **To arrest biodiversity declines, we may need an order of magnitude more restoration than we are planning at present**: Restoring a much greater proportion of large landscapes (to achieve ~30% native vegetation cover at the scale of multiple catchments) may be needed to counteract the effects of climate-related changes in land use and native vegetation and ensure that we improve the ability of landscapes to support viable populations of native species into the future.
- **Concentrating effort could achieve persistence on small scales**: While achieving 30% native vegetation cover at the scales of multiple whole catchments may currently seem unattainable, that goal should be achievable at smaller scales in some landscapes. Thus, by concentrating effort in priority areas even more than we do at present, we could focus on creating single metapopulations likely to be viable into the future, then build greater landscape-scale effort from there. Given that it will take time for climate-related changes to occur, this could be a no-regrets approach right now that does not preclude greater climate adaptation in the future.
- **Spatial planning of all types of land uses could provide new, creative solutions**: There is the possibility that integrating spatial planning of productive land uses with planning restoration of native vegetation could significantly improve future landscapes for biodiversity without the need to achieve ~30% native vegetation cover. However, further research is needed to identify the options

1.3 Objectives of the Wimmera Validation

While our NSW study landscapes encompassed a broad range of land uses, vegetation types, and climatic environments, they did not fully encompass all those that might be currently found in Australian fragmented landscapes. As our intention was for our final conclusions and key messages to be broadly applicable across Australia's fragmented areas, the primary purpose of a validation exercise was to add a somewhat different study landscape in terms of these factors (e.g. drier climates, inland conditions, and slightly different vegetation types) and see if we still obtained the same statistical results and derived the same overall conclusions. In addition, it was useful to add a study landscape reasonably different in size from the NSW landscapes to ensure our conclusions and key messages from the NSW study landscapes were not strictly dependent on analysing the results at very large scales.

2 Research Activities and Methods

2.1 Summary of Methods for the Final Report

To achieve our objectives, the methods used to perform supplementary analyses of the Wimmera study landscape were broadly the same as those used to analyse the initial two study landscapes. Detailed descriptions of those methods can be found in our final report (Doerr et al. 2013), and we will not reproduce here but rather summarise them as follows:

1. Creating Future Landscape Replicates
    - Selecting case-study landscapes that incorporate much of the range of environmental and land-use variation currently present in fragmented areas of Australia
    - Developing a set of plausible storylines that combine a range of future climates (to 2070) with their likely consequences for changes in land use and applying these to create several future case-study landscapes, modelling at 100m grid-cell resolution
    - Determining the most common approaches to landscape design and management currently used in Australia and applying all of these to each future landscape at 100m grid-cell resolution
    - Modelling future changes in native vegetation communities (to 2070) for each future landscape at 100m grid-cell resolution
    - Combining the models of land-use changes, design principles, and future vegetation to create future case-study landscapes that incorporate all these elements

2. Evaluating Metapopulation Capacity of Future Landscapes
    - Selecting key functional groups of native species and example individual invasive species for modelling
    - Parameterising the Rapid Evaluation of Metapopulation Persistence (REMP) model (Drielsma and Ferrier 2009), treating each functional group of native species as a 'generic focal species' (Watts et al. 2010; see sections 2.3.1 and 2.3.2)
    - Running the REMP model for each species/species group over each modelled future landscape and extracting results in terms of capacity of each landscape to support viable metapopulations as of the year 2070

3. Analysing General Performance of Design Principles
    - Analysing effects of treatments on metapopulation capacity parameters
    - Exploring the influence of confounding factors and interaction terms

We did make some modifications to these methods to apply them to the Wimmera as a validation exercise. Thus, the methods section of this supplementary report focuses specifically on describing those modifications.

2.2 Modifications to Methods for the Wimmera Validation

2.2.1 Study landscapes

The Wimmera study landscape incorporated the area managed by the Wimmera Catchment Management Authority in western Victoria (Figure 1). Thus, this study landscape is further west than either of our NSW study landscapes receives less rainfall and incorporates more shrubland environments, with negligible wet forest environments. It also does not contain major urban centres or border the coast, so sea level rise issues were not relevant in modelling future Wimmera landscapes.

For the modelling, each study landscape was buffered to include data from surrounding areas that could influence the results.

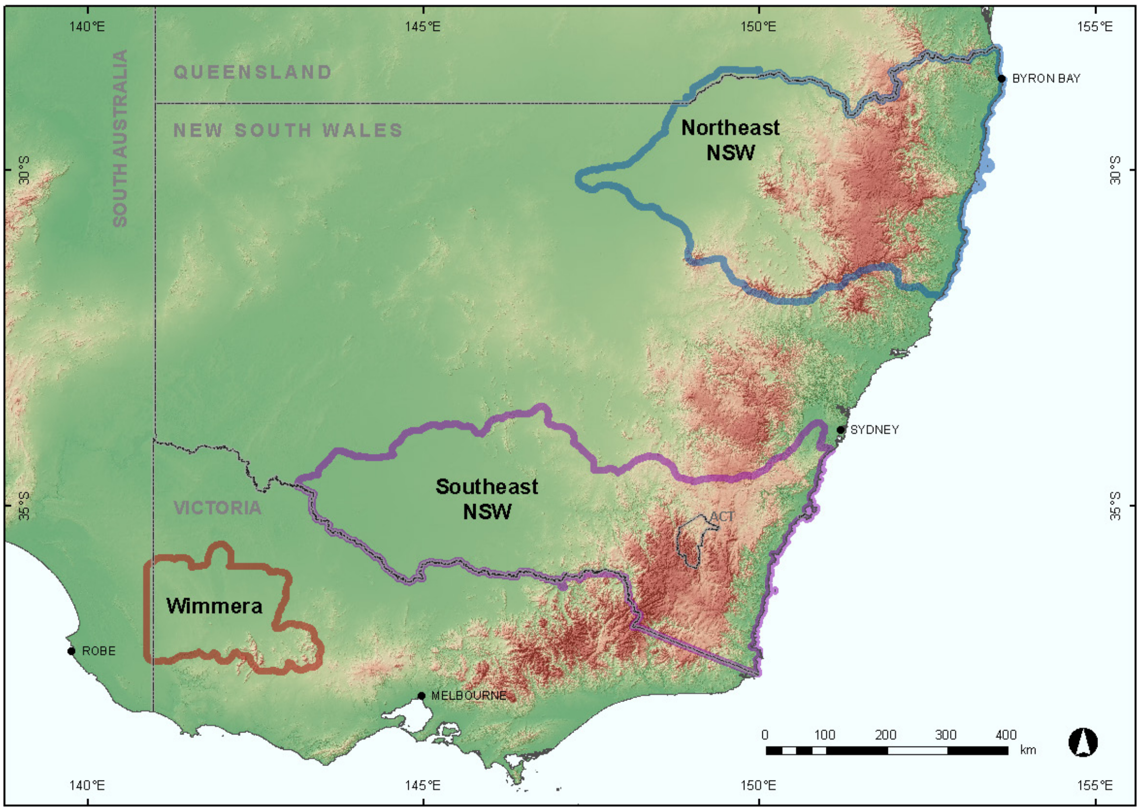


Figure 1. Boundaries of the three study landscapes. Two for initial modelling, the South-East NSW landscape and the North-East NSW landscape, and the third landscape for validation, the Wimmera Catchment Management Authority area, buffered for analysis.

2.2.2 Land-use change

Selecting a Subset of Storylines

As detailed in the final report (Doerr et al. 2013), to incorporate changes in land uses into the future we used a storyline approach. We gathered experts together for a land-use change workshop, linking a range of plausible drivers of and responses to climate change that will naturally be linked and associating the resulting suite of drivers and responses with changes in land use. Four land-use change storylines resulted from this workshop process and were modelled for the New South Wales study landscapes, with each storyline describing key characteristics of both the environment and society in the future that could drive different land-use change outcomes. We chose to restrict the Wimmera validation to two of these land-use change storylines. Those selected were:

Storyline 1, Adaptation Without Global Mitigation: In this storyline (associated with A1FI emissions scenario, high sensitivity), the world's major greenhouse gas producers fail to make significant emissions reductions. As a result, Australia does not advance its own mitigation policies much further than it has already. However, Australia recognises that even if it must rely on the rest of the world to achieve significant mitigation, Australia still has control over its ability to *adapt* to a changing climate. Thus, some effort is devoted to coping with the effects of climate change, though not so much that it might weaken our economy relative to other countries. Without a strong carbon market to make environmental plantings profitable, their main purpose becomes adaptation of biodiversity (rather than carbon sequestration). Thus, using land for environmental plantings tends to be devalued relative to using it for food and biofuel production because of the strong pressure to adapt agriculture and find solutions to high fuel prices.

Storyline 4, Global Fix with Proactive Australia: In this storyline (associated with A1B emissions scenario, medium sensitivity), the world's major greenhouse gas producers tackle mitigation relatively early and in a serious way, employing a combination of many different solutions such as increased reliance on various non-fossil-fuel energy sources as well as a variety of approaches to increasing carbon sequestration. As a forward-thinking developed nation, Australia joins with this group of leading nations. We concentrate on both mitigation and adaptation both in significant ways. But because the world is somewhat successfully tackling mitigation, we have less need to adapt relative to some other storylines in which climate change continues to accelerate.

We restricted the validation analyses to two storylines because we only had the resources to do a subset of the original modelling in the third study landscape. We chose Storylines 1 and 4 because they represented the two most extreme storylines in terms of negative and positive change, so should still encapsulate the same range of variation that we considered in our original New South Wales models.

To translate these storylines into landscape-specific scenarios of land-use change, we used the more detailed results of the land-use change workshop because the Wimmera study landscape was included in that process. In brief, each expert sub-group (native vegetation, agriculture and biofuels, and forestry and carbon plantings) was asked to consider the Wimmera study landscape under each storyline of land-use change. They estimated the percentages of current land uses that would be likely to shift, what they would shift to, and whether those shifts could be anywhere in the landscape or would be spatially constrained (e.g., to areas with lower profitability, near urban areas, etc.). Through this process, each expert sub-group indirectly developed sets of guiding principles about the likely ***relative*** differences between study landscapes and between land-use change storylines, which then gave us the flexibility to later adjust the specific percentages of land-use change to achieve consistency across different expert sub-groups. See the final report (Doerr et al. 2013) for more details.

Modelling Current and Future Land Uses

The nine land-use classes that we selected for modelling (see row and column headings, Table 3) considered the types of land uses most likely to influence the suitability and/or permeability of an area for the native species groups we planned to model, matched with the types of land-use changes identified by experts in our land-use change scenario workshop, constrained by the types of existing data available. Two classes were relevant only to future landscapes – two age-classes of environmental plantings for plantings yet to occur, which will still be in a regrowth phase by 2070. Note that throughout, we use the term ‘environmental plantings’ to refer to both active plantings and natural regeneration projects.

To assign one of these land-use classes to each 100m grid cell of our Wimmera study landscape, we used the vector land-use data for Victoria, which describes the land tenure, land use and land cover for each cadastral parcel across the state as it was in 2009 (Morse-McNabb 2009). The Victorian land use data were subset to the Wimmera study landscape. The 147 unique land use descriptions and corresponding land cover descriptions (e.g. native woody cover, pasture/grassland) in the Wimmera study landscape were then used to manually assign polygons (using database queries) to each of the study land-use classes. The land use overlapping South Australia in the analysis buffer was assigned using the ALUM classification of the National Catchment level land-use dataset (ABARE-BRS 2010).

The distinction between land uses 2 and 3, crops and pastures without and with scattered trees, was further evaluated using the 2009 NCAS forest and regrowth cover dataset (DCCEE 2012). Four other land cover datasets specific to the Wimmera region (provided by the CMA) were also evaluated and used to update the land use / cover assignments where applicable (riparian zones, 2005 tree density, 2005 native vegetation extent, and modelled quality of Terrestrial Native Vegetation). The riparian zones for the Wimmera River dataset describes the condition of woody vegetation as scattered, bare, thin, good, or fair based on aerial photography interpretation in November 2004. These classes were interpreted into the cover classes used for the study landscape: natural vegetation removed, modified native woody, crops and pastures with paddock trees. The 2005 tree density dataset which classified woody vegetation cover as dense, medium or scattered was also used to inform the cover classification. The 2005 native vegetation extent dataset defines areas as possibly native vegetation. This dataset was used to validate the assignment of the 2005 tree density and 2009 NCAS woody vegetation as native or exotic. All raster data combinations were conducted at 25m grid resolution, representing the application resolution of the Victorian land use and cover datasets. The resulting dataset was compared with the modelled quality of Terrestrial Native Vegetation as per the "Habitat Hectares" approach, and we concluded no further changes need be made. The 1sec resolution base land-use dataset was then projected to Victorian Lamberts using a 100m grid (majority area resampling). The difference in application of the Victorian base land use assignments compared with NSW reflects the greater detail available locally about land use, land cover and native vegetation condition. While a resolution of 25m was feasible for this study landscape, a comparable resolution with NSW of 100m was chosen.

To apply the land-use change storylines and model future land uses based on this model of current land uses, we used the same methods as for the New South Wales study landscapes (Doerr et al. 2013).

2.2.3 Landscape design principles

Selecting a Subset of Design Principles

As detailed in the final report (Doerr et al. 2013), to ensure the results of the project could be used by land managers right now to potentially improve their approaches to landscape design and management, we wanted to compare the most common *existing* landscape design approaches. This is because in practice, landscape designs have been challenging to implement given that the real world involves many social, political and economic complicating factors (Whitten et al. In press). Existing approaches as they are realised on the ground inherently overcome many of these constraints and complicating factors. Thus, we elicited three of the most common approaches to the spatial placement of environmental plantings (and natural regeneration sites) using interviews with land managers and compared them for the New South Wales landscapes with a random spatial control and both a positive and a negative control for the total amount of environmental planting. The design principles differed in the degree to which actions were concentrated in priority areas versus spread across the landscape, and they also differed in the relative proportion of effort devoted to four possible actions:

- Enlarging existing patches of native vegetation
- Restoring new patches of native vegetation in small (20ha) or large (100ha) chunks
- Managing existing local links
- Replanting new local links

We modelled a subset of the six design principles for the validation analyses, in part because we did not have the resources to reproduce the full set of original models and in part because the lack of variation among the four spatial design principles (the three common approaches and the random spatial control) suggested we could focus on detecting differences simply between the ones that were most different from each other. Thus, we chose to eliminate design principle 3 (DP3), which was Building Bridges and Vegetation Extent, and was essentially a hybrid of DP2 and DP4. Thus, the design principles we modelled in the Wimmera were:

Negative Control – No Further Restoration (DP0)

This 'design principle' was included as a control to ensure we could compare all design approaches, which involve some degree of environmental plantings and natural regeneration projects in the future, with doing nothing. Thus, this design principle involves no further environmental plantings beyond what is on the ground now.

Random Spatial Control (DP1)

This 'design principle' was included as a control to compare what could be accomplished via landscape design activities (the other design principles) versus simpler approaches that lack a broader design view, yet still involve the same amount of environmental plantings. Under these simpler approaches, landscape managers would deliver incentives to any willing landowner who comes forward regardless of where they are in the landscape, so the relative effort devoted to different actions was randomly determined.

Building Bridges & Islands (DP2)

This design principle involves a high degree of regional targeting (i.e. 90% of environmental plantings occur in predefined regional priority areas that constitute ~25% of the landscape), a high emphasis on local links (e.g., fenceline corridors, scattered trees), and creating new patches in the landscape via large-scale restoration programs such as Greening Australia's Whole of Paddock Rehabilitation (WOPR, Fifield and Streatfield 2009). As a result of a significant statistical association between using large-scale restoration approaches (as opposed to small-scale) and doing more *restoration* of new local links compared to management of existing local links, this design approach also involves an emphasis on replanting new local links. Under

Storyline 4, we relaxed the degree of regional targeting to reflect that it will likely become more difficult to concentrate actions in priority areas when investment levels are high (Doerr et al. 2013).

Increasing Vegetation Extent (DP4)

This design principle involves only a moderate amount of regional targeting (50% of environmental plantings occur in predefined regional priority areas that constitute ~25% of the landscape), a low emphasis on local links, and the creation of new patches using small-scale restoration activities. Given that this design principle already involves lower regional targeting than the others we chose to model, we applied it in the same way across all storylines rather than adjusting for lower ability to regionally target at higher investment levels.

Positive Control – Achieving ~30% Native Vegetation Cover (DP5)

This 'design principle' was included as a positive control to assess whether the sheer volume of effort devoted to restoration of native ecosystems might be more important than the details of the spatial placement of restoration projects. This represented approximately 5-10 times more environmental plantings than any of the other design principle/storyline combinations. Such a large volume of investment in environmental plantings would be impossible to achieve on the ground using any complex spatial rules. Thus, we implemented this design principle by simply converting all crops and pastures with scattered trees to environmental plantings and then selecting areas of crops and pastures without scattered trees until approximately 30% cover was achieved.

Each combination of design principle and storyline was then converted into specific area-based targets for conversion of crops and pastures with and without scattered trees to the four actions, within and outside priority areas. See the final report for more details (Doerr et al. 2013).

Modelling Design Principles

As detailed in the final report (Doerr et al. 2013), the process we used to model the design principles involved defining a large number of candidate patches adjacent to existing native vegetation, candidate patches not adjacent to existing native vegetation, candidate existing links, and candidate restored links. We then iteratively selected or removed candidates until two sets of targets were reached: targets for the four types of actions inside and outside priority areas and targets for the total amount of land uses being converted (crops and pastures both with and without scattered trees). We executed this same process to model the design principles in the Wimmera study landscape.

For the New South Wales study landscapes, given the challenge in meeting all targets simultaneously, we considered a target to be met if our conversions came within 10% of the target value and we achieved that for all targets simultaneously. However, there was more limited availability of crops and pastures with paddock trees in the Wimmera landscape, particularly where it might be possible to manage existing links between areas of more intact native vegetation. As a result, we found it particularly challenging in the Wimmera to meet the conversion targets specifically for managing existing links. Thus, in the Wimmera, we applied the goal of reaching targets within 10% to the overall target for all links (new or existing) rather than to each link type separately. Where insufficient candidate existing links were available, we added additional new links to reach the overall links target.

2.2.4 Change in native vegetation

For consistency with the vegetation types mapped in the NSW study landscapes and the associated REMP parameters for the study species, we extrapolated the model of NSW vegetation types (see Doerr et al. 2013) to the Wimmera study landscape. Results were projected to Victorian Lamberts, majority resampled to a 100m grid, and clipped to the respective study region. That is, in the current and future Wimmera study landscape, we modelled the vegetation formations as defined by Keith (2004) to estimate vegetation responses to shifts in environmental suitability, using the training data compiled for NSW (Table 1). These vegetation formations represent predominantly structural and functional vegetation types, which might be expected to be broad enough to still apply to future communities with different compositions, and which are also well suited to use in the metapopulation capacity models. For comparison, we also developed a model of vascular plant species compositional turnover using data compiled for the Wimmera and broadly surrounding regions and applied this to the vegetation communities that are specific to Victoria and used by the Wimmera CMA for their planning. These model outputs (shown in Appendix A) demonstrate how the approach can be customised in future work to local conditions and data.

Table 1. Vegetation formations and subformations for NSW as defined by Keith (2004), the vegetation types used in this project and applied to model the Wimmera study landscape. See Doerr et al. (2013) for classification schema.

Formation or Subformation	Brief Description
Rainforests (wet, littoral and dry subformations)	Forests of broad-leaved mesomorphic trees, with vines, ferns and palms
Wet sclerophyll forests (shrubby subformation)	Tall forests of scleromorphic trees (typically eucalypts) with dense understories of mesomorphic shrubs
Wet sclerophyll forests (grassy subformation)	Tall forests of scleromorphic trees (typically eucalypts) with dense understories of ferns and forbs
Grassy woodlands	Woodlands of scleromorphic trees (typically eucalypts), with understories of grasses and forbs and sparse shrubs
Grasslands	Closed tussock grasslands with a variable compliment of forbs
Dry sclerophyll forests (shrub/grass subformation)	Forests of scleromorphic trees (typically eucalypts), with mixed semiscleromorphic shrub and grass understories
Dry sclerophyll forests (shrubby subformation)	Low forests of scleromorphic trees (typically eucalypts), with understories of scleromorphic shrubs and sparse groundcover
Heathlands	Dense to open shrublands of small-leaved scleromorphic shrubs and sedges
Alpine complex	Mosaics of herbfields, grasslands and

Formation or Subformation	Brief Description
	shrublands
Forested wetlands	Ephemerally inundated wetlands with permanent tree cover, such as River Red Gum forests
Other wetlands (freshwater and saline)	Wet shrublands or sedgelands, usually with a dense groundcover of graminoids, and shrublands and herbfields of mangroves, succulent shrubs or marine herbs
Semi-arid woodlands (grassy subformation)	Open woodlands of scleromorphic trees (eucalypts, acacias, casuarinas), with open understories of grasses and forbs
Semi-arid woodlands (shrubby subformation)	Open woodlands of scleromorphic trees (eucalypts, acacias, casuarinas), with open understories of xeromorphic shrubs and some grasses and forbs
Arid shrublands (chenopod subformation)	Open shrublands of xeromorphic shrubs, hummock or tussock grasses and ephemeral herbs, often dominated by chenopods
Arid shrublands (acacia subformation)	Open shrublands of xeromorphic shrubs, hummock or tussock grasses and ephemeral herbs, often dominated by Acacia spp.

2.2.5 Bringing together design principles, land-use change and changes in native vegetation to create future landscapes

The land-use changes estimated at our expert workshop, the spatial placement of environmental plantings according to design principles elicited from current landscape managers, and the effects of climate on the distributions of native vegetation communities were all modelled into the future using parallel modelling processes. The resulting layers were combined for the Wimmera landscape just as they were for the New South Wales landscapes, by overlaying environmental plantings according to design principles on top of the land use storyline layers, then combining these future land-use layers with the future vegetation layers in cross grids, used in the metapopulation capacity models (Rapid Evaluation of Metapopulation Persistence; REMP). The result for the Wimmera was 20 future landscapes (2 storylines of land-use change x 5 design principles x 2 GCMs; Figure 2), represented as cross grids, which we could then evaluate for their capacity to support native species without intensifying problems with invasive species.

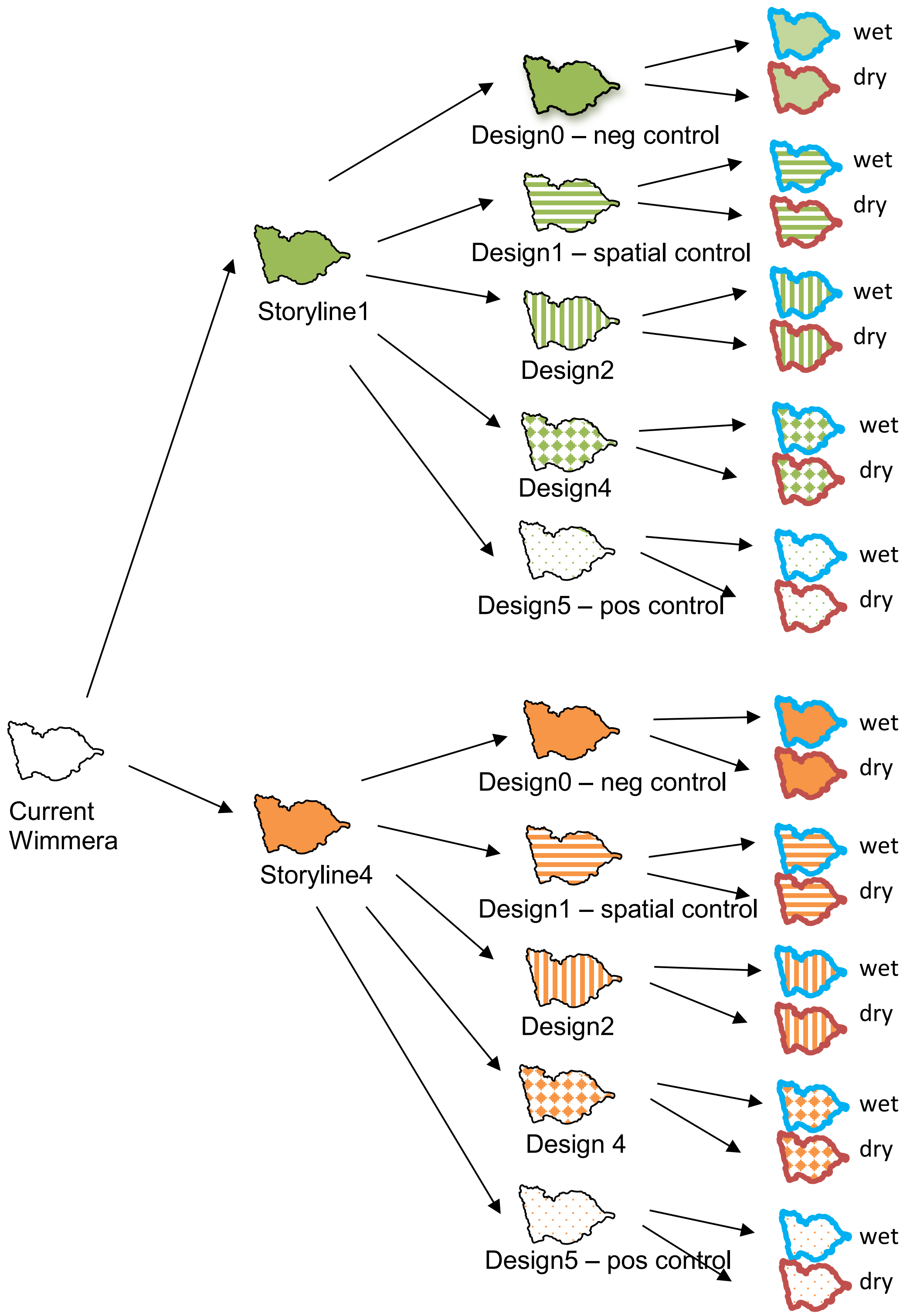


Figure 2. **Diagram showing generation of the 20 future landscapes for the Wimmera. We implemented two different storylines of land-use change (associated with emissions scenarios), overlayed those with three different design principles for environmental plantings plus two controls for amount of restoration, and combined those future land uses with projections of future vegetation community distributions based on two different global climate models (GCMs) for each emissions scenario (storyline) considered.**

2.3 Evaluating Metapopulation Capacity of Future Landscapes

To determine the degree to which our different future landscapes might benefit biodiversity, we used Rapid Evaluation of Metapopulation Persistence (REMP). This is a modelling approach that estimates the capacity of a landscape to support viable populations of species chosen by the user (Drielsma and Ferrier 2009; Drielsma et al. 2007). A number of other modelling approaches focus on presence of many species at once, including those originally developed for planning conservation reserves like Marxan (Ball et al. 2009), which optimises a set of reserves based on representativeness of entities present. Such conservation planning tools have been popular because of the need for landscape managers to design and manage landscapes that support all native species. However, the stated objectives of most landscape management initiatives are to ensure the persistence of native species – a more process-based goal and one that is not necessarily synonymous with species presence. Thus, we chose to use a modelling approach that is process-based and fundamentally structured around the goal of persistence, but considered how we could apply it in a novel way that would take it beyond its current single-species application.

For the Wimmera validation, we used the same methodology as for the initial analyses of the New South Wales study landscapes. We used REMP to evaluate current and future capacity of landscapes to support four native generic focal species (Watts et al. 2010): native orchids, wet forest specialist fauna, and two woodland and dry forest specialist fauna. We also modelled two individual invasive species: red foxes (*Vulpes vulpes*) and peppercorn tree (*Schinus molle*). The individual species that defined the generic focal species, the data used to derive model parameters, and the final model parameters were the same for the Wimmera landscape as for the New South Wales landscapes (see bolded rows in Table 25 of Doerr et al. 2013).

2.4 Analysing Performance of Design Principles

Using the Wimmera data only, we calculated summary statistics for future values and change from current for both variables related to metapopulation capacity for each of our species and species groups: 1) the largest potential metapopulation in the future landscape (LPM; expressed as a proportion of the threshold estimated to provide viability), 2) the total area occupied by all potential viable metapopulations in the future landscape. Each of these summary statistics has a slightly different interpretation which could be used to help inform management. Note that all values for wet forest specialist fauna were zero, because there was insufficient habitat to support even one viable metapopulation of these species in the current Wimmera or in any modelled future Wimmera landscapes. Thus, this species group is excluded from our presentation of summary statistics and further analyses.

For formal statistical analyses, we focused on the change in values from the current landscapes, as this most directly represents the effect of design principles (and our other covariates) rather than the effect of starting conditions. When evaluating the cost-effectiveness of different landscape design approaches, this would also be the parameter that would be analysed relative to cost. To facilitate comparison of native species groups (which we hope to respond positively to design principles) and invasive species (which we hope to respond negatively to design principles) in the same final models, we reversed the sign of the response variable for invasive species. Thus, the response variable represents the amount of 'improvement' in metapopulation capacity, with improvement defined for native species groups as an increase and improvement defined for invasive species as a decrease.

We used a Generalised Linear Modelling (GLM) approach, with species within future landscapes as our units of analysis. For our first set of formal analyses, we combined the Wimmera data with data from the same subset of storylines and design principles in the New South Wales landscapes (n=300; 60 future landscapes x 5 species or GFSs) and compared the results to those obtained from the full analysis of the NSW-only data (n=576). We chose this approach rather than simply analysing the Wimmera data alone because the smaller sample size of Wimmera-only results (n=100) meant that we would not have sufficient degrees of freedom to run the same basic models that we had used in the final report (Doerr et al. 2013).

For these three-landscape models, we used an information theoretic approach, specifying a series of candidate models based on *a priori* hypotheses about the factors likely to affect changes in metapopulation capacity. Potential predictor variables were categorical and included: design principle (DP; five levels), land-use change storyline (SLine; two levels), Global Climate Model used in combination with emissions scenarios linked to storylines to model the vegetation change (GCM; two levels), study landscape (Lscape; three levels), and species or GFS (Species; five levels). We also considered as potential predictors all two-way interaction terms involving design principles, such as DP*SLine if, for example, design principles differ in their effectiveness depending on the amount of investment in environmental plantings inherent in the different storylines. Our *a priori* hypotheses and resulting candidate models are shown in Table 2. The only difference between these and the set of candidate models used in the final report for the NSW landscapes was that the sample size for the final report was large enough that we could also include three and four-way interaction terms among the covariates in BaseModel2 and its variants rather than just the two-way interaction terms.

Table 2. Candidate hypotheses about the factors likely to affect changes in metapopulation capacity in future landscapes and resulting model parameterisation. Abbreviations defined in preceding paragraph of the main text.

Model#	Hypothesis	Model
1	All factors except DP have main effects (BaseModel1)	Lscape+Species+SLine+GCM
2	All factors including DP have main effects	BaseModel1 + DP
3	Main effects but DP effect differs between landscapes	BaseModel1 + DP + (DP*Lscape)
4	Main effects but DP effect differs between species	BaseModel1 + DP + (DP*Species)
5	Main effects but DP effect differs between storylines	BaseModel1 + DP + (DP*SLine)
6	Main effects but DP effect differs between GCMs	BaseModel1 + DP + (DP*GCM)
7	Main effects but DP effects differs between all others	BaseModel1 + DP + (DP*Lscape) + (DP*Species) + (DP*SLine) + (DP*GCM)
8	All factors except DP have main effects and two-way interactions (BaseModel2)	Lscape + Species + SLine + GCM + (Lscape*Species) + (Lscape*SLine) + (Lscape*GCM) + (Species*SLine) + (Species*GCM) + (SLine*GCM)
9	DP has main effects only but all other factors have main and two-way interaction effects	BaseModel2 + DP
10	DP has main effects and interaction with Lscape - all other factors have main and two-way interaction effects	BaseModel2 + DP + (DP*Lscape)
11	DP has main effects and interaction with Species - all other factors have main and two-way interaction effects	BaseModel2 + DP + (DP*Species)
12	DP has main effects and interaction with SLine - all other factors have main and two-way interaction effects	BaseModel2 + DP + (DP*SLine)
13	DP has main effects and interaction with GCM - all other factors have main and two-way interaction effects	BaseModel2 + DP + (DP*GCM)
14	DP has main effects and all two-way interactions - all other factors have main and two-way interaction effects	BaseModel2 + DP + (DP*Lscape) + (DP*Species) + (DP*SLine) + (DP*GCM)

Conceptually, the first seven models (#1-7) build on the background hypothesis that the factors that biodiversity managers cannot control – the landscape they work with, the species they manage, future climates and resulting land-use changes – all affect the change in metapopulation capacity of their landscapes in the future but in independent ways. For example, changes in metapopulation capacity may differ between landscapes and between future climates, but future climate has a similar effect in all landscapes. The second seven models (#8-14) build on the background hypothesis that all the factors that biodiversity managers cannot or generally do not control have complex interacting effects. This is essentially the hypothesis that the impacts of climate change on metapopulation capacity will be highly context-dependent and thus different everywhere and for all species. Within each of these two groups, we then explore hypotheses specifically about the effects of design principles – the primary factor that biodiversity managers can control. We only explore hypotheses about main effects of design principles and two-way interactions, because higher order interactions represent situations in which it would be too difficult for landscape managers to implement different design principles in different contexts (e.g., for different climate futures in different landscapes and for different species).

These candidate models were then compared using Akaike's Information Criterion, corrected for small sample size relative to the number of parameters modelled (AICc). The lowest AICc value from any model was subtracted from the AICc values of each model to yield ∆AICc values which were then used to rank candidate models. Using this approach, the model with the greatest support based on the data has a ∆AICc value of zero and models with increasing ∆AICc values have decreasing levels of support. We also calculated Akaike weights for each model (ω), which represent the approximate probability that the model is the best model of the candidate set.

We evaluated the overall effect of design principles by examining the Akaike weights of models that included a design principle effect and by performing post-hoc paired comparisons to calculate design principle effect sizes where design principle (DP) was included in the top-ranked model (with the greatest Akaike weight). Design principle effects were considered robust if the confidence interval did not include zero. Where an interaction between design principles and another variable was included in the top-ranked model, separate models were constructed for each of the different levels of the other variable to explore how design principle effects might vary within and across these levels. Finally, where the results of these three-landscape models differed somewhat from the analyses in the final report (based on NSW landscapes only but a larger sample size of storylines, design principles, and species), we modelled the Wimmera data separately, though we could only construct simple models of main effects and the single interaction term that was significant in the three-landscape models. The intent was to explore whether adding the Wimmera data changed the final results because of a substantial difference in the pattern of the results in the Wimmera or just a difference in the strength of the relationships. All analyses were performed in SYSTAT version 13.1 (Systat Software Inc., Chicago, Ill.).

3 Results and Outputs

3.1 Future Wimmera Landscapes

Our 20 modelled Wimmera future landscapes combined the effects of changes in land-use according to two storylines of likely future change, different approaches to landscape design in terms of the placement of environmental plantings in the landscape, and changes in native vegetation community distributions according to both relatively wet and relatively dry global climate models. Here we provide example results for each of these components separately, then provide the results of combining these types of landscape change to produce our future landscapes.

3.1.1 Land-use change storylines

The specific estimated percentages of conversions from one land use to another according to our two future storylines applied to the Wimmera are shown in two conversion tables, Table 3 for Storyline 1 and Table 4 for Storyline 4.

The modelled current land uses for the Wimmera are shown in Figure 3 and the spatial implementations of the storylines of land-use change are depicted in Figure 4, which shows the modelled changes except the new environmental plantings (which were modelled as design principles – see below). Figure 5 shows the same comparisons but depicts a smaller portion of the study landscape to show some of the detailed modelled changes. The modelling approach resulted in all changes being modelled in the Wimmera with an absolute error rate of <0.2%.

Note that the main differences between the Wimmera storylines and those for the NSW study landscapes were that increasing urbanisation was not projected for the Wimmera, so there was no conversion of other land uses into urbanised areas (i.e., non-habitat for natives). In addition, there is little woody production in the current Wimmera so no substantial projected conversions from that land use into the future. Perhaps most importantly, while increasing demand for food was modelled in the NSW landscapes as conversions from native vegetation to crops and pastures without scattered trees, the increasing demand for food was modelled in the Wimmera as conversions from native vegetation to crops and pastures with scattered trees. The rationale was that the Wimmera has lower water availability (even lower than at present in most future landscapes), so increasing food production might need to take the form of increasing meat production in more extensive systems rather than intensive agriculture. As a result, the two Wimmera storylines differed most in the degree to which native vegetation on private lands was completely lost or converted to scattered trees (see the patches west of Yanac in Figure 5), and thus the degree of retention of scattered trees in the landscapes. In addition to the amount of environmental plantings, the two storylines also differed in terms of the degree to which production-based land uses included woody components for taking advantage of biofuel and carbon markets (the dark brown squares in Figure 5).

Table 3. Proportional conversion from current to future land uses for Wimmera, Storyline 1

To From	Storyline 1: Adaptation Without Global Mitigation (A1FI, High intensity) by 2070						
	1. Non-habitat for natives	2. Crops and pastures	3. Crops and pastures with paddock trees	4. Woody production	6. Environmental plantings 2050	8. Modified native woody	9. Native protected
1. Non-habitat for natives							
2. Crops and pastures				0.2% - in small bits around biofuel processing centres 0.1% - in small bits in areas with best growth potential	0.7% - in areas with lowest profit		
3. Crops and pastures with paddock trees		55%			12% - in areas with lowest profit		
4. Woody production							
5. Env. planting c.2009						100%	
8. Modified native woody			10% - next to existing crops and pastures				
9. Native protected							

Table 4. Proportional conversion from current to future land uses for Wimmera, Storyline 4

To From	Storyline 4: Global Fix with Proactive Australia (A1B, Medium intensity) by 2070						
	1. Non-habitat for natives	**2. Crops and pastures**	**3. Crops and pastures with paddock trees**	**4. Woody production**	**7. Environmental plantings 2030**	**8. Modified native woody**	**9. Native protected**
1. Non-habitat for natives							
2. Crops and pastures				0.4% - in small bits around biofuel processing centres 2.0% - in small bits in areas with best growth potential	1.2% - in areas with lowest profit		
3. Crops and pastures with paddock trees		25%			40% - in areas with lowest profit (increasing to moderate profit)		
4. Woody production							
5. Env. planting c.2009						100%	
8. Modified native woody			2% - next to existing crops and pastures				
9. Native protected							

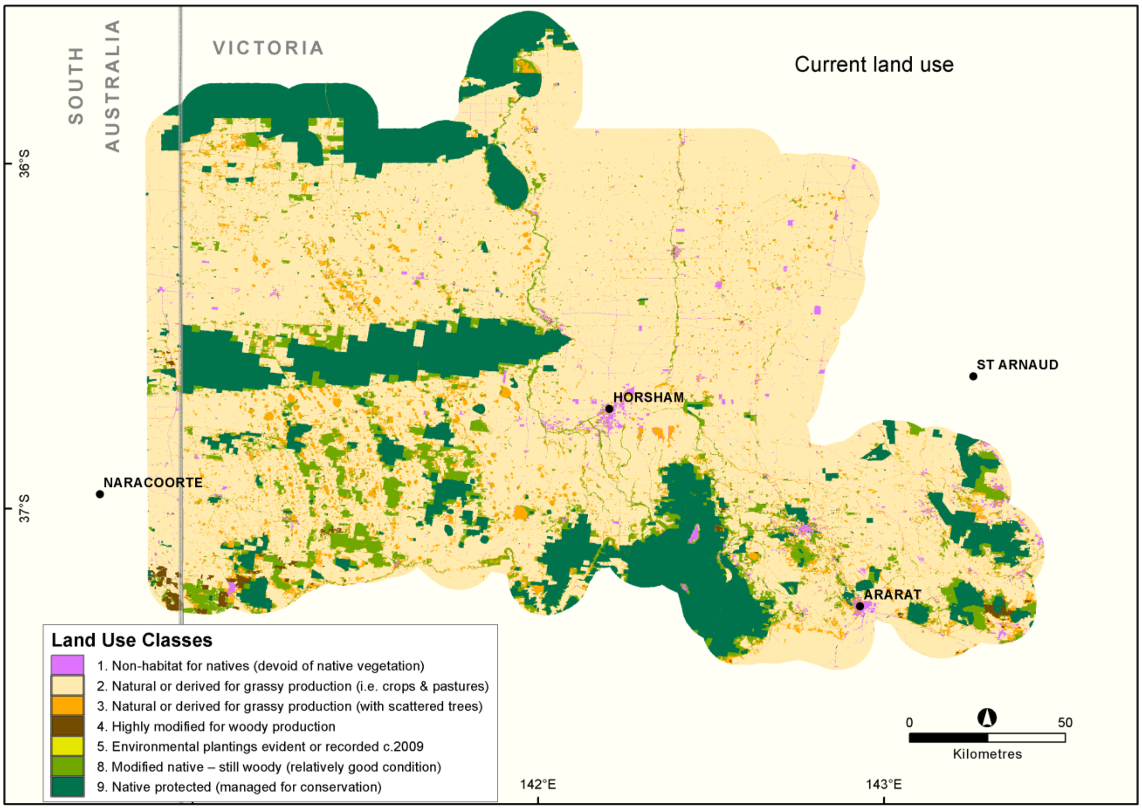


Figure 3. Modelled current land uses in the Wimmera study landscape.

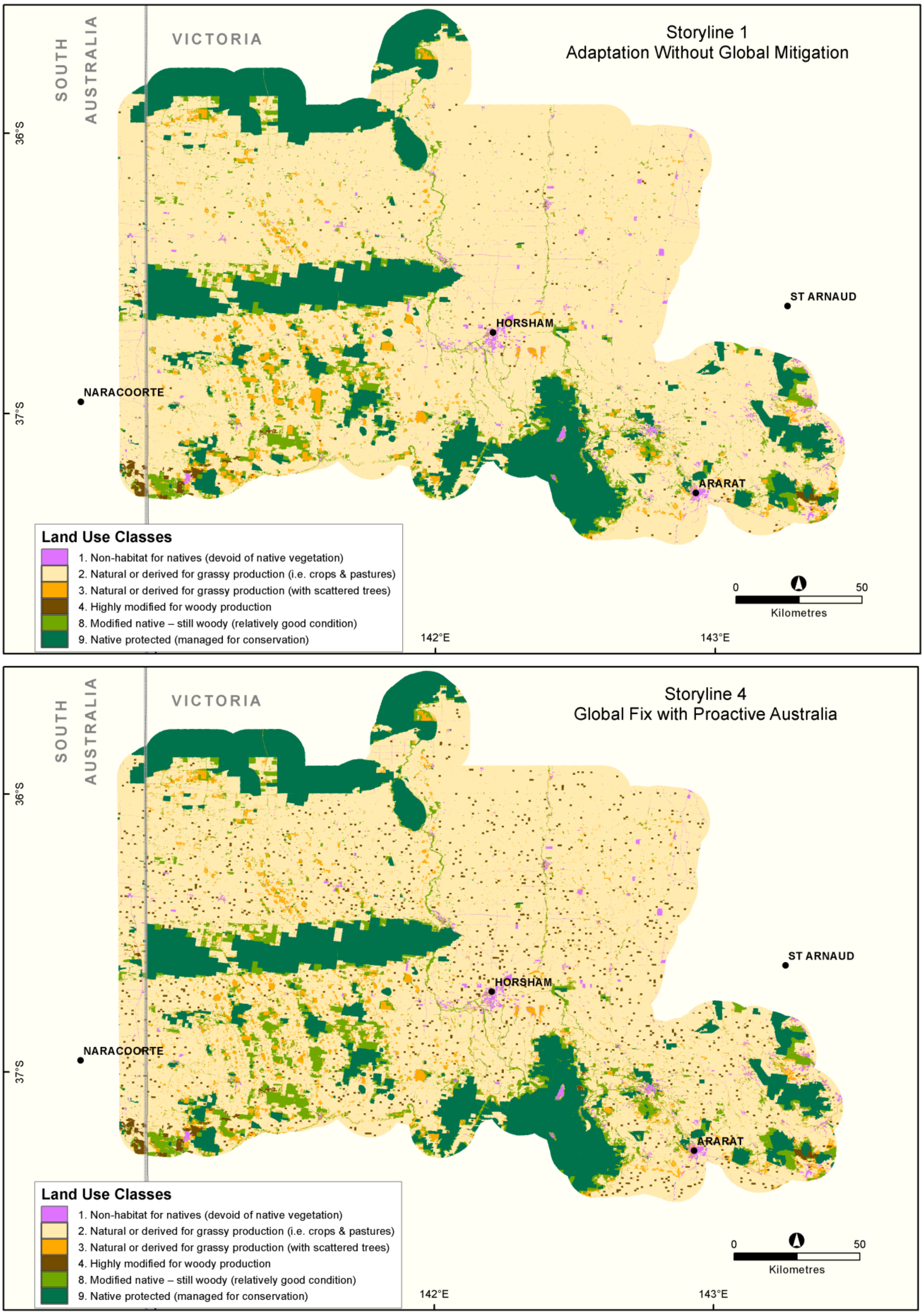


Figure 4. **Future land uses in the Wimmera landscape according to Storyline 1 (top) and Storyline 4 (bottom). All land-use changes are depicted except the establishment of environmental plantings.**

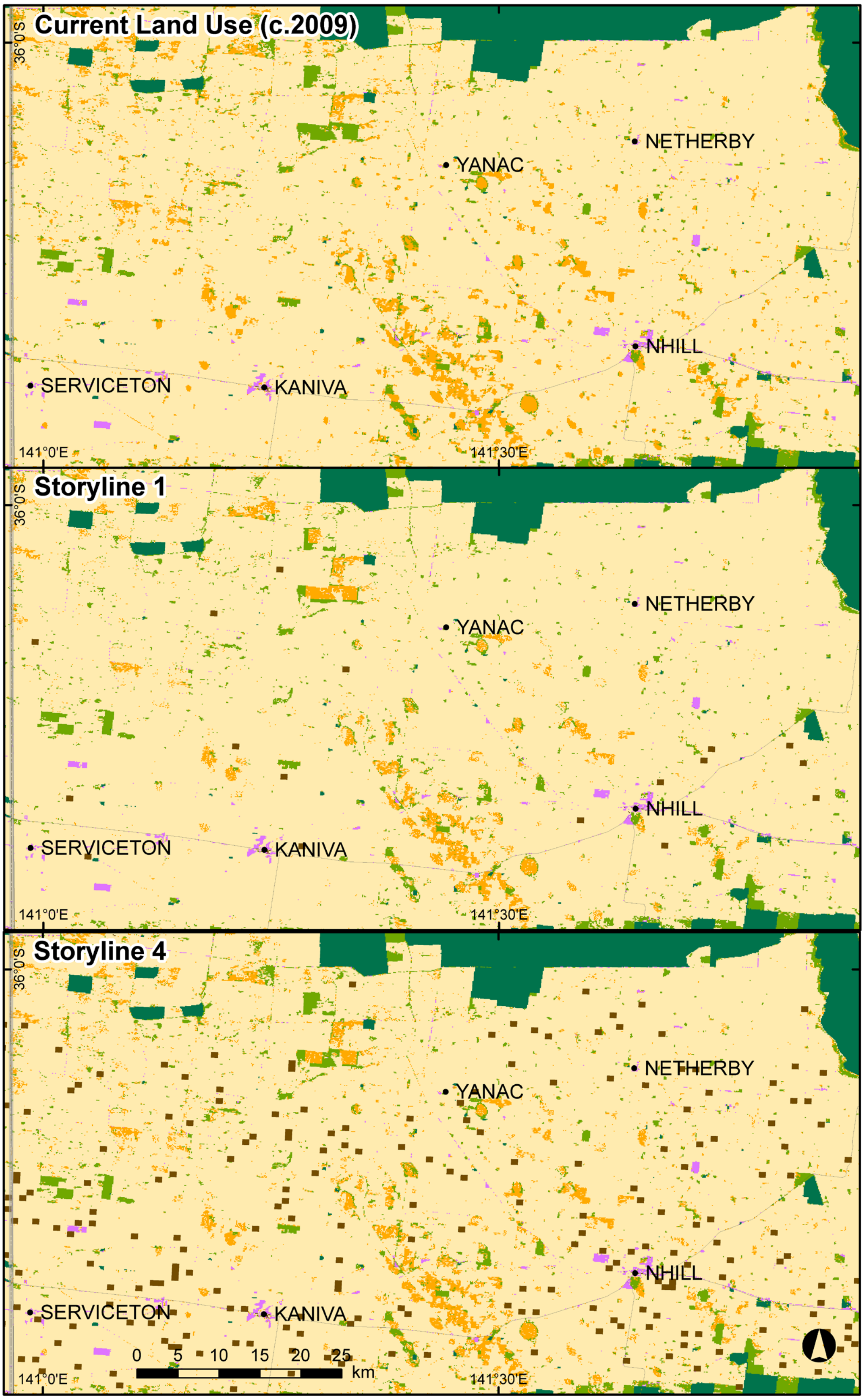


Figure 5. **Portions of the current (top) and future (middle=Storyline 1 and bottom=Storyline 4) Wimmera study landscapes. All land-use changes are depicted except the establishment of environmental plantings. Legend is given in Figures 5 & 6.**

3.1.2 Design principles

As detailed in the final report (Doerr et al. 2013), we calculated specific area-based targets for land uses to be converted to environmental plantings according to each combination of land-use change storyline and design principle. These target tables for the Wimmera are available from the authors upon request.

Examples of the spatial implementation of these design principles are depicted in Figure 6 and Figure 7, which show design principles 2, 4 and 5 applied according to land-use change Storyline 1 (with the size of environmental plantings enhanced to make them visible). At this scale, one of the most obvious differences between the design principles is in the amount of environmental plantings but also the degree of spatial targeting and thus concentration of on-ground actions in particular portions of the landscape. Figure 8 also shows the design principles (also with sizes of areas enhanced), but depicts a smaller portion of the study landscape to show some of the detailed modelled changes. Note the detailed targeting of new environmental plantings under design principle 2, with plantings concentrated near existing patches of native vegetation and scattered trees, but the more extensive nature of plantings under both design principles 4 and 5. The total area of each land use under the different storylines and design principles is listed in Table 5. While the amount of plantings is often highly aspirational in these models, the spatial placement (including small variations in spatial placement between the design principles) reflects reality, where spatial placement is often constrained by the locations of willing land owners.

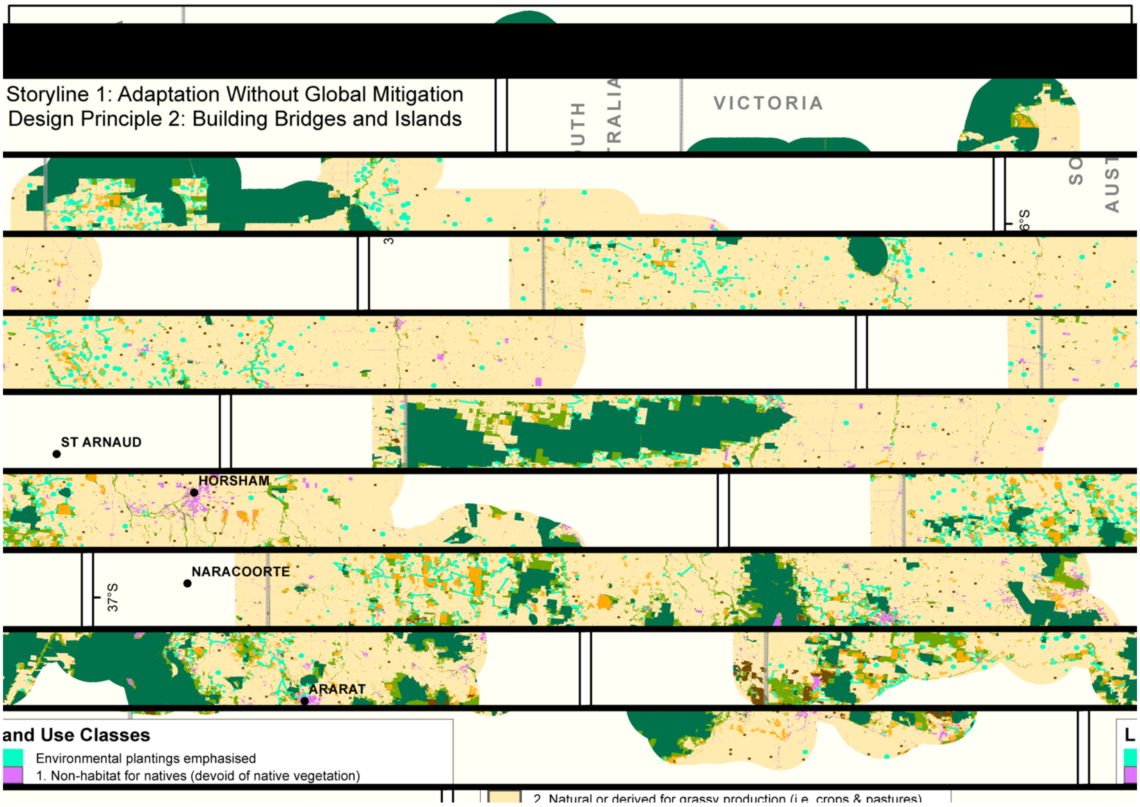
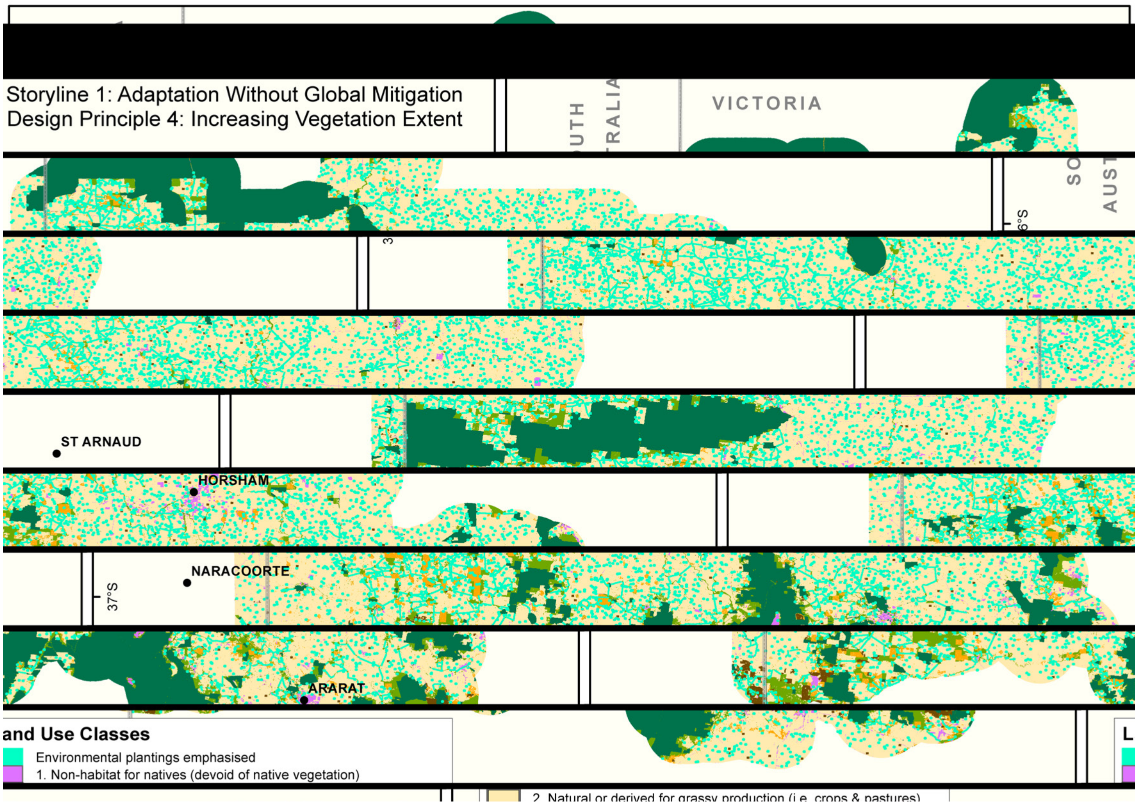


Figure 6. The Building Bridges & Islands design principle applied to the placement of new environmental plantings under Storyline 1 in the Wimmera study landscape. Note that the size of environmental plantings has been enhanced to ensure visibility at this scale.



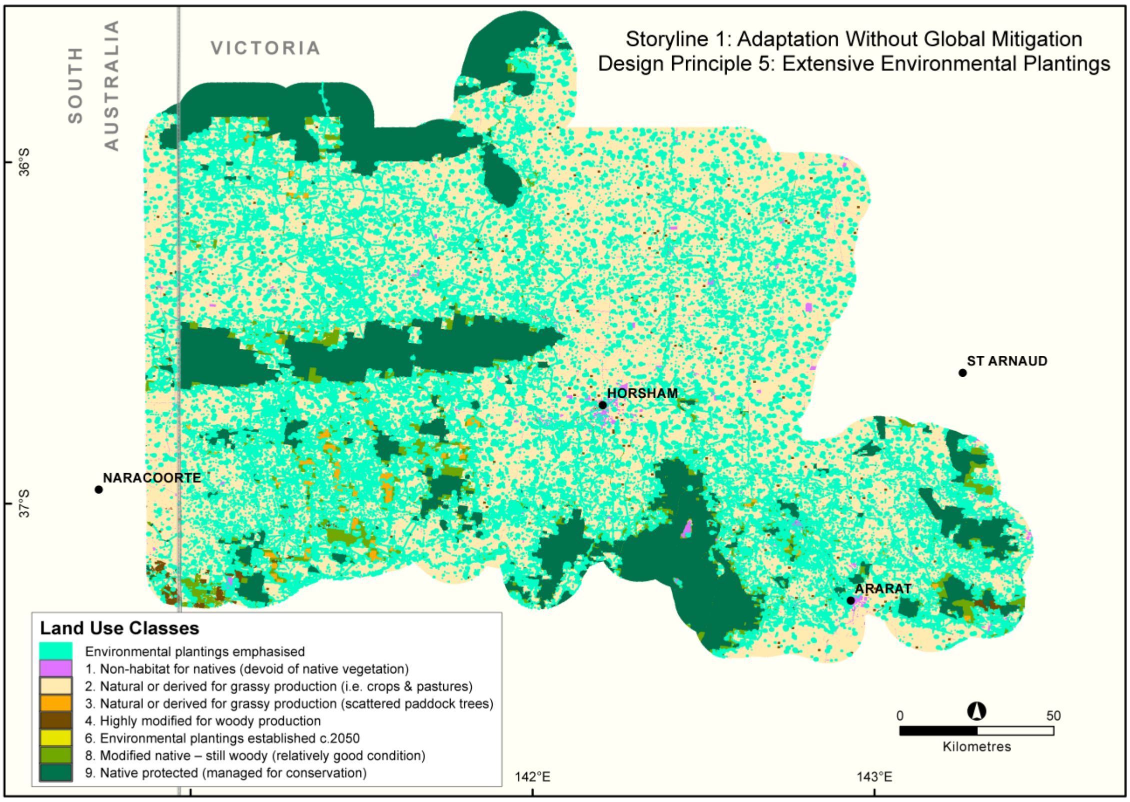


Figure 7. The Increasing Vegetation Extent (top) and Extensive Environmental Plantings (bottom) design principles applied to the placement of new environmental plantings under Storyline 1 in the Wimmera study landscape. Note that the size of environmental plantings has been enhanced to ensure visibility at this scale.

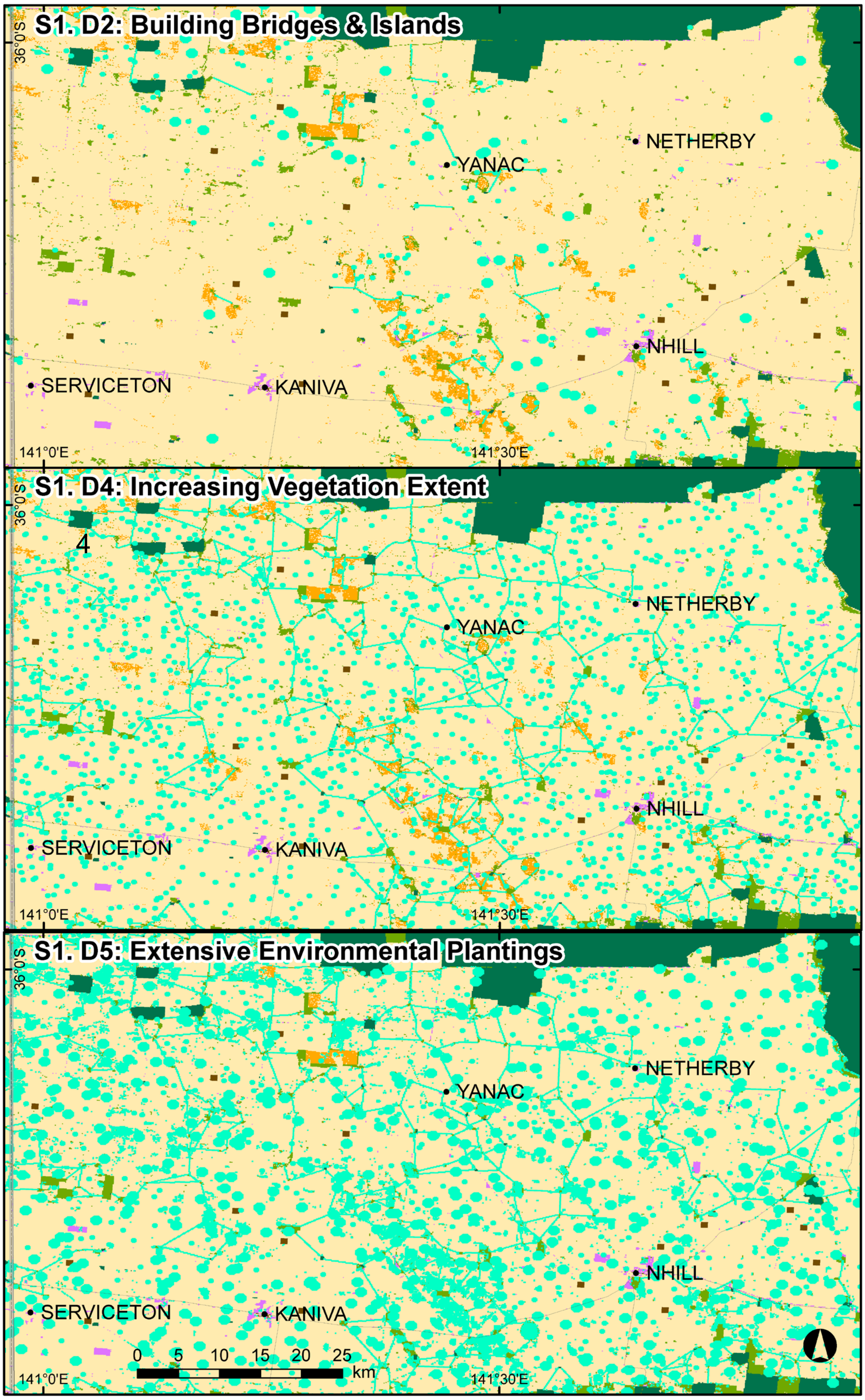


Figure 8. Portions of the Wimmera landscape showing three design principles, Building Bridges & Islands (top), Increasing Vegetation Extent (middle), and Extensive Environmental Plantings (bottom) applied to the placement of new environmental plantings under Storyline 1. Legend is given in Figure 6 & 7.

Table 5. Total area (in hectares) under each land use in the future Wimmera study landscapes based on each land-use change storyline and design principle combination

Land Use Class	Storyline 4					Storyline 1				
	DP0	DP1	DP2	DP4	DP5	DP0	DP1	DP2	DP4	DP5
1. Non-habitat for natives	35,839	34,741	34,161	33,492	32,582	35,839	35,328	35,541	33,492	32,582
2. Crops & pastures-no scattered trees	2,290,219	2,210,168	2,155,350	2,094,896	1,967,049	2,392,445	2,360,780	2,360,370	2,187,529	2,012,100
3. Crops & pastures-with scattered trees	134,276	129,921	122,392	119,387	3,398	98,667	97,417	95,569	88,487	17,495
4. Highly modified for woody production	72,449	70,106	68,735	67,269	64,645	22,273	22,133	22,059	21,054	20,330
6. Environmental plantings established c.2050	0	0	0	0	0	0	36,947	41,266	233,675	496,758
7. Environmental plantings established c.2030	0	96,850	165,622	233,675	496,758	0	0	0	0	0
8. Modified native woody (relatively good condition)	197,548	192,039	186,974	185,013	176,384	181,107	179,118	176,783	169,495	161,551
9. Native protected (managed for conservation)	560,332	556,838	557,429	556,931	549,847	560,332	558,940	559,075	556,931	549,847

3.1.3 Current and future vegetation

The modelling of current and future vegetation for the Wimmera used the same models as reported in Doerr et al. (2013). The resulting modelled map of current vegetation extent in the absence of disturbance across the Wimmera study landscape is presented in Figure 9. Rare formation type 3 (grassy wet sclerophyll forests) was predicted to not have a dominant occurrence and was dropped from the legend. The maximum predicted probability at each cell, derived as an aggregate of all predicted probabilities for the vegetation classes within each formation/subformation, is shown in the bottom panel of Figure 9. This provides a measure of confidence in the prediction at each 100m grid cell location.

The model was then used to derive future vegetation extents by substituting current climate variables with future climate variables. The resulting changes in the number of hectares of each vegetation formation are listed in Table 6.

Table 6. Extent in hectares of current and projected future vegetation formations across the Wimmera study landscape (3,290,663 ha)

Vegetation Formation	Current	Story 1 dry	Story 1 wet	Story 4 dry	Story 4 wet
01. Rainforests (humid & dry forms)	0	505	5,252	1,695	2,196
02. Wet sclerophyll forests (shrubby form)	0	0	1	0	0
03. Wet sclerophyll forests (grassy form)	0	0	0	0	0
04. Grassy woodlands	1,403,848	896,701	1,333,332	1,229,295	1,417,890
05. Grasslands	366,212	66,606	431,694	128,911	494,325
06. Dry sclerophyll forests (shrubby/grass)	662,276	143,615	289,677	226,446	444,438
07. Dry sclerophyll forests (shrubby form)	9	58,544	46,443	13,746	5,014
08. Heathlands	26	21,434	6,839	8,954	1,463
09. Alpine complex	0	0	0	0	0
10. Forested wetlands	4,197	11,146	1,322	27,493	2,142
11. Other wetlands (freshwater and saline)	740	29,745	19,658	27,368	3,476
12. Semi-arid woodlands (grassy form)	116,644	97,114	208,211	87,629	115,710
13. Semi-arid woodlands (shrubby form)	390,908	1,268,795	305,527	877,601	265,611
14. Arid shrublands (chenopod form)	345,803	696,458	642,707	661,525	538,398
15. Arid shrublands (acacia form)	0	0	0	0	0

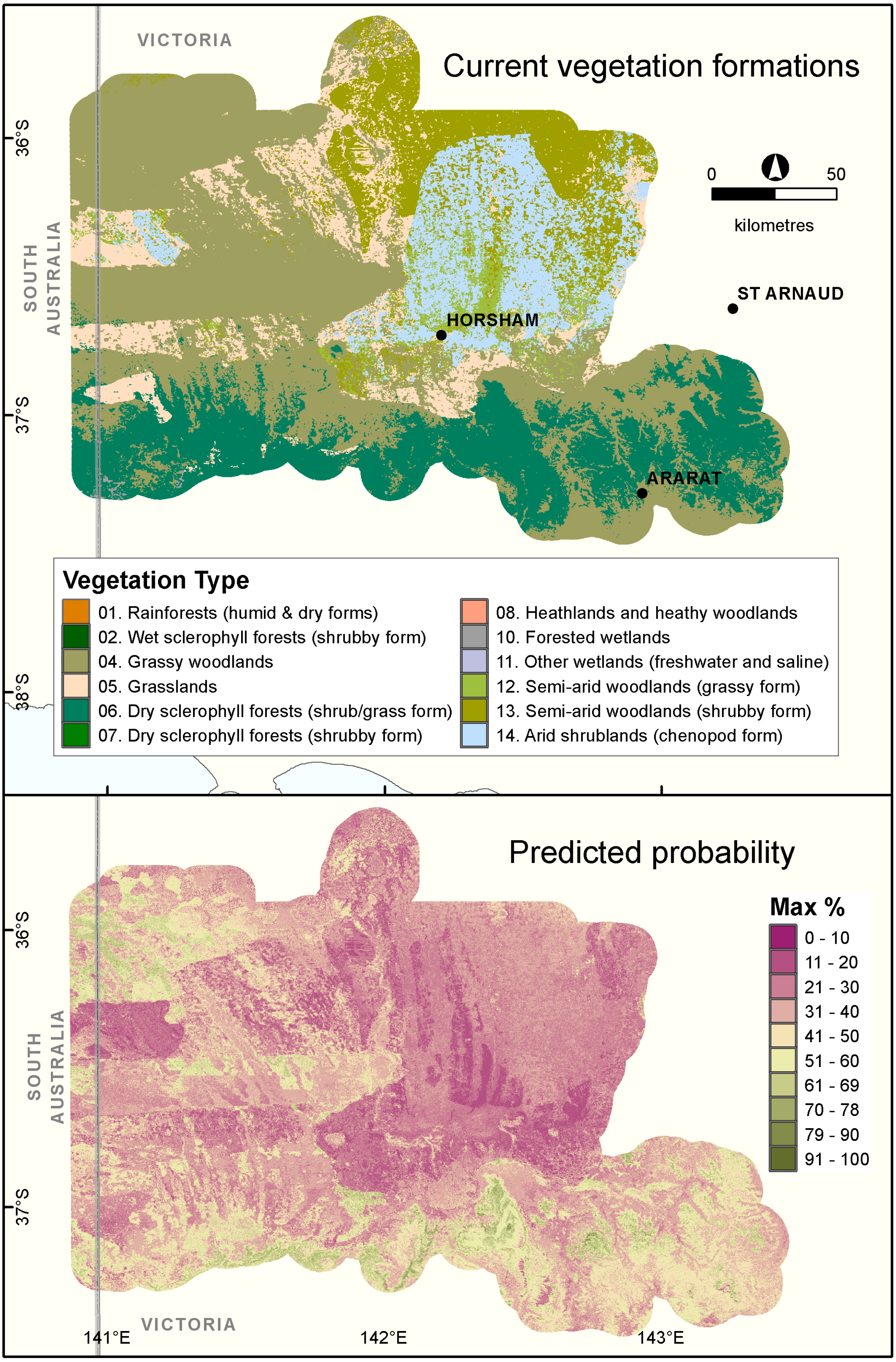


Figure 9. **Current predicted vegetation formations for the Wimmera study landscape (above) and the maximum predicted probabilities associated with the modelled vegetation classes aggregated into formations (below)**

Across almost all emissions scenarios and GCMs, the models show a reduction in the extent of grassy woodlands, which are generally replaced by semi-arid woodlands (shrubby subformation) and dry sclerophyll forests (see maps of the modelled future vegetation in Figure 10 and Figure 12). In addition, most of the future vegetation models show an increase in the extent of semi-arid woodlands, though minimally under a wetter GCM. The percentage change in vegetation extents relative to current under Storyline 1 is given as an example in Table 7.

These results are indicative of relative differences rather than precise predictions of future vegetation because they do not take into account all influences on future vegetation communities. The extension of the NSW vegetation models to the Wimmera, while reasonably applicable to some vegetation types, results in increased uncertainty due to extrapolation (see Figure 11 and Figure 13). Improvement in model prediction can be attained through the use of local datasets (e.g. Appendix A).

Table 7. Change in current and projected extents of vegetation across the Wimmera study landscape (15,371,220 ha), comparing Storyline 1 wet (S1W) and dry (S1D) plausible climate futures

Vegetation Formation	%current	%S1D	%change	%S1W	%change
01. Rainforests (humid & dry forms)	0.00	0.02	0.02	0.16	0.16
02. Wet sclerophyll forests (shrubby form)	0.00	0.00	0.00	0.00	0.00
03. Wet sclerophyll forests (grassy form)	0.00	0.00	0.00	0.00	0.00
04. Grassy woodlands	42.66	27.25	-15.41	40.52	-2.14
05. Grasslands	11.13	2.02	-9.10	13.12	1.99
06. Dry sclerophyll forests (shrubby/grass)	20.13	4.36	-15.76	8.80	-11.32
07. Dry sclerophyll forests (shrubby form)	0.00	1.78	1.78	1.41	1.41
08. Heathlands	0.00	0.65	0.65	0.21	0.21
09. Alpine complex	0.00	0.00	0.00	0.00	0.00
10. Forested wetlands	0.13	0.34	0.21	0.04	-0.09
11.Other wetlands (freshwater and saline)	0.02	0.90	0.88	0.60	0.57
12. Semi-arid woodlands (grassy form)	3.54	2.95	-0.59	6.33	2.78
13. Semi-arid woodlands (shrubby form)	11.88	38.56	26.68	9.28	-2.59
14. Arid shrublands (chenopod form)	10.51	21.16	10.66	19.53	9.02
15. Arid shrublands (acacia form)	0.00	0.00	0.00	0.00	0.00

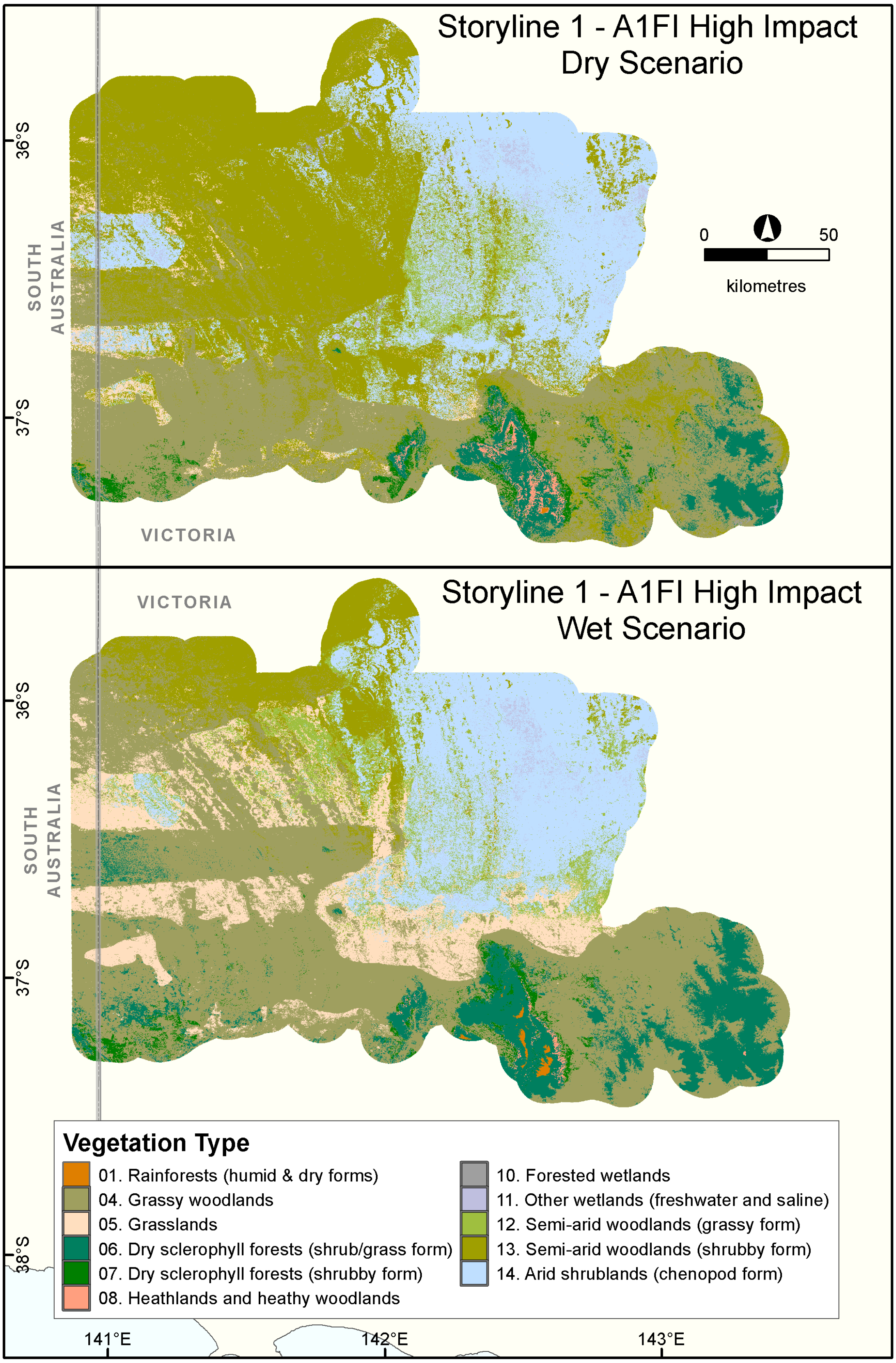


Figure 10. Vegetation formations for Storyline 1 projected across the Wimmera study landscape. The dry scenario derives from the CSIRO Mk 3.5 Global Climate Model (GCM) and the wet scenario derives from the Miroc-M GCM.

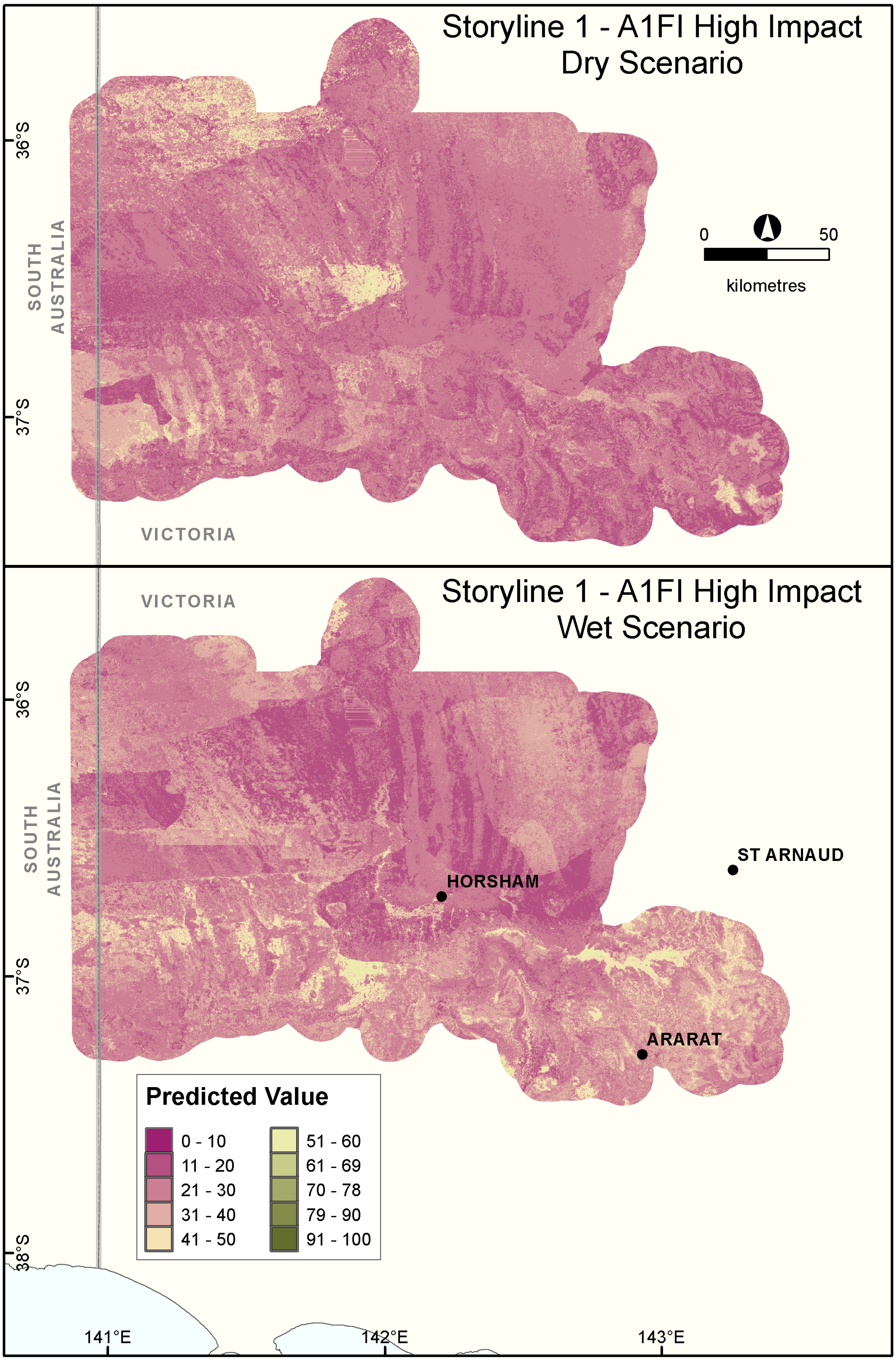


Figure 11. Maximum predicted probabilities for Storyline 1 vegetation formations projected across the Wimmera study landscape

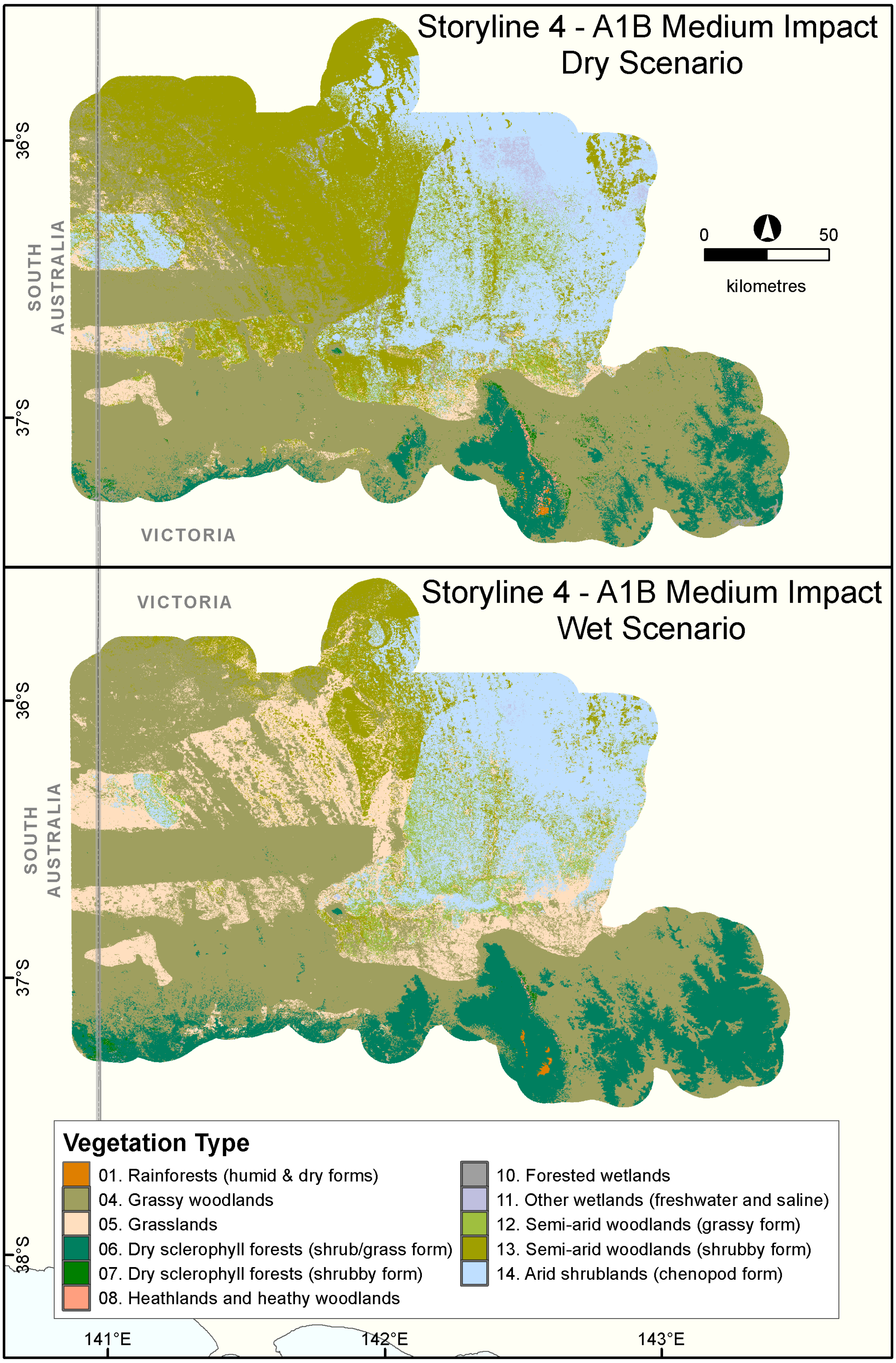


Figure 12. Vegetation formations for Storyline 4 projected across the Wimmera study landscape. The dry scenario derives from the CSIRO Mk 3.5 Global Climate Model (GCM) and the wet scenario derives from the Miroc-M GCM.

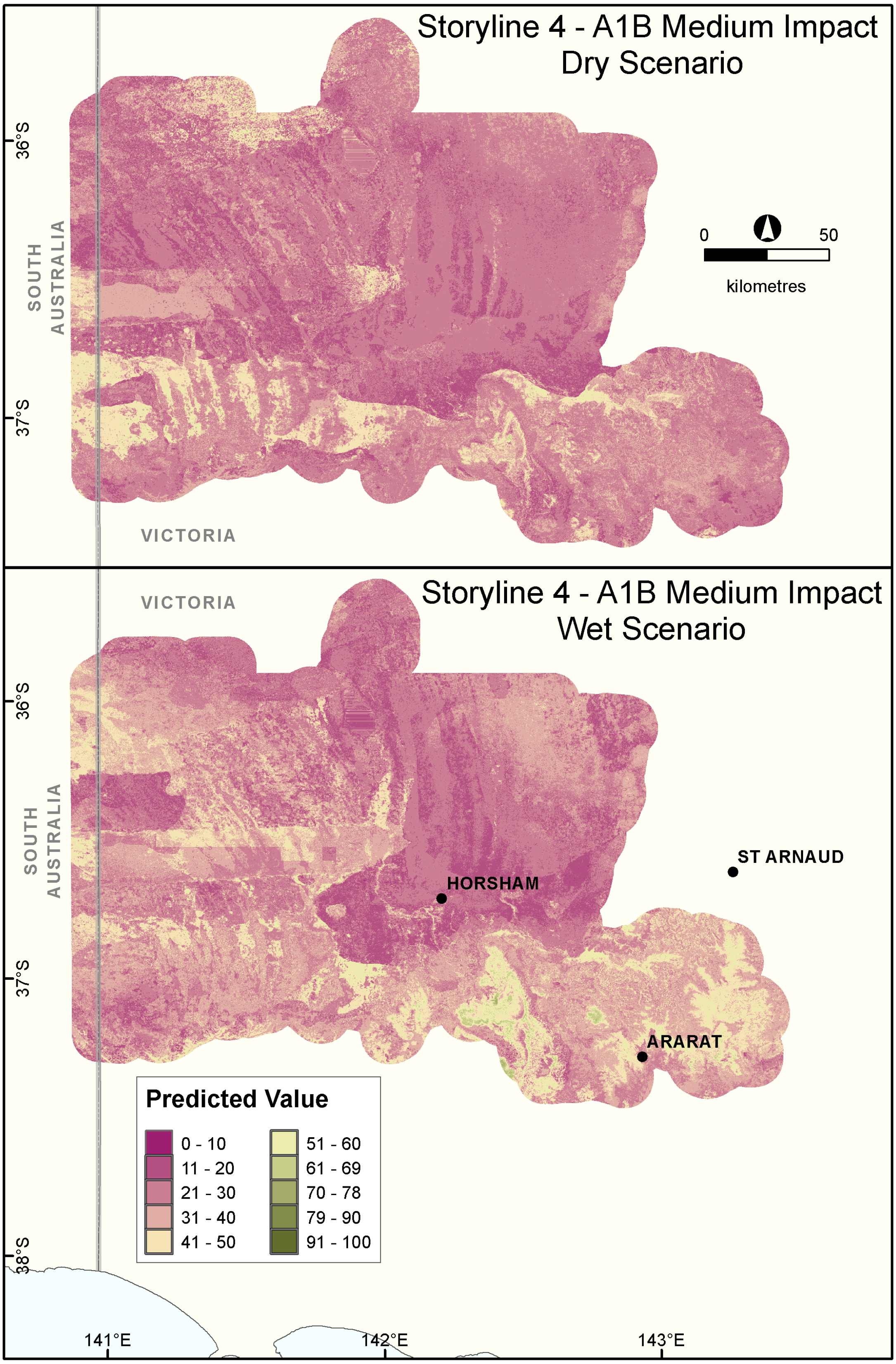


Figure 13. Maximum predicted probabilities for Storyline 4 vegetation formations projected across the Wimmera study landscape

3.2 Metapopulation Capacity of Future Wimmera Landscapes

Summary statistics revealed there was substantial variation within and among species in terms of the metapopulation capacity of future Wimmera landscapes, just as there was for the NSW study landscapes. This was true both when metapopulation capacity was expressed as the largest potential metapopulation in the landscape (divided by the threshold metapopulation size required for sustaining a viable population) as well as when it was expressed as the total area occupied by all potential viable metapopulations.

After excluding wet forest specialist fauna, the largest potential metapopulation (LPM) for each species in every future landscape was larger than the estimated threshold (i.e., LPM was always >1). Yet the challenges we found in parameterising the REMP models to ensure that design principles could be compared without bias meant that we cannot interpret the metapopulation capacity estimates in an absolute sense – only in a relative or comparative sense. Thus, the average future LPM values (Figure 14) suggest that in future Wimmera landscapes, orchids will be least well supported and dry woodland and forest fauna specialists may be best supported. In terms of the invasive species we examined, peppercorn trees will be supported much more so than foxes. These same patterns were observed in the NSW study landscapes.

While these results seem to suggest that orchids may be of most concern into the future, it is actually the change in size of the LPM from current that gives a better indication of climate and design principle effects separate from the legacy of current landscape conditions. The changes in LPM, expressed as future minus current LPM (Figure 14), show that reductions or increases in LPM for orchids were negligible. In contrast, there were on average slight increases in LPM for dry woodland and forest fauna specialists and decreases in LPM for the invasive species. However, with the exception of foxes, which showed consistent declines in LPM, there were high levels of variability in future LPMs, with some futures showing substantial declines and some showing increases in LPMs. This suggests a strong potential for effects of design principles, climate, and land-use storylines.

On average, these results are more optimistic than those for the NSW study landscapes, where distinct declines in LPM were seen on average for native species, along with more consistent increases in LPM for peppercorn trees. However, they also show somewhat greater variability than the NSW study landscape results.

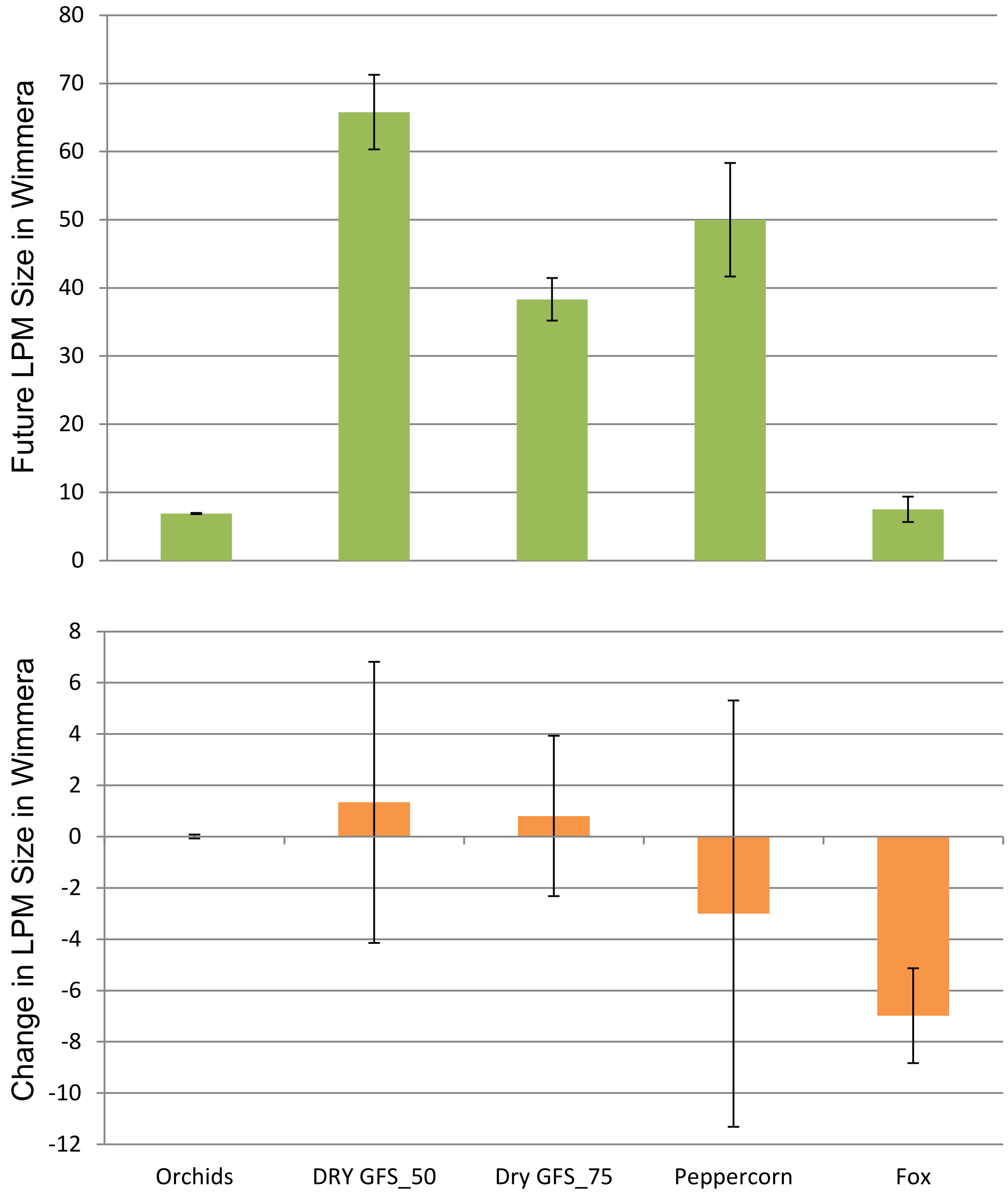


Figure 14. Average size of the largest potential metapopulation (LPM) in future Wimmera landscapes, expressed as a factor of the minimum viable metapopulation size (top) and average change in the size of the largest potential metapopulation (LPM), expressed as future LPM minus current LPM (bottom). Error bars show one standard deviation.

While the largest potential metapopulation expresses something about the maximum capacity of a landscape, it is not a whole-of-landscape measure. As a result, these results do not present a sufficiently complete picture because the largest metapopulation in a landscape may only be minimally influenced by the design principles, which involve spreading environmental plantings and natural regeneration projects throughout the landscape. In contrast, the total area occupied by all potential viable metapopulations (i.e. all those larger than the threshold for a viable metapopulation) is a whole-of-landscape measure, though its weakness is that an increase in this parameter can be due in part to larger areas needing to be occupied when habitat quality is lower. Thus, interpreting the results from these two response variables in concert should give the most useful indication of the metapopulation capacity of future landscapes.

The average area occupied by potential viable metapopulations of each species in future Wimmera landscapes was largest for the invasive species we modelled, and smallest for orchids (Figure 15).

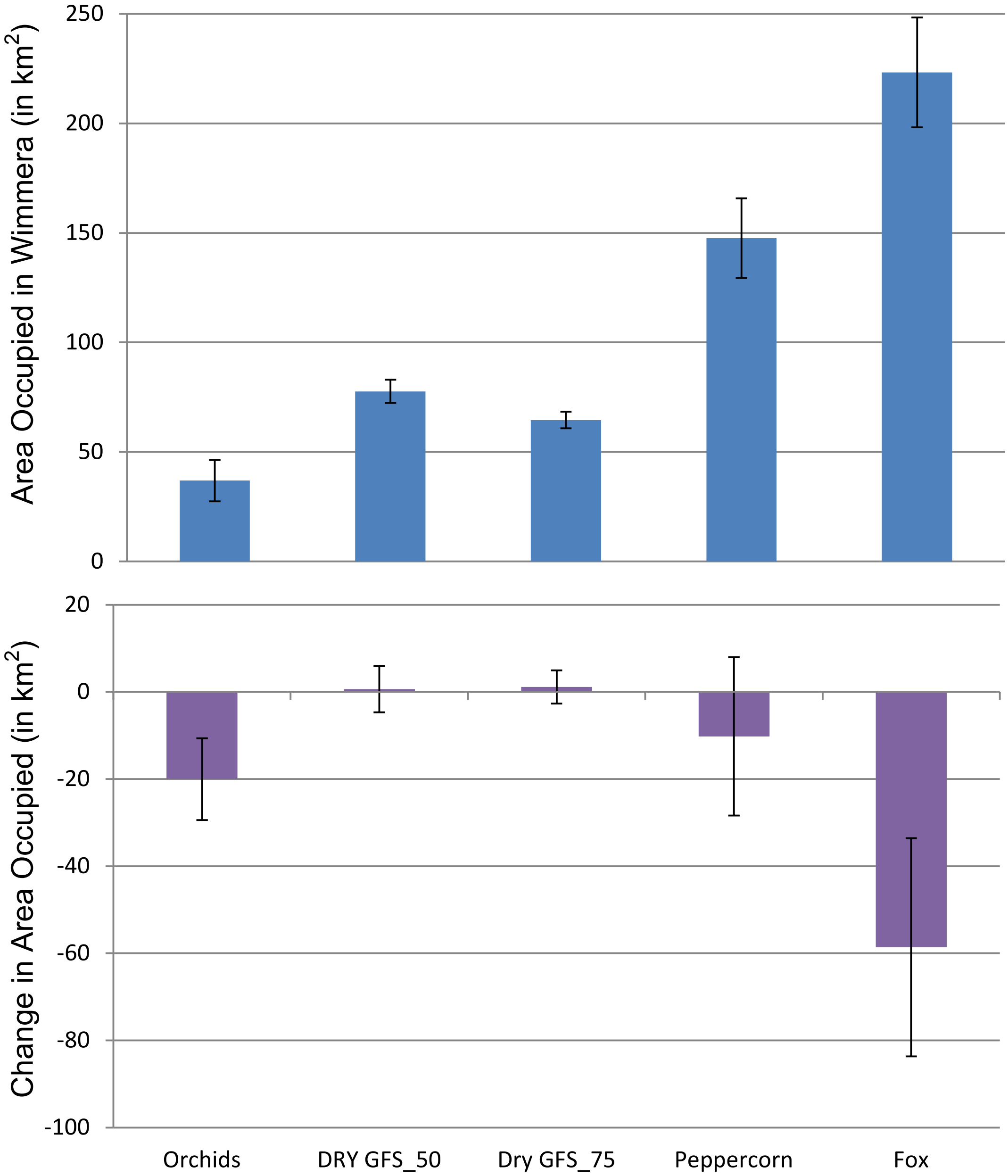


Figure 15. Average area occupied (in km^2) by all potential viable metapopulations in future Wimmera landscapes (top) and the change in area occupied (in km2) by all potential viable metapopulations in future Wimmera landscapes (bottom). Error bars show one standard deviation.

Yet, again, it is actually the change in area occupied from current area occupied that gives a better indication of climate and design principle effects separate from the legacy of current landscape conditions. On average, smaller areas were occupied in our future Wimmera landscapes by orchids and both invasive species, with dry forest and woodland fauna specialists showing little change on average in area occupied by potential viable metapopulations (Figure 15). Again, variances were moderately large and spanned substantial positive and negative values for the dry forest and woodland specialist fauna and for peppercorn trees, suggesting that design principle, climate, or land-use storyline effects may have a significant influence.

Again, on average, these results are slightly more optimistic than those for the NSW study landscapes, where average declines in area occupied by all potential viable metapopulations were seen for the dry forest and woodland specialist fauna in addition to the other species/species groups.

3.3 General Performance of Design Principles

3.3.1 Largest metapopulation - model selection results

When we analysed all three study landscapes to determine the factors affecting the amount of improvement in the size of the largest potential metapopulation (future minus current LPM values for native species groups and current minus future LPM values for invasive species), the comparison of AICc values across our 14 candidate models revealed that there was only one model that was likely to be the best model given the data (Table 26). This was the model that incorporated all factors except DP (design principle) and their two-way interaction effects. All other models had substantially smaller Akaike weights, though the next best model did incorporate a main effect of DP. Models that did not incorporate interaction terms among the covariates (Landscape, Species, Storyline, GCM) had vanishingly small Akaike weights and thus very little support from the data.

Table 8. Comparison of AICc values of all candidate models with improvement in the largest potential metapopulation size as the response variable, ordered from the model with the greatest support (largest Akaike weight, w) to the model with the least support

Model#	Hypothesis	df	AICc	∆AICc	w
8	All factors except DP have main effects and two-way interactions (BaseModel2)	29, 270	2118.64	0.00	0.993026
9	DP has main effects only but all other factors have main and two-way interaction effects	33, 266	2128.58	9.94	0.006895
12	DP has main effects and interaction with SLine - all other factors have main and two-way interaction effects	37, 262	2138.87	20.23	4.01E-05
13	DP has main effects and interaction with GCM - all other factors have main and two-way interaction effects	37, 262	2138.95	20.31	3.86E-05
10	DP has main effects and interaction with Lscape - all other factors have main and two-way interaction effects	41, 258	2149.54	30.90	1.94E-07
11	DP has main effects and interaction with Species - all other factors have main and two-way interaction effects	49, 250	2161.52	42.88	4.85E-10
14	DP has main effects and all two-way interactions - all other factors have main and two-way interaction effects	65, 234	2210.87	92.23	9.31E-21
1	All factors except DP have main effects (BaseModel1)	8, 291	2352.02	233.38	2.09E-51
2	All factors including DP have main effects	12, 287	2360.65	242.01	2.78E-53
5	Main effects but DP effect differs between storylines	16, 283	2369.55	250.91	3.25E-55
6	Main effects but DP effect differs between GCMs	16, 283	2369.58	250.94	3.2E-55
3	Main effects but DP effect differs between landscapes	20, 279	2378.72	260.08	3.31E-57
4	Main effects but DP effect differs between species	28, 271	2393.88	275.24	1.69E-60
7	Main effects but DP effects differs between all others	44, 255	2435.85	317.21	1.3E-69

The best ranked of our candidate models had an adjusted R^2 value of 0.78, suggesting it explained 78% of the variation in the amount of improvement (increase for native species groups or loss for invasive species) in the size of the largest potential metapopulation across all our future landscapes and species/species groups. Significance tests revealed that all parameters in the model were significant predictors of improvement in LPM except GCM and an interaction between GCM and Storyline (Table 9).

Our prior analyses of just the NSW study landscapes (but with a larger number of storylines, design principles, and species and thus a much larger sample size) had produced a top model with the same covariates and interaction terms, but that also included a significant interaction between DP and Species, albeit without a significant main effect of DP. However, the only species for which there was a significant effect of DP was foxes, with DP5 significantly better than all others at reducing the LPM of foxes in future NSW landscapes.

Table 9. Analysis of variance table for the top-ranked candidate model with improvement in the largest potential metapopulation size as the response variable. Model *F*=34.72; df=30, 270; *p*<0.0001.

Predictor	df	F-Ratio	p-Value
Lscape	2	51.328	0.000
SLine	1	5.18	0.024
GCM	1	0.011	0.918
Species	4	108.251	0.000
SLine*Lscape	2	5.849	0.003
GCM*Lscape	2	5.797	0.003
Species*Lscape	8	32.082	0.000
GCM*SLine	1	0.74	0.390
Species*SLine	4	3.792	0.005
Species*GCM	4	31.346	0.000
Error	270		

3.3.2 Area of occupancy - model selection results

When we analysed all three study landscapes to determine the factors affecting the amount of improvement in the area occupied by all potential viable metapopulations (future minus current area occupied for native species groups and current minus future area occupied for invasive species), the comparison of AICc values across our 14 candidate models revealed that there was only one model that was likely to be the best model given the data (Table 10). This was the model that incorporated DP (design principle), an interaction between DP and Species, and all additional factors plus their two-way interaction effects. This was the same top model as for our previous analyses of this response variable for only the NSW landscapes, except that previous analyses were based on a larger sample size and could thus include more than just two-way interactions among the covariates. All other models had extremely small Akaike weights, and thus very little support from the data.

Table 10. Comparison of AICc values of all candidate models with improvement in the area occupied by all potential viable metapopulations as the response variable, ordered from the model with the greatest support (largest Akaike weight, w) to the model with the least support

Model#	Hypothesis	df	AICc	∆AICc	w
11	DP has main effects and interaction with Species - all other factors have main and two-way interaction effects	49, 250	8842.04	0.00	0.999998
8	All factors except DP have main effects and two-way interactions (BaseModel2)	29, 270	8869.72	27.678	9.75E-07
9	DP has main effects only but all other factors have main and two-way interaction effects	33, 266	8870.44	28.40	6.79E-07
13	DP has main effects and interaction with GCM - all other factors have main and two-way interaction effects	37, 262	8880.50	38.461	4.44E-09
12	DP has main effects and interaction with SLine - all other factors have main and two-way interaction effects	37, 262	8880.71	38.66	4.01E-09
14	DP has main effects and all two-way interactions - all other factors have main and two-way interaction effects	65, 234	8886.96	44.921	1.76E-10
10	DP has main effects and interaction with Lscape - all other factors have main and two-way interaction effects	41, 258	8888.38	46.34	8.65E-11
1	All factors except DP have main effects (BaseModel1)	8, 291	8975.74	133.70	9.24E-30
4	Main effects but DP effect differs between species	28, 271	8975.84	133.80	8.8E-30

Model#	Hypothesis	df	AICc	ΔAICc	w
2	All factors including DP have main effects	12, 287	8978.87	136.83	1.94E-30
6	Main effects but DP effect differs between GCMs	16, 283	8987.59	145.55	2.47E-32
5	Main effects but DP effect differs between storylines	16, 283	8987.71	145.67	2.33E-32
3	Main effects but DP effect differs between landscapes	20, 279	8995.10	153.06	5.78E-34
7	Main effects but DP effects differs between all others	44, 255	9015.40	173.36	2.27E-38

The best ranked of our candidate models had an adjusted R^2 value of 0.69, suggesting it explained over 69% of the variation in the amount of improvement (increase for native species groups or loss for invasive species) in the area occupied by all potential viable metapopulations across all our future landscapes and species/species groups. Significance tests revealed that both DP and the interaction between DP and Species were significant predictors of improvement in area occupied, though a number of covariates and two-way interaction terms were not significant contributors to the model (Table 11). In our prior analyses using only the NSW study landscapes, all factors in the same top model were significant predictors of improvement in area occupied.

Table 11. Analysis of variance table for the top-ranked candidate model with improvement in area occupied by all potential viable metapopulations as the response variable. Model F=12.25; df=50, 250; p<0.0001.

Predictor	df	F-Ratio	p-Value
Lscape	2	4.094	0.018
SLine	1	0.841	0.360
GCM	1	1.276	0.260
Species	4	62.916	0.000
DP	4	2.536	0.041
SLine*Lscape	2	0.421	0.657
GCM*Lscape	2	0.343	0.710
Species*Lscape	8	7.495	0.000
GCM*SLine	1	0.358	0.550
Species*SLine	4	20.278	0.000
Species*GCM	4	19.612	0.000
DP*Species	16	4.255	0.000
Error	250		

3.3.3 Area of occupancy – design principle effects

The design principle effect was significant as a main effect in the top-ranked model when analysing improvement in area of occupancy as the response variable. Post-hoc paired comparisons revealed that DP5 (environmental plantings to restore 30% native vegetation cover) achieved greater improvements than DP0 (no further environmental plantings), but there were no significant differences between any of the other design principles (Table 12). Least squares means based on the top-ranked model showed much more improvement under DP5 compared to DP0, but also a distinct trend for DP5 to be an improvement over DPs 1, 2 and 4 (Figure 16).

Our prior analyses involving only the NSW study landscapes (but with a larger number of storylines, design principles, and species and thus a larger sample size) showed the same general pattern, but with stronger effects. In those analyses, DP5 was significantly better at improving the area occupied in future landscapes than all the other design principles.

Table 12. Design principle effect sizes and upper and lower 95% Bonferroni confidence intervals for the top ranked model with improvement in the area occupied by all potential viable metapopulations as the response variable

Pair Comparison	Effect Size	lowerCI	upperCI
DP0-DP1	-41,647.10	-321,983.91	238,689.71
DP0-DP2	-61,293.25	-341,630.06	219,043.56
DP0-DP4	-44,881.27	-325,218.08	235,455.55
DP0-DP5	-281,018.67	-561,355.48	-681.854
DP1-DP2	-19,646.15	-299,982.96	260,690.66
DP1-DP4	-3,234.17	-283,570.98	277,102.65
DP1-DP5	-239,371.57	-519,708.38	40,965.25
DP2-DP4	16,411.98	-263,924.83	296,748.80
DP2-DP5	-219,725.42	-500,062.23	60,611.40
DP4-DP5	-236,137.40	-516,474.21	44,199.41

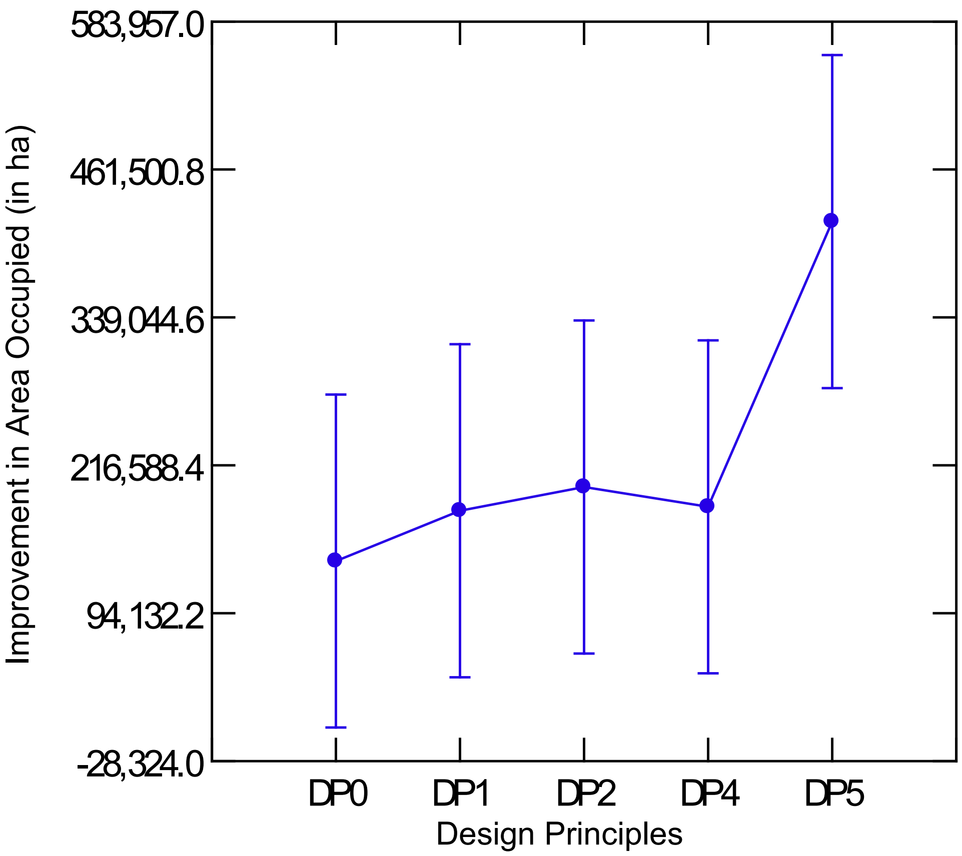


Figure 16. Least squares means of the amount of improvement in the area occupied by all potential viable metapopulations in future landscapes (in ha) as a function of design principles modelled, based on the top ranked of the candidate models

To further explore the interaction between DP and Species, we modelled all main effects (Lscape, SLine, DP and GCM) for each species individually to determine whether the design principle effect applied to all or only a subset of species and to perform post-hoc paired comparisons. Note that we had insufficient sample size to also include all interaction effects in these single-species models. When analysing the improvement in area occupied by all potential viable metapopulations, we found that the design principle effect was significant for foxes, peppercorn tree and orchids but not for either of the dry forest and woodland specialist fauna groups (DP effect for DryGFS75: F=1.26, p=0.296; DP effect for DryGFS50: F=1.90, p=0.125). Paired comparisons showed that for foxes, DP5 (environmental plantings to restore 30% native vegetation cover) improved landscapes more than any other design principle (Table 13). For orchids, DP5 improved landscapes significantly more than DP0 or DP2 (Table 14). The opposite pattern was observed for peppercorn trees, as DP5 decreased the quality of landscapes (i.e. increased the area occupied by all potential viable metapopulations of this invasive species) more than DP0 or DP2 (Table 15).

Least squares means suggested landscape improvement under DP5 compared to all other design principles for foxes and orchids, and a decline under DP5 compared to all other design principles for peppercorn trees (Figure 17, Figure 18, Figure 19), even though only some of the specific pair comparisons were significant. Indeed, the same non-significant trend was observed for the dry forest and woodland specialist fauna groups (Figure 20).

In our previous analyses of the NSW study landscapes, the same patterns were observed but they were stronger. Differences between design principles were significant for all the species considered in these validation analyses, and DP5 significantly improved landscapes for native species groups and foxes (and significantly increased the spread of peppercorn trees) compared to all other design principles.

Also note that as was true for our previous analyses of NSW study landscapes, it was only under DP5 that positive changes in occupancy (and thus actual improvement in occupancy relative to current landscapes) were seen on average for native species groups. The corollary was that the opposite pattern was true for peppercorn trees - only under DP5 were negative improvements (and thus an actual increase in occupancy) observed.

Table 13. For foxes only: design principle effect sizes and upper and lower 95% Bonferroni confidence intervals for model with the improvement in area occupied by all potential viable metapopulations as the response variable.

Pair Comparison	Effect Size	lowerCI	upperCI
DP0-DP1	-226,635.00	-904,207.91	450,937.91
DP0-DP2	-430,065.00	-1,107,637.91	247,507.91
DP0-DP4	-257,522.50	-935,095.41	420,050.41
DP0-DP5	-1,199,398.33	-1,876,971.24	-521,825.43
DP1-DP2	-203,430.00	-881,002.91	474,142.91
DP1-DP4	-30,887.50	-708,460.41	646,685.41
DP1-DP5	-972,763.33	-1,650,336.24	-295,190.43
DP2-DP4	172,542.50	-505,030.41	850,115.41
DP2-DP5	-769,333.33	-1,446,906.24	-91,760.43
DP4-DP5	-941,875.83	-1,619,448.74	-264,302.93

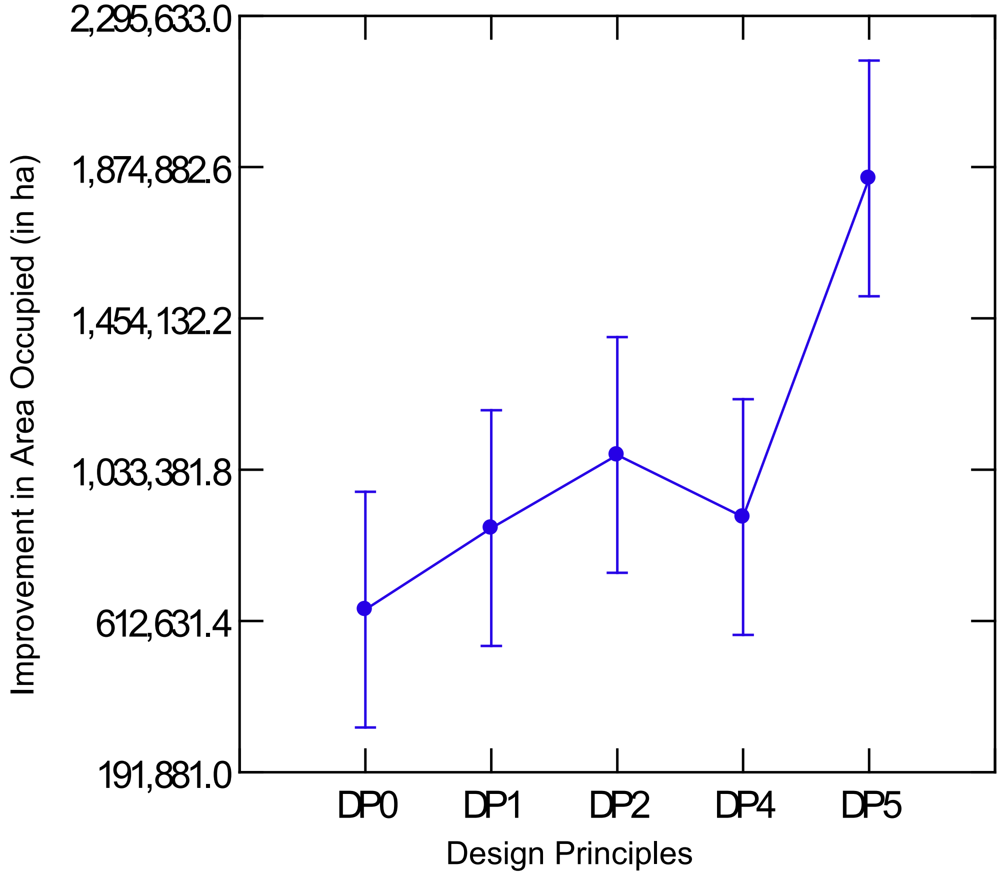


Figure 17. For foxes only: least squares means of the improvement in the area occupied by all potential viable metapopulations in future landscapes as a function of design principles modelled

Table 14. For orchids only: design principle effect sizes and upper and lower 95% Bonferroni confidence intervals for model with the largest potential metapopulation size as the response variable.

Pair Comparison	Effect Size	lowerCI	upperCI
DP0-DP1	-77,055.75	-385,319.66	231,208.16
DP0-DP2	10,675.92	-297,587.99	318,939.83
DP0-DP4	-82,139.83	-390,403.74	226,124.08
DP0-DP5	-371,658.75	-679,922.66	-63,394.84
DP1-DP2	87,731.67	-220,532.24	395,995.58
DP1-DP4	-5,084.08	-313,347.99	303,179.83
DP1-DP5	-294,603.00	-602,866.91	13,660.91
DP2-DP4	-92,815.75	-401,079.66	215,448.16
DP2-DP5	-382,334.67	-690,598.58	-74,070.76
DP4-DP5	-289,518.92	-597,782.83	18,744.99

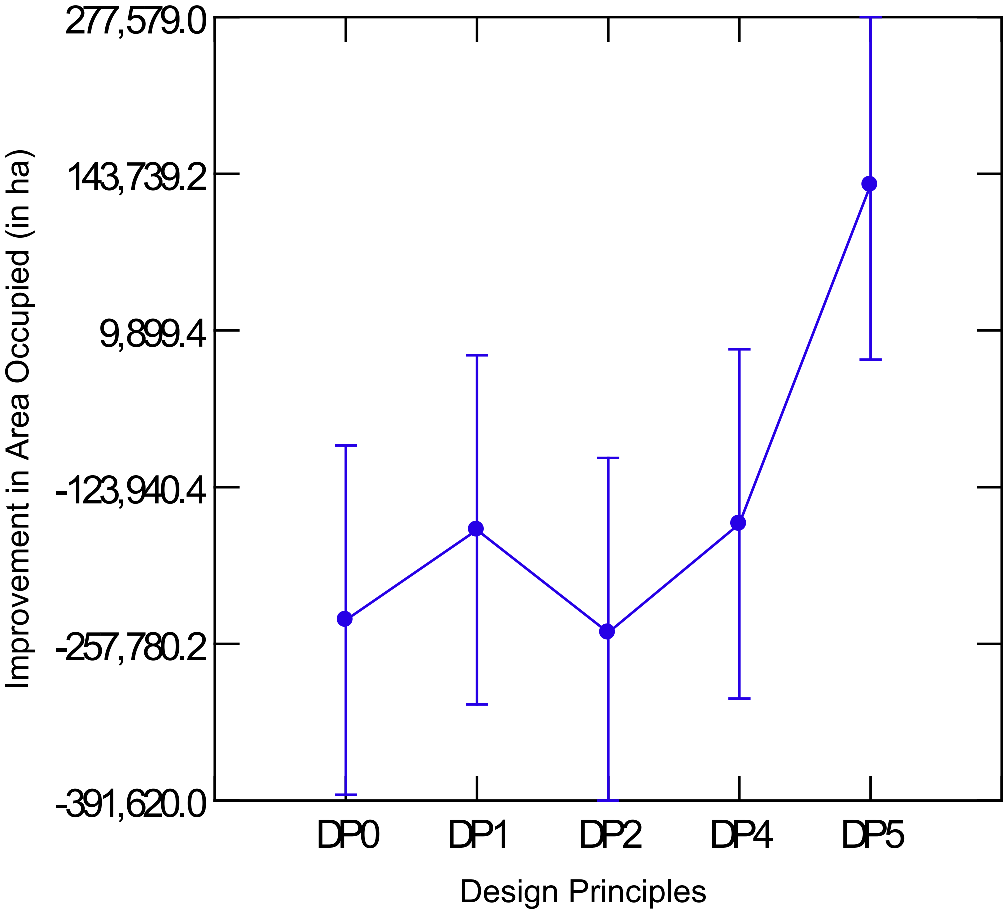


Figure 18. For orchids only: least squares means of the improvement in the area occupied by all potential viable metapopulations in future landscapes as a function of design principles modelled

Table 15. For peppercorn trees only: design principle effect sizes and upper and lower 95% Bonferroni confidence intervals for model with the improvement in area occupied by all potential viable metapopulations as the response variable

Pair Comparison	Effect Size	lowerCI	upperCI
DP0-DP1	247,396.67	-631,952.89	1,126,746.22
DP0-DP2	64,625.00	-814,724.55	943,974.55
DP0-DP4	284,452.50	-594,897.05	1,163,802.05
DP0-DP5	1,038,285.00	158,935.45	1,917,634.55
DP1-DP2	-182,771.67	-1,062,121.22	696,577.89
DP1-DP4	37,055.83	-842,293.72	916,405.39
DP1-DP5	790,888.33	-88,461.22	1,670,237.89
DP2-DP4	219,827.50	-659,522.05	1,099,177.05
DP2-DP5	973,660.00	94,310.45	1,853,009.55
DP4-DP5	753,832.50	-125,517.05	1,633,182.05

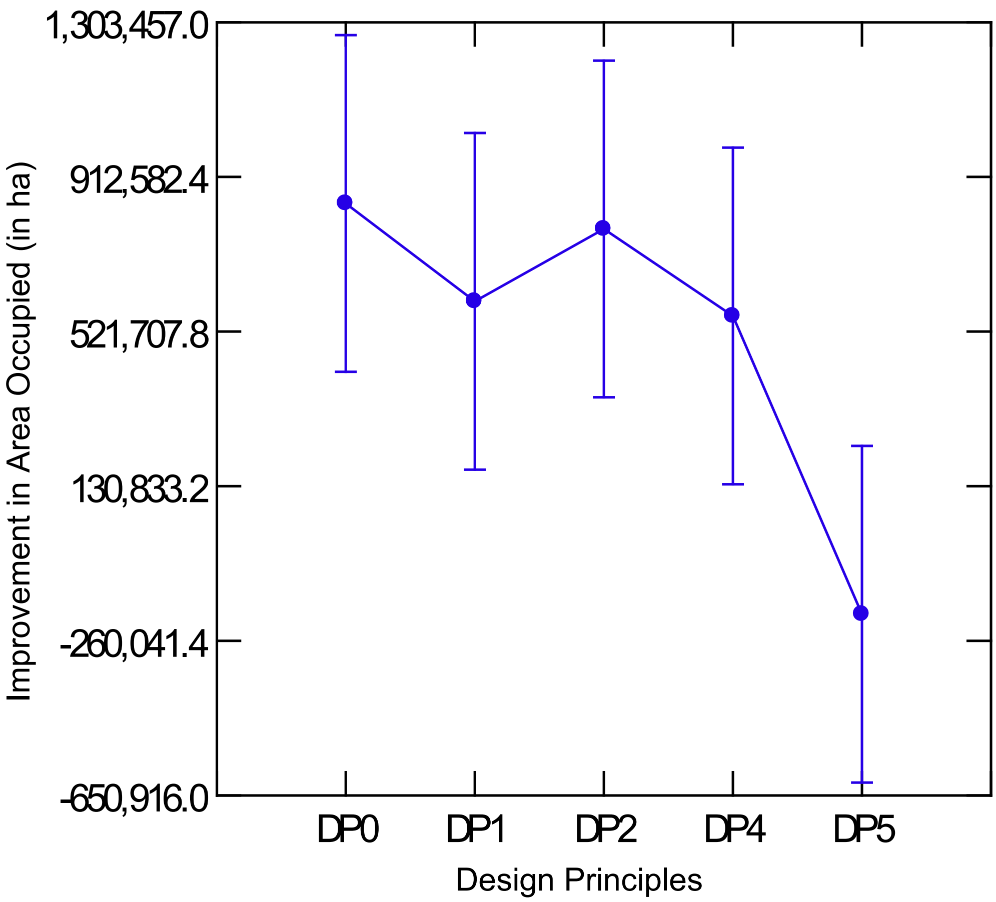


Figure 19. For peppercorn trees only: least squares means of the improvement in the area occupied by all potential viable metapopulations in future landscapes as a function of design principles modelled

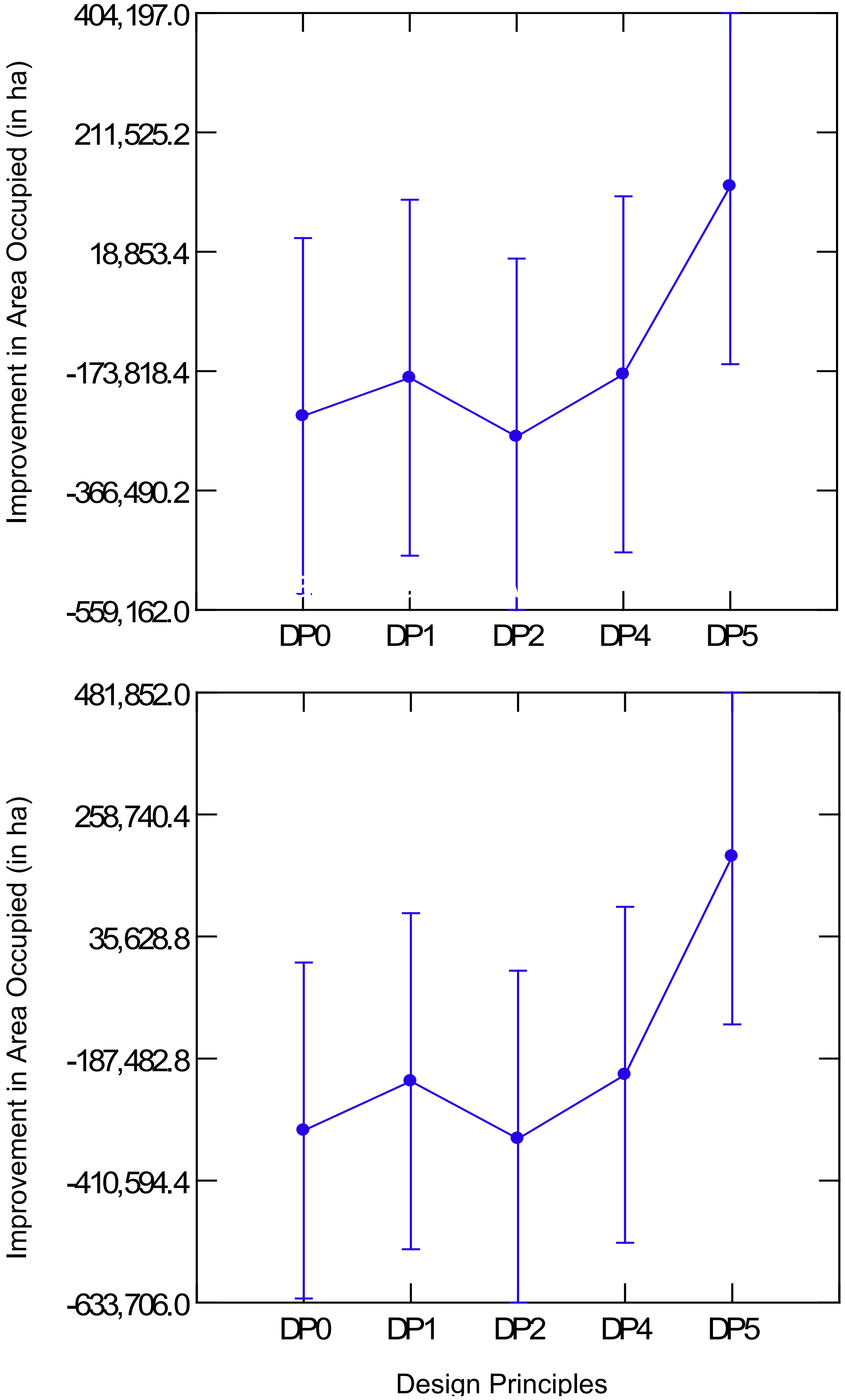


Figure 20. Least squares means of the improvement in area occupied by all potential viable metapopulations in future landscapes as a function of design principles modelled for DryGFS75 (top) and DryGFS50 (bottom). These are trends and the differences between design principles were not significant.

3.3.4 Analysing Wimmera Landscapes in Isolation

In this Wimmera validation, adding Wimmera data to previous models of NSW study landscapes (albeit a subset of the original storylines, design principles, and species) resulted in similar patterns in the results but weaker relationships. There could be several reasons why the Wimmera landscapes would weaken the results and we needed to explore these reasons because they would influence our overall conclusions. Wimmera landscapes could weaken the results if:

- somewhat different responses to design principles were observed for the Wimmera
- similar but weaker responses to design principles were observed for the Wimmera, possibly also with greater variance
- the same responses to design principles were observed for the Wimmera but the smaller sample size in the validation analyses reduced our power to detect the relationships

To evaluate which of these potential explanations is most applicable, we needed to analyse the Wimmera data in isolation to compare to the NSW study landscape results. However, because the sample size was much smaller when we restricted ourselves only to the Wimmera (n=100 compared to n=300 for the previous validation models and n=576 for the initial NSW study landscapes models), we were only able to run very simple models.

Initially, we modelled main effects of DP, Storyline, Species, and GCM along with an interaction between DP and Species as that was the significant interaction in the previous NSW study landscapes models. When analysing improvement in the largest potential metapopulation as the response variable, we found no significant effect of DP or the interaction between DP and Species (Table 16). However, the least squares means for each species across design principles suggested similar but weaker patterns to what we had previously seen in the NSW landscapes. In the NSW analyses, significant improvement was seen for DP5 compared to the other design principles in terms of the largest potential metapopulation for foxes. There was also a non-significant trend toward lack of improvement or increased metapopulation size under DP5 for peppercorn trees.

Table 16. Analysis of variance table for model investigating effect of design principles on improvement in the largest potential metapopulation for future Wimmera landscapes only

Predictor	df	F-Ratio	p-Value
SLine	1	0.936	0.337
DP	4	0.037	0.997
GCM	1	0.207	0.651
Species	4	5.57	0.001
DP*Species	16	0.182	0.999
Error	73		

To further investigate these species-specific patterns, we analysed each species separately using only the Wimmera data, incorporating DP as the only predictor variable given the very small sample size (n=20). Similar to the NSW study landscape results, we found a significant effect of DP only for foxes (F=28.403, df=5,15, p<0.0001), with DP5 producing the greatest improvement (Figure 21). For all other single-species models, the DP effect had an F-ratio of <1 and a p-value of >0.9.

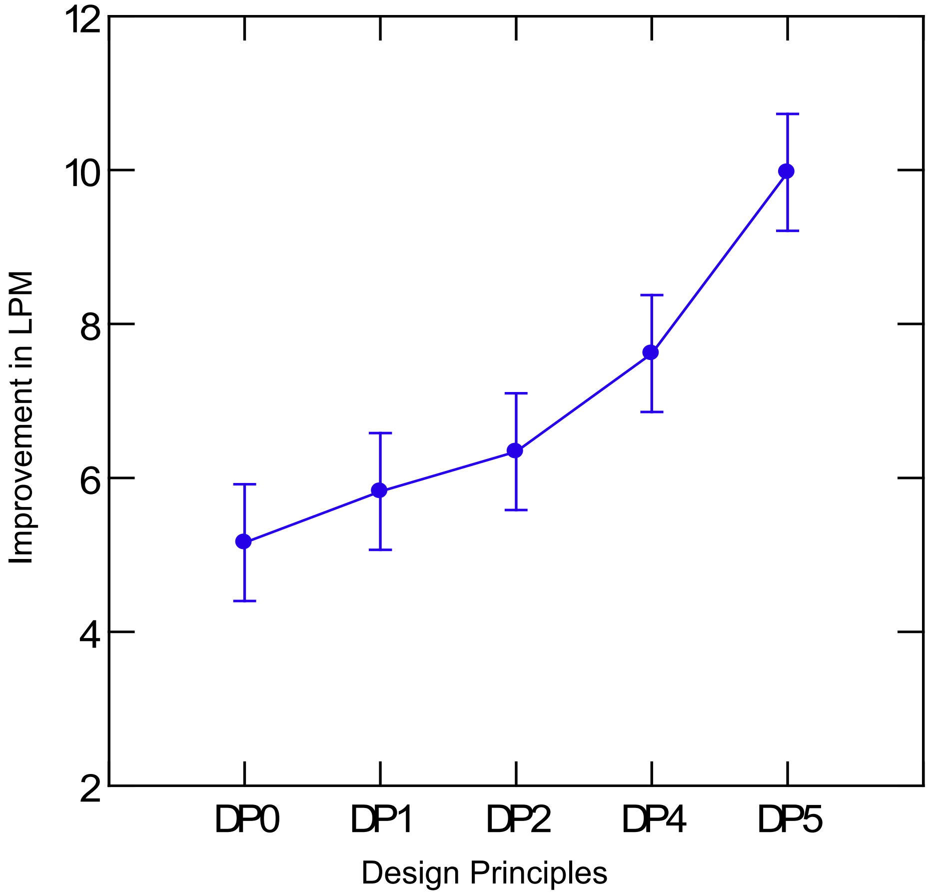


Figure 21. For foxes only: Least squares means of the improvement in largest potential metapopulation (LPM) in future Wimmera landscapes, as a function of design principles modelled

When analysing improvement in the total area occupied by all potential viable metapopulations for the Wimmera landscapes only, we did not find a significant main effect of DP but the interaction between DP and Species was significant (Table 17). Again, the least squares means for each species across the design principles suggested similar but weaker patterns to what we had previously seen in the NSW landscapes. In the NSW analyses, significant improvement was seen for DP5 compared to the other design principles in terms of the total area occupied by all potential viable metapopulations for orchids and the dry forest and woodland specialist fauna as well as for foxes. There was also significant reduction in improvement (or increase in total area occupied) under DP5 for peppercorn trees.

Table 17. Analysis of variance table for model investigating effect of design principles on improvement in the total area occupied by all potential viable metapopulations for future Wimmera landscapes only

Predictor	df	F-Ratio	p-Value
SLine	1	0.683	0.411
DP	4	1.537	0.200
GCM	1	4.109	0.046
Species	4	157.101	0.000
DP*Species	16	6.596	0.000
Error	73		

To further investigate these species-specific patterns, we analysed each species separately using only the Wimmera data, incorporating DP as the only predictor variable given the very small sample size (n=20). Similar to the NSW study landscape results, we found a significant effect of DP for the dry forest and woodland specialist fauna, foxes and peppercorn trees, with DP5 showing the greatest risk of spread of peppercorn trees (Figure 22) and the greatest improvement in landscapes for the other species/species groups (Figure 23 and Figure 24). The only difference between these patterns observed for the Wimmera and those seen for the NSW study landscapes was in terms of orchids. In the Wimmera, design principles had no significant effect on the total area occupied by all potential viable metapopulations of orchids (Figure 25).

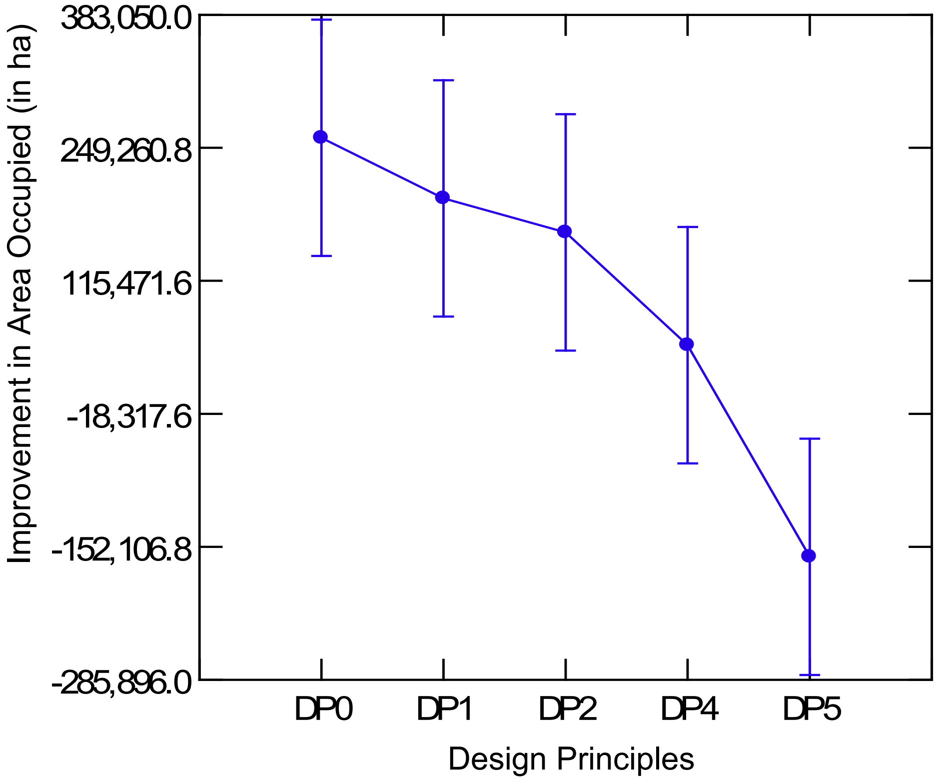


Figure 22. For peppercorn trees only: Least squares means of the improvement in area occupied by all potential viable metapopulations in future Wimmera landscapes, as a function of design principles (F=8.867, df=5,15, p=0.001)

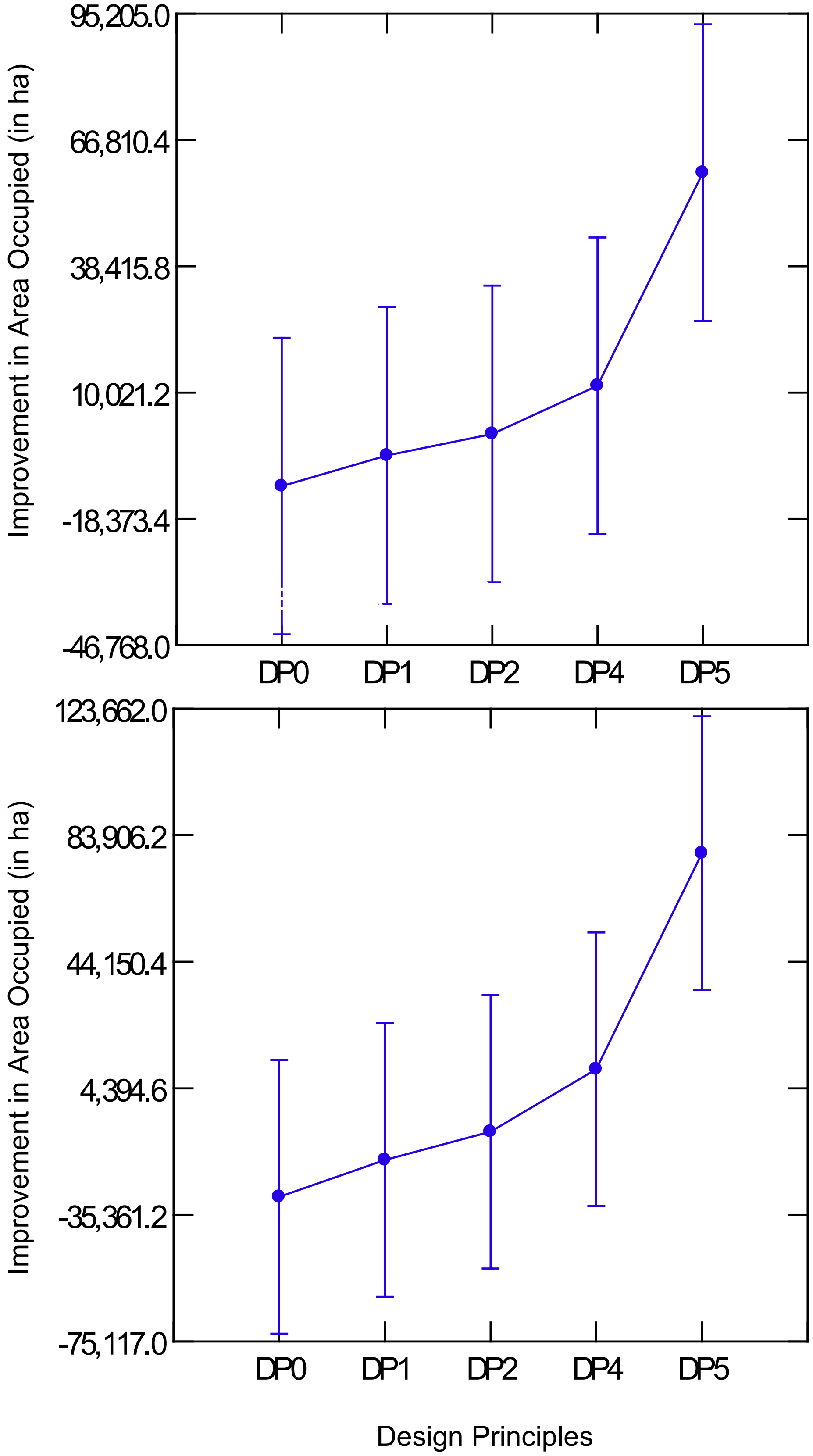


Figure 23. Least squares means of the improvement in area occupied by all potential viable metapopulations of DryGFS75 (top) and DryGFS50 (bottom) in future Wimmera landscapes, as a function of design principles (DryGFS75: F=3.233, df=5,15, p=0.042; DryGFS50: F=4.504, df=5,15, p=0.014)

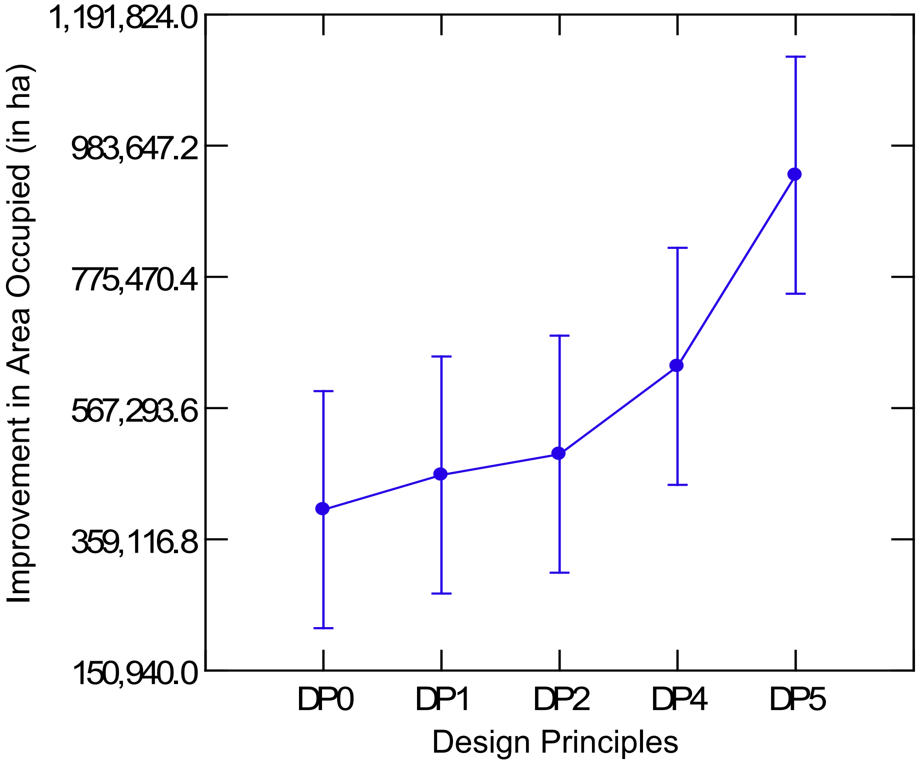


Figure 24. For foxes only: Least squares means of the improvement in area occupied by all potential viable metapopulations in future Wimmera landscapes, as a function of design principles modelled (*F*=5.835, df=5,15, *p*=0.005)

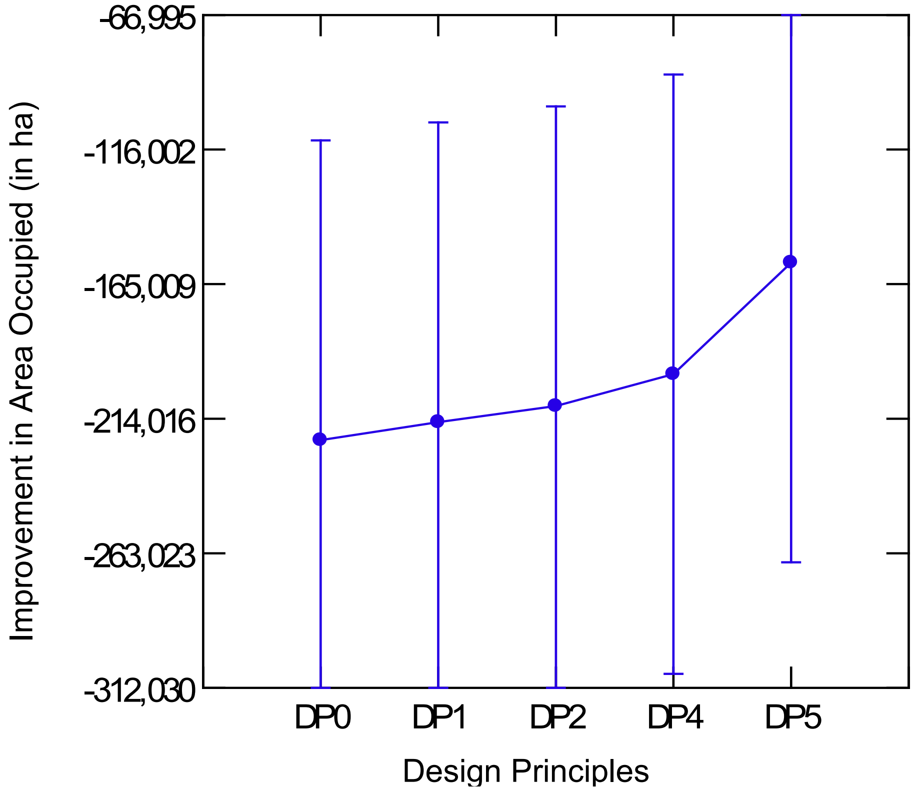


Figure 25. For orchids only: Least square means of the improvement in area occupied by all potential viable metapopulations in future Wimmera landscapes, as a function of design principles modelled (*F*=0.251, df=5,15, *p*=0.904)

4 Discussion

4.1 Comparing Design Principles

We analysed the effects of design principles using a subset of the original land-use change storylines and design principles we considered, but applied over three case study landscapes instead of two. These analyses suggested that while design principles had a minimal effect on the largest potential metapopulation of future landscapes, one of the design principles we tested tended to out-perform the others in terms of the total area occupied by all potential viable metapopulations in future landscapes. Our top-ranked model for this response variable had a high Akaike weight, explained a reasonably high percentage of the variance in the amount of improvement in metapopulation capacity, and included a significant main effect of design principles as well as an interaction between design principles and species. Post-hoc paired comparisons revealed that effect sizes for certain design principle comparisons were significantly different from zero. Design Principle 5, which involved restoring ~30% cover of native vegetation in our case study landscapes, consistently performed better than Design Principle 0 (no further environmental plantings), and there were trends indicating it consistently performed better than all other design principles. Compared to the others, this design principle significantly reduced the area occupied by potential viable metapopulations for foxes, tended to increase the area occupied by potential viable metapopulations for orchids, and showed a weak trend to increase the area occupied by dry woodland and forest specialist fauna (defined both narrowly and a bit more broadly).

The real-world design principles (DPs 2 & 4) and the spatial control (DP1), which all focused on details of spatial planning and were implemented within the storyline-based limits on amounts of environmental plantings, were not significantly different in their effects on the metapopulation capacity of landscapes. These results suggest that if DP5 is not implementable and landscape managers need to select the best of the current alternative options, effort devoted to careful and detailed spatial planning of environmental planting sites may not reliably produce better landscape-scale outcomes compared to a simpler random approach.

Compared to the results presented in the final report (Doerr et al. 2013), which involved only the NSW study landscapes but a larger sample size, these results and conclusions are slightly weaker but show the same trends. So in situations in the three-landscape analyses where DP5 was significantly better than DP0 only, in the original two-landscape analyses DP5 was significantly better than all the other design principles. When we analysed the Wimmera data only, albeit with simpler models, we found that the same patterns were present in the Wimmera but the relationships were weaker, leading to less marked differences in the three-landscape models compared to the two-landscape models.

4.2 Which Design Principles are Sufficient and at What Scales?

While DP5 performed better than all the other design principles, all of them or none of them might still constitute best practice. In other words, all of them could significantly improve landscapes for the future or all of them could be insignificant compared to negative effects of land-use and vegetation changes on biodiversity. We can only draw limited conclusions here, in part because we need to be cautious about absolute interpretation of the metapopulation capacity numbers. But on average in the three-landscape models, actual positive changes in landscapes in the future only occurred under Design Principle 5. All other design principles (and associated amounts of conversion to environmental plantings) resulted in average decreases in the area occupied by all potential viable populations in the future for native species groups. Only foxes improved across all design principles, with reductions in the area occupied by all potential viable metapopulations seen on average for all design principles, with significantly greater reductions under DP5.

The difference between these results from our three-landscape models and the original two-landscape model results is in terms of the amount of average decreases in area occupied and the variance around those averages. When adding the Wimmera data, the average decreases in area occupied in the future were smaller, with relatively large variances indicating that some futures could involve small increases in area occupied for native species under design principles other than DP5, depending on exactly which future climates and land-use changes actually eventuate. When we analysed the Wimmera data only, albeit with simpler models, average changes in area occupied by dry forest and woodland specialist fauna were fairly close to zero across the design principles other than DP5, though orchids showed average decreases in the Wimmera across all design principles. Thus, it is possible that design principles other than DP5 could be sufficient specifically in the Wimmera, at least for dry forest and woodland specialist fauna, but that would depend on the details of future climates and resulting land uses and changes in native vegetation communities. As these futures cannot be more precisely known at this stage, the only thing we can say with confidence is that DP5 is the only design principle we tested likely to be sufficient to arrest declines in most species.

However, we must reiterate our point about spatial scale and species inclusion from the original final report. Other design principles and amounts of restoration might still achieve positive benefits at smaller scales, and for less vulnerable species groups. This is a particularly important point as our results also showed only weak, non-significant trends for the real-world design principles and the random spatial control to be better than doing nothing. But our results apply specifically to achieving landscape benefits at quite large scales – scales that might be required to facilitate species' range shifts under climate change, but that are in fact much larger than the scale of individual metapopulations. We also deliberately decided to model species groups that are thought to be most vulnerable to landscape change in order to encompass the needs of most species, not just many species. Thus, these results should not be interpreted as over-riding a wealth of existing studies on landscape design which suggest that real-world design principles are still likely to be better than doing nothing when trying to achieve local goals, improve individual metapopulations, and support many native species. Instead, the primary conclusion should be that the details of spatial placement of environmental plantings might still influence local outcomes and should thus be planned based on local goals, knowledge, and local scale research, while larger landscape-scale goals for most species may best be achieved by simply increasing the amount of effort, with little need for detailed spatial planning.

4.3 What Falls Through the Cracks?

When including the Wimmera data in our analyses, there was still one key exception to the general conclusions presented above. The patterns of landscape improvement for peppercorn tree were exactly opposite to those presented above. In both our two-landscape and three-landscape models, peppercorn trees behaved almost exactly like the majority of native species groups. So while DP5 increased metapopulation capacity for most native species (an improvement in landscape quality), it also increased metapopulation capacity for peppercorn trees (a decline in landscape quality). Thus, it may not be possible to identify approaches to landscape design that are simultaneously good for native species and neutral or detrimental to all invasive species. It is likely that improving landscapes for native species will inherently involve some risk of proliferation by some invasive species, which will need to be managed in different, complementary ways. However, it is worth highlighting that these risks will only exist for a specific subset of invasive species. This conclusion is further supported by the fact that DP5 significantly reduced the area occupied by potential viable metapopulations of foxes, showing that landscape-scale restoration can actually assist with control of some types of invasive species. The species that are most likely to need special management as the amount of landscape restoration increases are those that behave in the landscape in similar ways to native species – for example, plants that are considered environmental weeds but not agricultural weeds, and that may be somewhat dispersal limited.

4.4 Why Were Differences Less Pronounced in the Wimmera?

It is certainly clear from our results that while much more restoration of native vegetation is still the reliable way to improve future landscapes in terms of the persistence of native species in the face of climate-related changes in land use and distributions of vegetation communities, the future for the Wimmera is not quite as bleak as it appeared to be for the NSW study landscapes. Certainly dry woodland and forest specialist fauna have a chance of remaining relatively stable in the future, though such stability may depend on the details of which climate changes actually occur. While our project was not designed in such a way that allows us to pick apart all the specific influences to say exactly why the results were slightly different in the Wimmera, it is worth reflecting on some of the differences in vegetation and land-use change storylines for the Wimmera (the inputs to our final models) which could be contributing factors.

The most obvious difference between the Wimmera and our NSW study landscapes was simply that the relative amount of restoration required to reach ~30% native vegetation cover (DP5) compared to the amounts implemented under the other storyline/design principle combinations. In the Wimmera, the amount required to reach ~30% cover was less than twice the amount required for some of the other storylines and design principles (see comparison between DP4 and DP5 in Figure 7 and Figure 8. In contrast, in the NSW landscapes, the amount required to reach ~30% cover was always at least three times the amount required for the other storylines and design principles and was more commonly 5-10 times the amount. Thus, the contrast between amount of restoration across the design principles was less pronounced in the Wimmera, so it is perhaps unsurprising that the contrast between the effects of the design principles was less pronounced. It certainly strengths our conclusion that when analysed at these large scales, the amount of restoration is far more important than the details of its spatial placement.

In addition, the obvious environmental difference between the Wimmera and the NSW study landscapes is that the Wimmera is a drier landscape. One consequence is that rather than having a mixture of dry and wet vegetation communities, the Wimmera contains almost exclusively dry communities (of forests, woodlands and shrublands). In parameterising the metapopulation capacity models, these communities were all given moderate to high habitat values for most of the species we modelled. Thus, from the perspective of the metapopulation capacity models, changes in vegetation distributions in the Wimmera resulted in relatively minor shifts in habitat suitability across the landscape. In contrast, in the NSW landscapes, changes in vegetation distributions could result in wet vegetation communities becoming dry ones, and potentially vice versa, which would result in more significant step-changes in habitat suitability for the species we modelled. These would be even more pronounced in the final models if they resulted in a previously viable metapopulation becoming too small to be viable, as this could be a relatively small change in habitat suitability that would result in an entire potentially viable metapopulation being dropped from the total area occupied. In contrast, the more subtle shifts in habitat suitability in the Wimmera would tend to produce smaller changes in the sizes of potential viable metapopulations in the REMP analyses, and would be less likely to result in the complete loss of some metapopulations. One key conclusion is thus that reductions in the persistence of native species under climate change are likely to be most pronounced where there are currently boundaries between relatively wet and relatively dry vegetation communities.

Another quite obvious difference between our Wimmera future landscapes and our NSW future landscapes was in terms of the specific land-use changes we modelled. In the Wimmera, reductions in native vegetation to support increasing world demands for food were modelled as increased use of native vegetation for grazing systems, rather than as an increase in the extent of intensive cropping (due to projections for future rainfall, which is likely to be insufficient to support a growth in cropping in this landscape). As a result, native vegetation was converted to pastures with paddock trees in the Wimmera, but was converted to crops and pastures without paddock trees in the NSW study landscapes. Particularly because we gave relatively high habitat suitability scores to crops and pastures with paddock trees when parameterising the metapopulation capacity models, the result was that climate-related changes in land use had a much less dramatic impact on habitat suitability for native species in the Wimmera.

While these models are merely hypotheses about plausible futures and are not necessarily right or wrong, the fact is that limiting the loss of scattered trees in the Wimmera was associated with less dramatic declines in future metapopulation capacity. Combined with the fact that land-use change storyline was a significant predictor of improvements in metapopulation capacity in some of our models, this strengthens our original suggestion that aspects of land-use change storyline have the potential to be influenced and planned at landscape scales much more than they are now. The intent would not be to prevent land-use change, but to encourage changes in the productive portions of our landscapes that will provide secondary biodiversity benefits on top of production benefits, either because of the type of change or its spatial placement in the landscape. This would involve truly integrated land-use planning and landscape design, simultaneously considering portions of the landscape reserved for conservation and portions of the landscape used for production.

4.5 Key Messages for Policy-Makers and Landscape Managers – What is Best-Practice?

Considering the results we obtained in this validation as well as in the original final report, plus the limitations to the research, we believe our original seven points about best-practice that were presented in the final report (Doerr et al. 2013) still stand. We hope these recommendations will help inform how best to use landscape design and management as a climate adaptation approach for terrestrial biodiversity. We have refined their presentation here into five key messages:

Act locally, but coordinate local efforts to manage a landscape

- As the detailed spatial arrangement of restoration projects may not have a strong influence on landscape-scale outcomes, we can enable local managers to make local decisions that suit their goals and opportunities without compromising goals at larger scales.
- Thus, to construct larger-scale landscape initiatives (which may be needed to facilitate species' range shifts), we may simply need to ensure that local efforts are spatially aligned to create large, continuous areas managed for landscape improvement. Such cross-boundary corridors for climate change could then be managed by letting different landscape managers within those boundaries make their own individual decisions.

Restoration should be paired with targeted alien invasive species management

- Not all alien invasive species will benefit from increasing the amount of native vegetation and landscape connectivity, but some will. These are most likely to be those that co-occur with native vegetation (i.e. those that tend to be invasive specifically within areas reserved for native communities rather than those that are problematic on agricultural or urban lands) and that may rely on native species as dispersal agents. Thus, landscape design and management initiatives should include coordinated plans to manage the risk of spread of these particular species.

We need much more restoration, but there will still be 'climate losers'

- To arrest biodiversity declines, we may need an order of magnitude more restoration than we are planning at present. Restoring ~30% native vegetation cover at the scale of multiple catchments may be needed to counteract the effects of climate-related changes in land use and native vegetation and ensure that we actually improve the ability of landscapes to support viable populations of native species into the future.
- Some species will still be 'climate losers' – species that will probably lose so much suitable area purely due to changes in climate (like those that are specialists on wet environments) that there may be little landscape managers can do to prevent local and regional declines in their chances of persisting.

Focus restoration efforts in priority areas

- Achieving 30% native vegetation cover at the scales of multiple whole catchments may currently seem unattainable. Yet that goal should be achievable at smaller scales in some landscapes. Thus, by concentrating restoration efforts in priority areas even more than we do at present, we could manage habitats to support single viable metapopulations, then build greater landscape-scale efforts over time.

Consider spatial planning of all types of land-use change, not just restoration

- Integrating spatial planning of productive land uses with restoration of native vegetation has the potential to improve future landscapes for biodiversity without the need to achieve ~30% native vegetation cover. Restricting the loss of paddock trees in areas where they best supplement and connect more intact native vegetation could be critical. We need to encourage innovative on-ground approaches to integrated land-use planning, where societal needs for both agriculture and biodiversity intersect, and monitor the results to gain better information about cost-effective options.

Appendix A Vegetation Change Modelling – a local application

This appendix presents the results of a local application of the Wimmera vegetation model to demonstrate how improvements in the confidence of vegetation modelling may be achieved in future work. The results presented here should be read in conjunction with the methods documented in Doerr et al. (2013).

The GDM models were generated using the same set of candidate environmental predictors considered in the development of the fitted GDM model for NSW (see Doerr et al. 2013). The overall approach to compiling predictors and testing them in a model of biodiversity pattern was outlined by Williams et al. (2012). A sample of 3439 survey locations comprising nearly 100,000 vascular plant species records was used (Figure 26). This sample was filtered by species richness per site greater than 15 to address potential sampling in disturbed locations, so that the model represented relatively intact species composition. The resulting sample comprised 2383 locations.

The GDM model used 900,000 site-pairs selected randomly from the total number of site pairs available based on the 2383 locations (Figure 27), explaining nearly 38% of the model deviance (Figure 28) using 19 predictors (Figure 29 and Figure 30), a result that is comparable with other GDM-based modelling of comprehensive survey data.

The Victorian schema for grouping the 144 Victorian ecological vegetation classes into 20 types occurring across the Wimmera is shown in

Table 19. Training sites were compiled using existing Victorian mapping of pre-1750 ecological vegetation classes (DSE 2007). A rigorous process ensured all vegetation types including rare types were represented. A regular grid of samples was used to compile an initial sample of training locations attributed with the vegetation type. More intense sampling of rare types ensured greater than 5 locations of each vegetation type were included, resulting in 13,500 training locations (Figure 31). The kernel regression was used with the transformed grids generated by the GDM model to produce probability surfaces for the 144 ecological vegetation classes. Spatial post-processing of the data applied to the maximum probability in any cell, with tied predictions resolved by the common type, was used to group the EVC into 20 types (Figure 32). Note that the resulting model of current vegetation types in the Wimmera was associated with much greater predicted probabilities than the equivalent models for the New South Wales study landscapes. This was largely the result of more and better on-ground data available for both building and training the model.

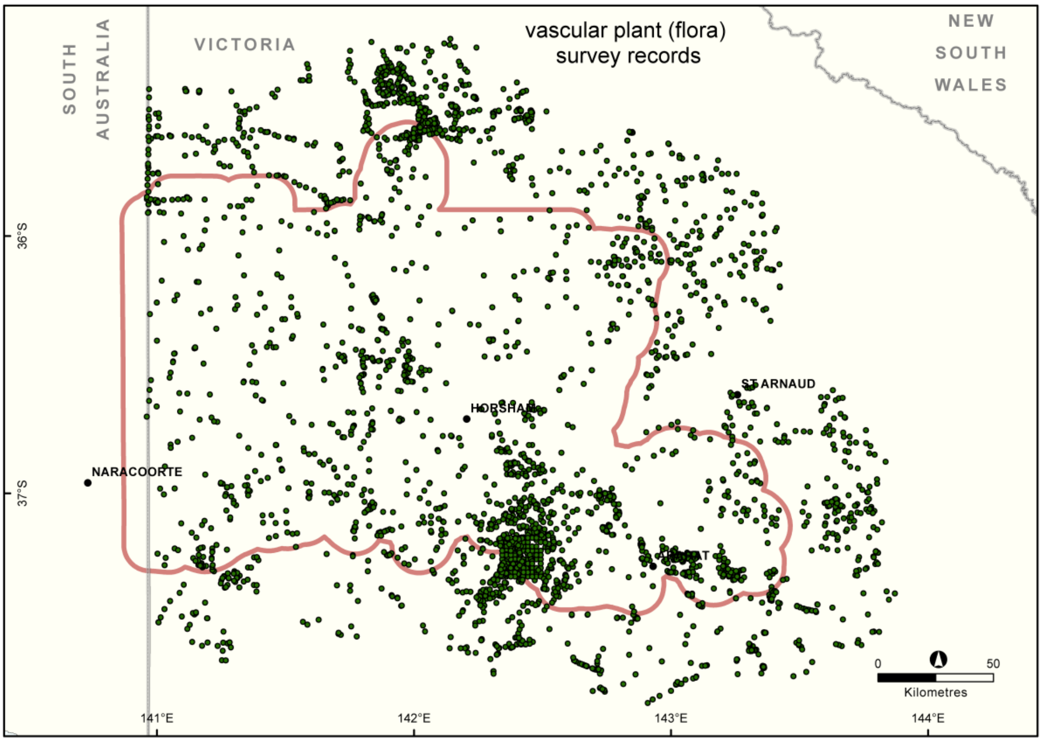


Figure 26. Location of vascular plant species surveys across the Wimmera study landscape and surrounding areas.

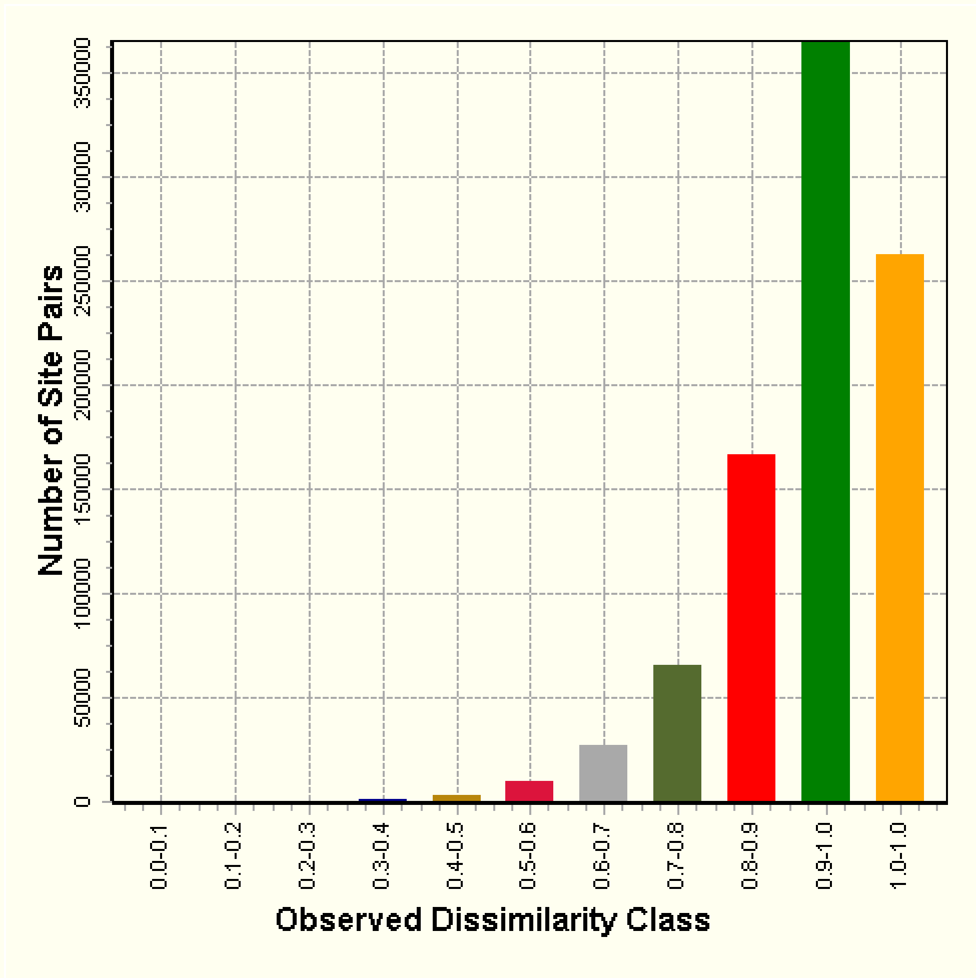


Figure 27. Frequency distribution of the observed dissimilarity class for the 900,000 site pairs (response variable) used in the GDM model of Wimmera flora.

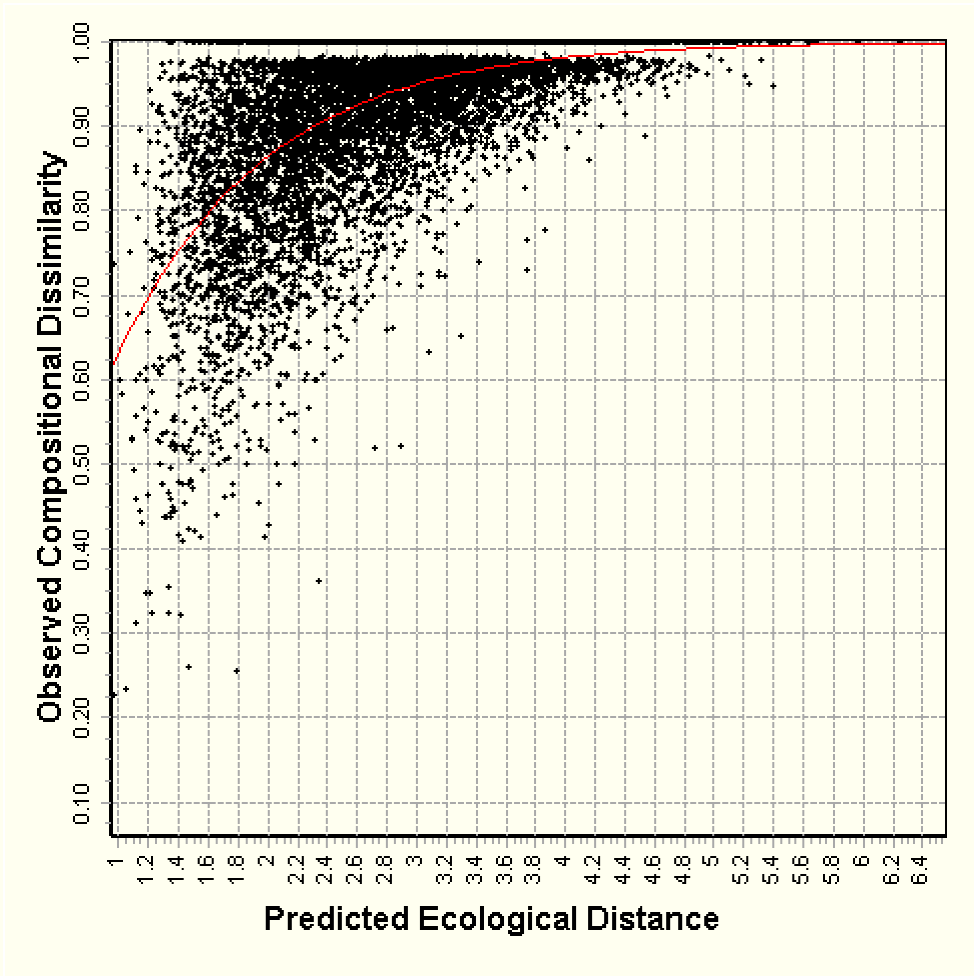


Figure 28. The overall fit of the GDM model (37.75% deviance explained) shown as the line scaled by the logistic link function. The scatter of points represent the observed versus predicted compositional dissimilarity scaled by the link function as ecological distance on the x-axis.

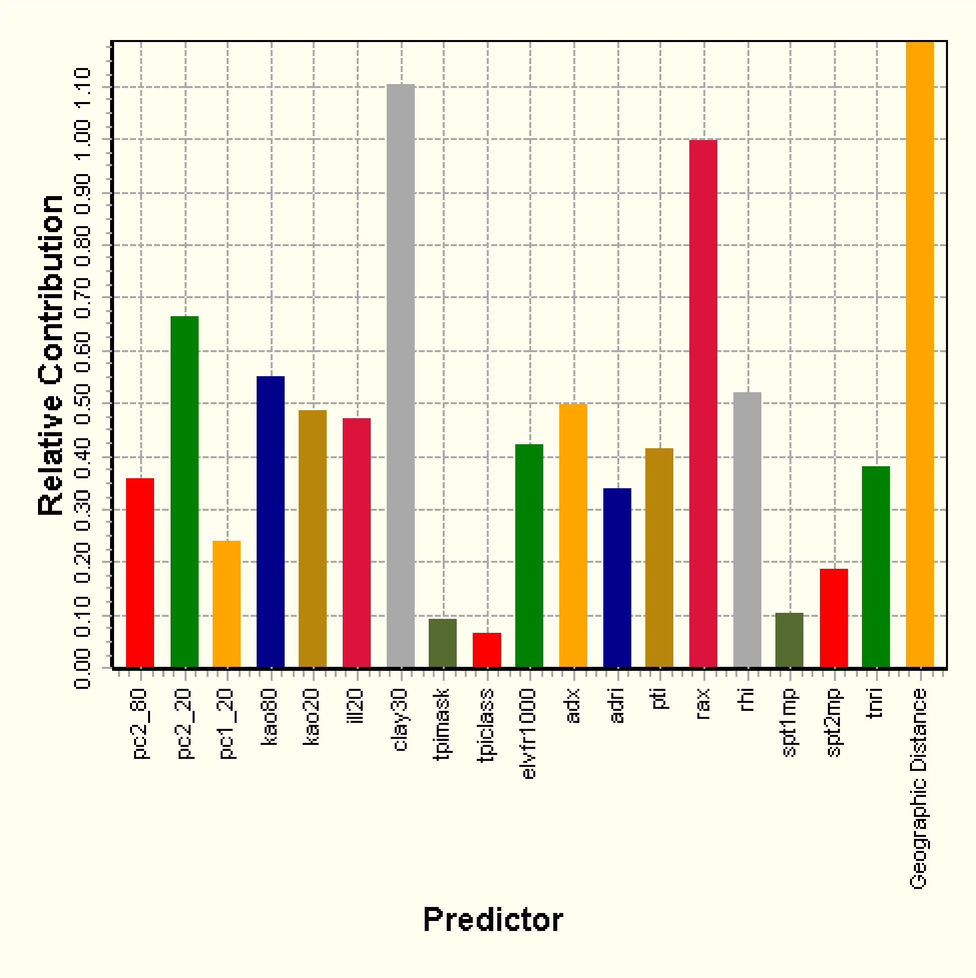


Figure 29. Relative contribution of predictors in the GDM model. Labels are defined in (Table 18). Geographic distance is the Euclidean distance between site pairs. The combined set of predictors resulted in a total summed coefficient value of 9.06 (sum of relative contributions), indicating the level of compositional turnover described by the model, a useful statistic for comparison between models.

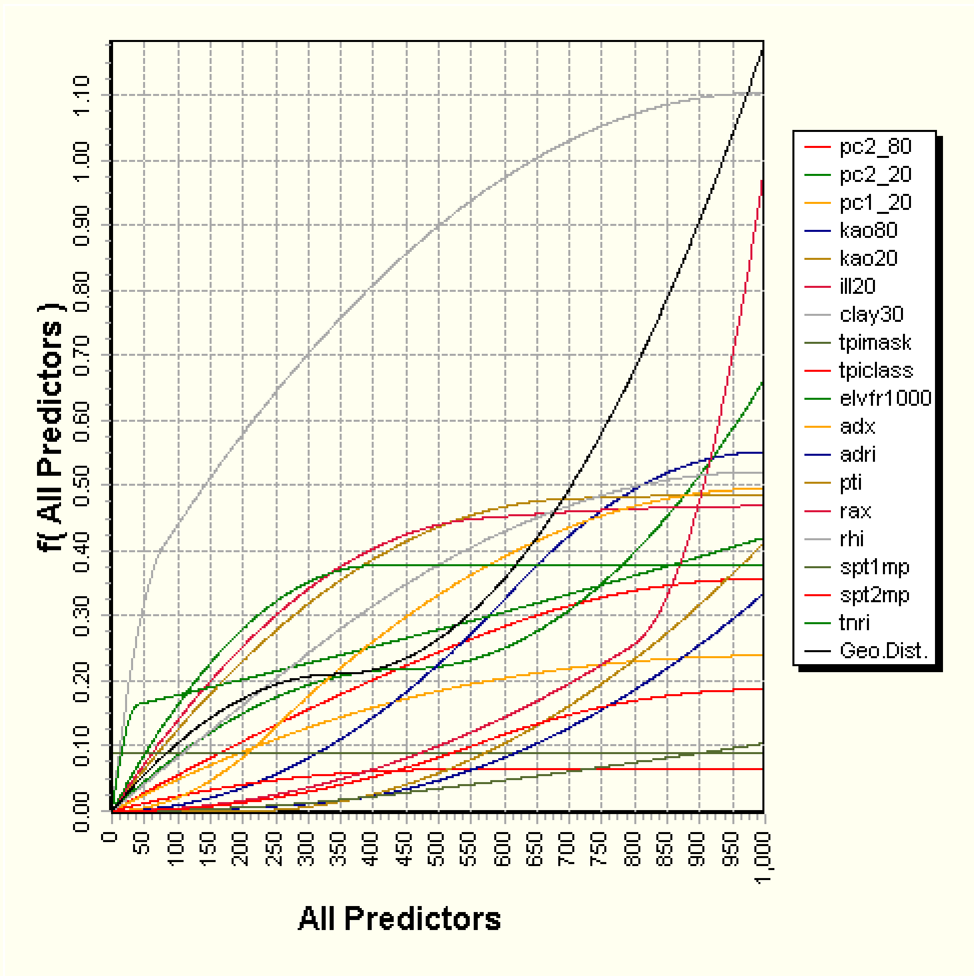


Figure 30. Shape of the I-spline functions for each of the predictors in the GDM model. Labels are defined in (Table 18).

Table 18. Candidate environmental predictor variables compiled at 3sec resolution for use in the GDM model of compositional turnover. See main text for the variables remaining in the final fitted model.

Group	Short name	Name	Units	Source citation
Topoclimate	ADX	Precipitation deficit (precipitation relative to evaporation) - monthly maximum	Mm	(Xu and Hutchinson 2011), (Williams et al. 2012)
Climate	PTI	Precipitation - monthly minimum	Mm	(Xu and Hutchinson 2011)
Topoclimate	RAX	Solar radiation (rainfall-cloudiness modified) - monthly maximum	$MJ/m^2/day$	(Xu and Hutchinson 2011), (Wilson and Gallant 2000)
Topoclimate	RHI	Humidity - month max relative	%	(Xu and Hutchinson 2011), (Wilson and Gallant 2000)
Climate	SPT1MP	Precipitation - solstice seasonality ratio	Ratio	(Xu and Hutchinson 2011), (Williams et al. 2012)
Climate	SPT2MP	Precipitation - equinox seasonality ratio	Ratio	(Xu and Hutchinson 2011), (Williams et al. 2012)
Climate	TNRI	Temperature - min difference in min between successive months	°C/day	(Xu and Hutchinson 2011), (Williams et al. 2012)
Regolith	CLAY30	soils - clay fraction in top 30cm from ASRIS best composite mapping	%	(Jacquier 2011)
Regolith	PC1_20	Spectra of surficial topsoils 0-20cm – Principal component 1	Index	(Viscarra-Rossel and Chen 2011)
Regolith	PC2_20	Spectra of surficial topsoils 0-20cm – Principal component 2	Index	(Viscarra-Rossel and Chen 2011)
Regolith	PC2_80	Spectra of surficial subsoils 60-80cm – Principal component 2	Index	(Viscarra-Rossel and Chen 2011)
Regolith	ILL20	relative abundance of illite clay minerals in surficial topsoil (0-20cm)	Proportion	(Viscarra Rossel 2011)
Regolith	KAO20	relative abundance of kaolinite clay minerals in surficial topsoil (0-20cm)	Proportion	(Viscarra Rossel 2011)
Regolith	KAO80	relative abundance of kaolinite clay minerals in surficial subsoil (60-80cm)	proportion	(Viscarra Rossel 2011)
Landform	ELVFR1000	elevation focal range within 1000m	M	(Gallant et al. 2012)
Landform	TPICLASS	Topographic position index	index	(Gallant and Austin 2012)
Landform	TPIMASK	Topographic position mask	Index	(Gallant and Austin 2012)

Table 19. Schema for grouping 144 Victorian ecological vegetation classes (EVC) into groups defined by the Victorian classification. The EVC_code was used to attribute the training data for the kernel regression to predict probabilities.

EVC_CODE	EVC_SUBGP	EVC_GP	EVCNAME	GROUPNAME	SUBGGROUP
0489	2.1	2	Heathy Woodland/Shrubby Woodland Complex	Heathy Woodlands	Dry and/or better drained
0790	2.1	2	Heathy Woodland/Heathy Herb-rich Woodland Mosaic	Heathy Woodlands	Dry and/or better drained
0048	2.1	2	Heathy Woodland	Heathy Woodlands	Dry and/or better drained
0673	2.2	2	Dune Soak Woodland	Heathy Woodlands	Damp and/or less well-drained
0756	2.2	2	Heathy Woodland/Seasonally Inundated Shrubby Woodland Mosaic	Heathy Woodlands	Damp and/or less well-drained
0134	2.1	2	Sand Forest	Heathy Woodlands	Dry and/or better drained
0704	2.1	2	Lateritic Woodland	Heathy Woodlands	Dry and/or better drained
0481	2.1	2	Heathy Woodland/Heathy Dry Forest Complex	Heathy Woodlands	Dry and/or better drained
0892	2.1	2	Heathy Woodland/Sand Heathland Mosaic	Heathy Woodlands	Dry and/or better drained
0179	2.1	2	Heathy Herb-rich Woodland	Heathy Woodlands	Dry and/or better drained
0282	2.1	2	Shrubby Woodland	Heathy Woodlands	Dry and/or better drained
0278	2.1	2	Herb-rich Heathy Forest	Heathy Woodlands	Dry and/or better drained
0650	2.2	2	Heathy Woodland/Damp Heathy Woodland/Damp Heathland Mosaic	Heathy Woodlands	Damp and/or less well-drained
0016	3.1	3	Lowland Forest	Lowland Forests	
0072	4.1	4	Granitic Hills Woodland	Box Ironbark Forests or dry/lower fertility Woodlands	
0061	4.1	4	Box Ironbark Forest	Box Ironbark Forests or dry/lower fertility Woodlands	
0751	5.1	5	Seasonally Inundated Shrubby Woodland/Plains Sedgy Woodland Mosaic	Lower Slopes or Hills Woodlands	Seasonally inundated and/or shrubby
0065	5.1	5	Sedge-rich Woodland	Lower Slopes or Hills Woodlands	Seasonally inundated and/or shrubby
0066	5.2	5	Low Rises Woodland	Lower Slopes or Hills Woodlands	Grassy
0709	5.2	5	Scree-slope Woodland	Lower Slopes or Hills Woodlands	Grassy
0076	5.2	5	Grassy Woodland/Alluvial Terraces Herb-rich Woodland Mosaic	Lower Slopes or Hills Woodlands	Grassy

EVC_CODE	EVC_SUBGP	EVC_GP	EVCNAME	GROUPNAME	SUBGGROUP
0401	5.3	5	Hills Herb-rich Woodland/Heathy Woodland Complex	Lower Slopes or Hills Woodlands	Herb-rich
0195	5.1	5	Seasonally Inundated Shrubby Woodland	Lower Slopes or Hills Woodlands	Seasonally inundated and/or shrubby
0285	5.1	5	Dry Creekline Woodland	Lower Slopes or Hills Woodlands	Seasonally inundated and/or shrubby
0175	5.2	5	Grassy Woodland	Lower Slopes or Hills Woodlands	Grassy
0450	5.1	5	Shrubby Woodland/Sedgy Riparian Woodland Complex	Lower Slopes or Hills Woodlands	Seasonally inundated and/or shrubby
0071	5.3	5	Hills Herb-rich Woodland	Lower Slopes or Hills Woodlands	Herb-rich
0789	5.3	5	Hills Herb-rich Woodland/Grassy Dry Forest Complex	Lower Slopes or Hills Woodlands	Herb-rich
0802	5.2	5	Grassy Woodland/Heathy Woodland Mosaic	Lower Slopes or Hills Woodlands	Grassy
0070	5.3	5	Hillcrest Herb-rich Woodland	Lower Slopes or Hills Woodlands	Herb-rich
0896	5.2	5	Grassy Woodland/Heathy Dry Forest Complex	Lower Slopes or Hills Woodlands	Grassy
0376	6.2	6	Shrubby Foothill Forest/Lowland Forest Complex	Dry Forests	Sheltered and/or higher altitude
0045	6.2	6	Shrubby Foothill Forest	Dry Forests	Sheltered and/or higher altitude
0587	6.2	6	Valley Grassy Forest/Grassy Dry Forest Complex	Dry Forests	Sheltered and/or higher altitude
0023	6.2	6	Herb-rich Foothill Forest	Dry Forests	Sheltered and/or higher altitude
0047	6.2	6	Valley Grassy Forest	Dry Forests	Sheltered and/or higher altitude
0390	6.1	6	Heathy Dry Forest/Valley Grassy Forest Complex	Dry Forests	Exposed and/or lower altitude
0379	6.2	6	Herb-rich Foothill Forest/Damp Sands Herb-rich Woodland Complex	Dry Forests	Sheltered and/or higher altitude
0022	6.1	6	Grassy Dry Forest	Dry Forests	Exposed and/or lower altitude
0020	6.1	6	Heathy Dry Forest	Dry Forests	Exposed and/or lower altitude
0783	6.2	6	Grassy Dry Forest/Heathy Woodland Mosaic	Dry Forests	Sheltered and/or higher altitude
0371	7.2	7	Damp Forest/Herb-rich Foothill Forest Complex	Wet or Damp Forests	Damp
0019	8.1	8	Riparian Shrubland	Riparian Scrubs or Swampy Scrubs and Woodlands	
0018	8.2	8	Riparian Forest	Riparian Scrubs or Swampy Scrubs and Woodlands	
0083	8.1	8	Swampy Riparian Woodland	Riparian Scrubs or	

EVC_CODE	EVC_SUBGP	EVC_GP	EVCNAME	GROUPNAME	SUBGGROUP
				Swampy Scrubs and Woodlands	
0641	8.2	8	Riparian Woodland	Riparian Scrubs or Swampy Scrubs and Woodlands	
0191	8.1	8	Riparian Scrub	Riparian Scrubs or Swampy Scrubs and Woodlands	
0192	10.1	10	Montane Rocky Shrubland	Montane Grasslands, Shrublands or Woodlands	Shrublands or Grasslands
0826	12.1	12	Plains Savannah	Plains Grasslands and Chenopod Shrublands	Clay soils
0132	12.1	12	Plains Grassland	Plains Grasslands and Chenopod Shrublands	Clay soils
0652	13.3	13	Lunette Woodland	Plains Woodlands or Forests	Lunettes or beach ridges or shallow sands
0097	13.4	13	Semi-arid Woodland	Plains Woodlands or Forests	Semi-arid(non-Eucalypt)
0098	13.4	13	Semi-arid Chenopod Woodland	Plains Woodlands or Forests	Semi-arid(non-Eucalypt)
0787	13.1	13	Plains Woodland/Damp Sands Herb-rich Woodland Mosaic	Plains Woodlands or Forests	Freely-draining
0895	13.1	13	Escarpment Shrubland	Plains Woodlands or Forests	Freely-draining
0657	13.2	13	Freshwater Lignum Shrubland	Plains Woodlands or Forests	Poorly-draining
0283	13.2	13	Plains Sedgy Woodland	Plains Woodlands or Forests	Poorly-draining
0264	13.3	13	Sand Ridge Woodland	Plains Woodlands or Forests	Lunettes or beach ridges or shallow sands
0882	13.3	13	Shallow Sands Woodland	Plains Woodlands or Forests	Lunettes or beach ridges or shallow sands
0724	13.2	13	Plains Woodland/Plains Sedgy Woodland/Damp Sands Herb-rich Woodland Mosaic	Plains Woodlands or Forests	Poorly-draining
0660	13.2	13	Plains Woodland/Plains Grassy Wetland Mosaic	Plains Woodlands or Forests	Poorly-draining
0780	13.2	13	Plains Sedgy Woodland/Shallow Sands Woodland/Heathy Woodland Mosaic	Plains Woodlands or Forests	Poorly-draining
0803	13.2	13	Plains Woodland	Plains Woodlands or Forests	Poorly-draining
0055	13.1	13	Plains Grassy Woodland	Plains Woodlands or Forests	Freely-draining
0750	13.3	13	Shallow Sands Woodland/Plains Sedgy Woodland/Seasonally Inundated Shrubby	Plains Woodlands or Forests	Lunettes or beach ridges or shallow sands

EVC_CODE	EVC_SUBGP	EVC_GP	EVCNAME	GROUPNAME	SUBGGROUP
			Woodland/Damp Sands Herb-rich Woodland Mosaic		
0749	13.3	13	Shallow Sands Woodland/Plains Sedgy Woodland/Seasonally Inundated Shrubby Woodland Mosaic	Plains Woodlands or Forests	Lunettes or beach ridges or shallow sands
0748	13.3	13	Shallow Sands Woodland/Heathy Woodland Mosaic	Plains Woodlands or Forests	Lunettes or beach ridges or shallow sands
0729	13.3	13	Sand Ridge Woodland/Damp Sands Herb-rich Woodland Mosaic	Plains Woodlands or Forests	Lunettes or beach ridges or shallow sands
0711	13.3	13	Shallow Sands Woodland/Plains Sedgy Woodland Mosaic	Plains Woodlands or Forests	Lunettes or beach ridges or shallow sands
0198	14.2	14	Sedgy Riparian Woodland	Riverine Grassy Woodlands or Forests	Creekline and/or swampy
0813	14.2	14	Intermittent Swampy Woodland	Riverine Grassy Woodlands or Forests	Creekline and/or swampy
0822	14.2	14	Intermittent Swampy Woodland/Riverine Grassy Woodland Complex	Riverine Grassy Woodlands or Forests	Creekline and/or swampy
0659	14.2	14	Plains Riparian Shrubby Woodland	Riverine Grassy Woodlands or Forests	Creekline and/or swampy
0516	14.2	14	Sedgy Riparian Woodland/Dry Creekline Woodland Complex	Riverine Grassy Woodlands or Forests	Creekline and/or swampy
0056	14.2	14	Floodplain Riparian Woodland	Riverine Grassy Woodlands or Forests	Creekline and/or swampy
0658	14.1	14	Riverine Grassy Woodland/Sedgy Riverine Forest/Aquatic Herbland Mosaic	Riverine Grassy Woodlands or Forests	Broader plain
0663	14.1	14	Black Box Lignum Woodland	Riverine Grassy Woodlands or Forests	Broader plain
0068	14.2	14	Creekline Grassy Woodland	Riverine Grassy Woodlands or Forests	Creekline and/or swampy
0640	14.2	14	Creekline Sedgy Woodland	Riverine Grassy Woodlands or Forests	Creekline and/or swampy
0823	14.2	14	Lignum Swampy Woodland	Riverine Grassy Woodlands or Forests	Creekline and/or swampy
0103	14.1	14	Riverine Chenopod Woodland	Riverine Grassy Woodlands or Forests	Broader plain
0679	14.2	14	Drainage-line Woodland	Riverine Grassy Woodlands or Forests	Creekline and/or swampy

EVC_CODE	EVC_SUBGP	EVC_GP	EVCNAME	GROUPNAME	SUBGGROUP
0785	15.2	15	Heathy Herb-rich Woodland/Damp Sands Herb-rich Woodland Mosaic	Herb-rich Woodlands	Damp Sands
0779	15.2	15	Damp Sands Herb-rich Woodland/Shallow Sands Woodland Mosaic	Herb-rich Woodlands	Damp Sands
0757	15.2	15	Damp Sands Herb-rich Woodland/Seasonally Inundated Shrubby Woodland Mosaic	Herb-rich Woodlands	Damp Sands
0672	15.2	15	Damp Sands Herb-rich Woodland/Shrubby Woodland Mosaic	Herb-rich Woodlands	Damp Sands
0414	15.2	15	Damp Sands Herb-rich Woodland/Shrubby Woodland Complex	Herb-rich Woodlands	Damp Sands
0164	15.1	15	Creekline Herb-rich Woodland	Herb-rich Woodlands	Alluvial terraces and/or creeklines
0003	15.2	15	Damp Sands Herb-rich Woodland	Herb-rich Woodlands	Damp Sands
0732	15.2	15	Damp Sands Herb-rich Woodland/Plains Swampy Woodland/Aquatic Herbland Mosaic	Herb-rich Woodlands	Damp Sands
0152	15.1	15	Alluvial Terraces Herb-rich Woodland/Plains Grassy Woodland Complex	Herb-rich Woodlands	Alluvial terraces and/or creeklines
0885	15.2	15	Damp Sands Herb-rich Woodland/Plains Grassy Woodland Mosaic	Herb-rich Woodlands	Damp Sands
0067	15.1	15	Alluvial Terraces Herb-rich Woodland	Herb-rich Woodlands	Alluvial terraces and/or creeklines
0089	16.1	16	Dunefield Heathland	Heathlands	Sandy and/or well drained
0008	16.2	16	Wet Heathland	Heathlands	Not well drained
0006	16.1	16	Sand Heathland	Heathlands	Sandy and/or well drained
0165	16.2	16	Damp Heath Scrub	Heathlands	Not well drained
0710	16.2	16	Damp Heathland	Heathlands	Not well drained
0595	16.2	16	Damp Heathland/Riparian Scrub Mosaic	Heathlands	Not well drained
0981	17.4	17	Parilla Mallee	Mallee	Sandstone ridges and rises
0087	17.1	17	Lowan Sands Mallee	Mallee	Siliceous sands
0088	17.1	17	Heathy Mallee	Mallee	Siliceous sands
0093	17.4	17	Sandstone Ridge Shrubland	Mallee	Sandstone ridges and rises
0095	17.4	17	Red Swale Mallee	Mallee	Sandstone ridges and rises
0096	17.3	17	Ridged Plains Mallee	Mallee	Clay plains
0824	17.2	17	Woorinen Mallee	Mallee	Calcareous dunefields
0832	18.1	18	Plains Grassy Wetland/Red Gum Swamp Mosaic	Wetlands	Freshwater
0718	18.1	18	Freshwater Lake Aggregate	Wetlands	Freshwater

EVC_CODE	EVC_SUBGP	EVC_GP	EVCNAME	GROUPNAME	SUBGGROUP
0681	18.1	18	Deep Freshwater Marsh	Wetlands	Freshwater
0831	18.1	18	Red Gum Swamp/Spike-sedge Wetland Mosaic	Wetlands	Freshwater
0680	18.1	18	Freshwater Meadow	Wetlands	Freshwater
0833	18.1	18	Cane Grass Wetland/Lignum Swampy Woodland Mosaic	Wetlands	Freshwater
0834	18.1	18	Red Gum Swamp/Lignum Swampy Woodland Mosaic	Wetlands	Freshwater
0886	18.1	18	Red Gum Wetland/Aquatic Herbland Mosaic	Wetlands	Freshwater
0939	18.1	18	Lake Bed Herbland/Red Gum Swamp Mosaic	Wetlands	Freshwater
0941	18.2	18	Cane Grass Wetland/Salt Paperbark Woodland Mosaic	Wetlands	Brackish/estuarine
0013	18.2	18	Brackish Sedgeland	Wetlands	Brackish/estuarine
0830	18.1	18	Red Gum Swamp/Cane Grass Wetland Mosaic	Wetlands	Freshwater
0643	18.2	18	Brackish Drainage-line Aggregate	Wetlands	Brackish/estuarine
0291	18.1	18	Cane Grass Wetland	Wetlands	Freshwater
0292	18.1	18	Red Gum Swamp	Wetlands	Freshwater
0136	18.1	18	Sedge Wetland	Wetlands	Freshwater
0104	18.1	18	Lignum Swamp	Wetlands	Freshwater
0074	18.1	18	Wetland Formation	Wetlands	Freshwater
0647	18.1	18	Plains Sedgy Wetland	Wetlands	Freshwater
0653	18.1	18	Aquatic Herbland	Wetlands	Freshwater
0656	18.2	18	Brackish Wetland	Wetlands	Brackish/estuarine
0107	18.1	18	Lake Bed Herbland	Wetlands	Freshwater
0636	19.2	19	Brackish Lake Aggregate	Salt-tolerant and/or succulent Shrublands	Inland
0677	19.2	19	Inland Saltmarsh	Salt-tolerant and/or succulent Shrublands	Inland
0676	19.2	19	Salt Paperbark Woodland	Salt-tolerant and/or succulent Shrublands	Inland
0741	19.2	19	Salt Paperbark Woodland/Samphire Shrubland Mosaic	Salt-tolerant and/or succulent Shrublands	Inland
0193	20.1	20	Rocky Outcrop Herbland	Rocky Outcrop or Escarpment Scrubs	
0351	20.1	20	Rocky Outcrop Shrubland/Rocky Outcrop Herbland/Grassy Dry Forest Complex	Rocky Outcrop or Escarpment Scrubs	
0598	20.1	20	Rocky Outcrop Shrubland/Rocky Outcrop Herbland/Heathy Dry Forest Mosaic	Rocky Outcrop or Escarpment Scrubs	
0028	20.1	20	Rocky Outcrop Shrubland	Rocky Outcrop or Escarpment Scrubs	
0073	20.1	20	Rocky Outcrop Shrubland/Rocky	Rocky Outcrop or	

EVC_CODE	EVC_SUBGP	EVC_GP	EVCNAME	GROUPNAME	SUBGGROUP
			Outcrop Herbland Mosaic	Escarpment Scrubs	
0726	20.1	20	Rocky Outcrop Shrubland/Rocky Outcrop Herbland/Heathy Woodland Mosaic	Rocky Outcrop or Escarpment Scrubs	
0753	20.1	20	Rocky Outcrop Shrubland/Rocky Outcrop Herbland/Sandstone Ridge Shrubland Mosaic	Rocky Outcrop or Escarpment Scrubs	
0683	99.1	99	Semi-Permanent Saline	No native vegetation recorded	
0982	99.1	99	No EVC assigned - need editing	No native vegetation recorded	
0983	99.1	99	Water Body - to be determined	No native vegetation recorded	
0991	99.1	99	Water body - salt	No native vegetation recorded	
0992	99.1	99	Water Body - Fresh	No native vegetation recorded	

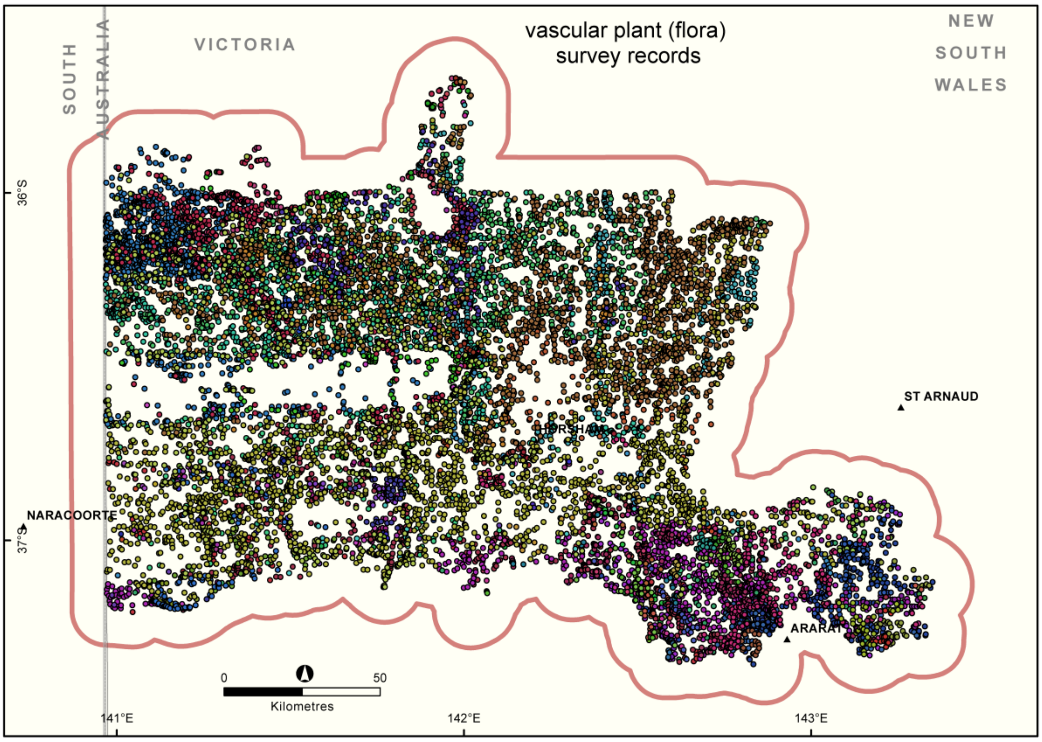


Figure 31. Training locations attributed with ecological vegetation class based on pre-1750 vegetation mapping encompassing the Wimmera.

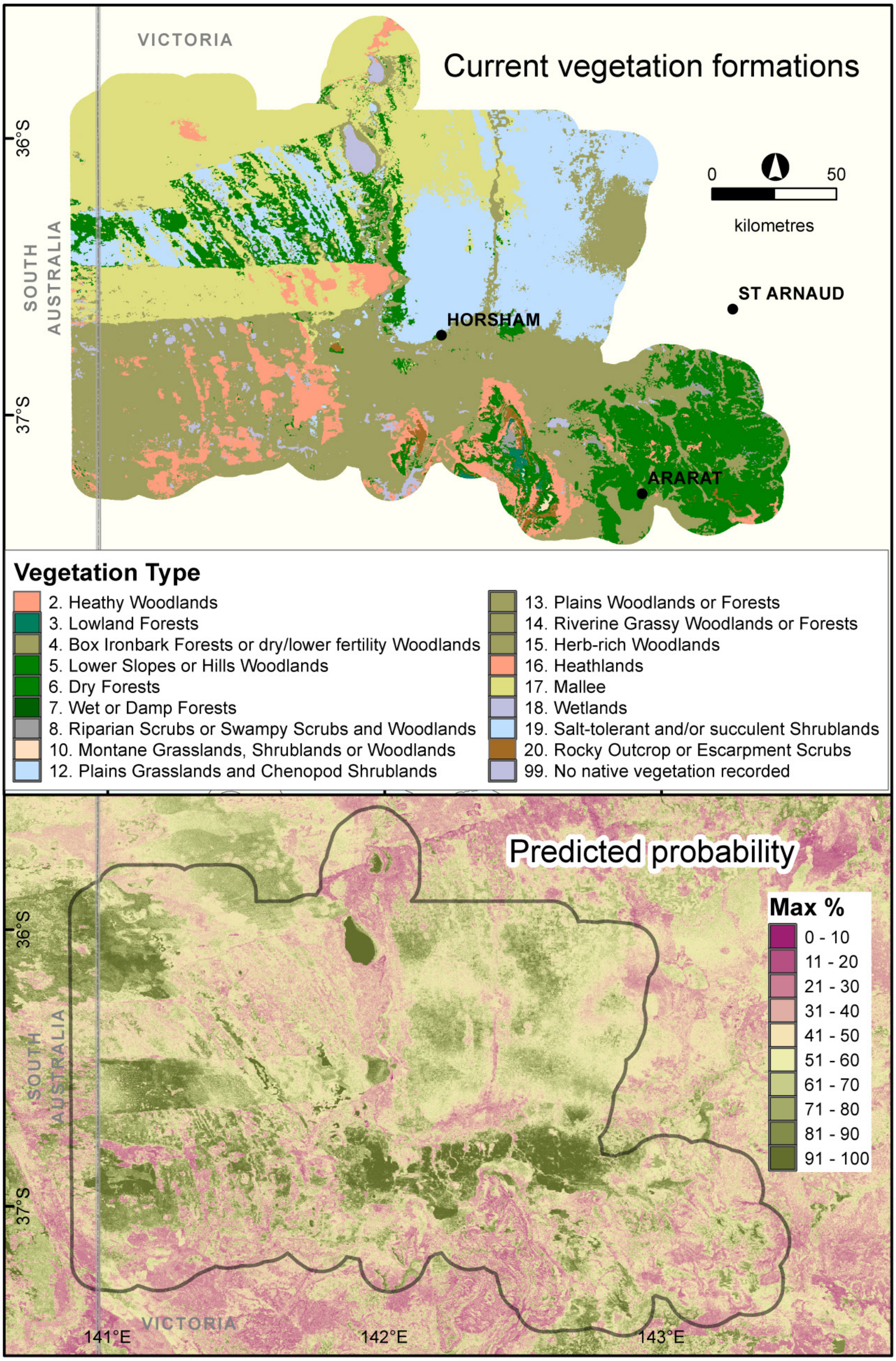


Figure 32. Classification of Wimmera ecological vegetation classes into 20 groups based on a model of Victorian vascular flora distributions derived from comprehensive survey data inclusive of surrounding areas

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CONTACT CSIRO
t 1300 363 400
+61 3 9545 2176
e enquiries@csiro.au
w www.csiro.au

FOR FURTHER INFORMATION
Division of Ecosystem Sciences
Veronica Doerr
t +61 2 6246 4099
e veronica.doerr@csiro.au
w www.csiro.au/climateadaptationflagship

Division of Ecosystem Sciences
Kristen Williams
t +61 2 6246 4213
e kristen.williams@csiro.au
w www.csiro.au/climateadaptationflagship

Division of Ecosystem Sciences
Craig James
t +61 2 6246 4091
e craig.james@csiro.au
w www.csiro.au/climateadaptationflagship

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