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Queensland's biodiversity under climate change:

ecological scaling of terrestrial environmental change

Climate Adaptation Flagship Working Paper #12B

Simon Ferrier, Thomas D. Harwood and Kristen J. Williams
September 2012

National Library of Australia Cataloguing-in-Publication entry

Title:	Queensland's biodiversity under climate change: Ecological scaling of terrestrial environmental change / Simon Ferrier
ISBN:	978-1-4863-0279-6 (pdf)
Series:	CSIRO Climate Adaptation Flagship Working Paper series; 12B.
Other Authors/Contributors:	Tom Harwood and Kristen J. Williams Climate Adaptation Flagship

Enquiries

Enquiries regarding this document should be addressed to:

Kristen J Williams
CSIRO Ecosystem Sciences
GPO Box 1700, Canberra 2601
kristen.williams@csiro.au

Enquiries about the Climate Adaptation Flagship or the Working Paper series should be addressed to:

Working Paper Coordinator
CSIRO Climate Adaptation Flagship
CAFworkingpapers@csiro.au

Citation

This document can be cited as:

Ferrier, S., Harwood, T. and Williams, K.J. (2012) *Queensland's biodiversity under climate change: Ecological scaling of terrestrial environmental change.* CSIRO Climate Adaptation Flagship Working Paper No. 12B. http://www.csiro.au/resources/CAF-working-papers.html

Acknowledgements

This work has been funded by the Queensland Government and the CSIRO through the Climate Adaptation Flagship (Managing Species and Ecosystems Theme).

The ecological scaling of terrestrial environmental change used the models and data described in Ferrier *et al.* (2010) and Williams *et al.* (2010a); the authors and acknowledgements therein apply also here.

This manuscript was improved by comments from Michael Berkman (OCC), Craig James and Alistair Hobday, John Scott and Helen Murphy. Thanks to Serena Henry for proof reading.

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1. PREAMBLE

This report is one of seven background documents prepared by the CSIRO Climate Adaptation Flagship for the Queensland Government, Brisbane. Content from this report contributed to the synthesis report titled “Queensland's biodiversity under climate change: impacts and adaptation” by Williams *et al.* (2012a).

The seven background reports are:

A. Overview of climate change in Queensland (Williams & Crimp 2012)

B. Ecological scaling of terrestrial environmental change (Ferrier *et al.* 2012)

C. Terrestrial ecosystems (Murphy *et al.* 2012)

D. Freshwater aquatic ecosystems (Kroon *et al.* 2012)

E. Coastal and marine ecosystems (Bustamante *et al.* 2012)

F. Ecosystem services (Williams *et al.* 2012b)

G. Adaptation principles and options (Dunlop *et al.* 2012)

2. EXECUTIVE SUMMARY

Generalised dissimilarity modelling (GDM) is a powerful way of assessing the ecological significance of environmental changes projected to result from climate change, to inform policy and management responses. GDM is here used to analyse distributional data for many thousands of vascular-plant species to develop a measure that scales the ecological implications of environmental variation in terrestrial ecosystems. Applying this ecological scaling to two different climate change scenarios at 2030 and 2070 suggests the potential for ecologically-significant environmental changes in many parts of Queensland. However, the actual level of change eventuating in any particular place will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

The key results are that:

- Modelling indicates potential for major changes in the species composition of plant communities in many parts of Queensland.
- Even under a moderate-emissions scenario, modelling indicates that most of the State will have experienced sufficient environmental change by 2070 to result (over the longer term) in more than 50% change in the composition of plant species occurring at any given location, relative to the middle of last century. (Section 3.1)
- Some current ecologically-scaled environments, such as those presently found in the higher peaks of the wet tropics, may disappear completely from the State (and from the Australian continent) as a result of climate change. (Section 3.2)
- Novel ecologically-scaled environments not currently occurring anywhere in the State may also appear; for example, in parts of the semi-arid and arid country. (Section 3.2)
- Some of the regional effects of global warming can be visualised using forward- and backward-comparisons of projections of modelled ecological change. For example, over the long term, the natural environments and therefore habitats of the Moreton basin subregion of Southeast Queensland, will begin to appear (structurally at least) more like habitats that are presently a few hundred kilometres to the north. (Section 3.7)
- Preliminary mapping of trial "adaptation indices" demonstrate that priorities for applying different types of adaptation management (e.g., actions enhancing long-distance migration or colonisation *versus* actions restoring native habitat in local landscapes) vary greatly between different regions of the State. (Section 3.5, 3.6, 4.4 and 4.5).

Ecological modelling to inform landscape designs at the level of detail needed for adaptation planning (e.g., to identify priority regions and ecosystems for establishment of connectivity and trade-offs with other values) requires further development of objectives, principles, methodologies, tools and applied information products.

3. INTRODUCTION

Climate and weather are principle determinants of biodiversity and ecosystem distribution patterns at a variety of scales. This relationship between biodiversity response and environment, incorporating indicators of climatic variation, has long been exploited in experimental and modelling studies based on equilibrium conditions (e.g., Nix & Austin 1973; Austin & Smith 1989; Battaglia & Williams 1996; Elith *et al.* 2006; Ferrier *et al.* 2007). However, the current and projected rate of global warming is faster than ever recorded in the past (Solomon *et al.* 2007) and is already affecting species composition through a range of mechanisms (Walther *et al.* 2005), with potential for mass extinction associated with human activity (Sala *et al.* 2000; Pereira *et al.* 2010); heralding a new era – the *Anthropocene* (Crutzen 2002; Crutzen & Steffen 2003; Steffen *et al.* 2011).

These concerns are driving an increased emphasis on integrated modelling approaches to forecast changes in species distributions and compositional diversity aligned with projected change in climate and land use patterns (Kearney *et al.* 2010; Ferrier 2011). Many approaches to projecting future distributions are based on models of current distributions (e.g., Elith *et al.* 2010; Kissling *et al.* 2010; Austin & Van Niel 2011) by assuming space for time substitution of climatic predictors (see discussion in: Guisan & Thuiller 2005; Araújo & Rahbek 2006; Elith & Leathwick 2009; Isaac *et al.* 2011). Although the level of uncertainty and assumptions associated with distribution models sometimes limits their applicability to management decision-making (Sinclair *et al.* 2010), they continue to be useful in assessing potential trends and risks associated with alternative global-change and policy-response scenarios, thereby informing high-level policy development (Alkemade *et al.* 2009; Leadley *et al.* 2010; sCBD 2010).

Previous efforts to forecast impacts of climate change on biodiversity have focused almost exclusively on modelling potential changes in the distribution and abundance of individual species, commonly called “species distribution modelling” (Elith & Leathwick 2009). This “bottom-up” strategy plays an important role in planning for better-known species of particular ecological, social or economic concern. However, its capacity to address changes in compositional diversity as a whole (the full variety of biological elements across all taxa and all levels of organisation) is challenged by the sheer number of elements involved and the grossly incomplete state of our knowledge of both these elements and their interactions. Interest has therefore been growing in recent years in “top-down”, macroecological approaches to addressing this problem, which focus on modelling change in emergent properties of biodiversity at the community level (compositional turnover and richness; or attributes of structural and functional diversity) rather than change in the individual elements constituting this diversity (Ferrier & Guisan 2006; Kerr *et al.* 2007; Fitzpatrick *et al.* 2011; Mokany & Ferrier 2011). These approaches are not intended to replace or compete with, species-level approaches to modelling global-change impacts, but rather to complement and add value to these existing efforts.

We here describe how we used a particular top-down macroecological modelling approach—generalised dissimilarity modelling—to ecologically translate or scale, projected scenarios of climate change for Queensland (from Williams & Crimp 2012), in terms of the potential pressure these scenarios may apply towards altering the species composition of plant communities. Although the realised ecological response of any area to climate change is highly uncertain, this approach can help to highlight areas where such change is likely to have the greatest potential impact on biological composition and where adaptation responses or policies for managing this change could be focussed (see Dunlop *et al.* 2012). The results are presented as maps with Queensland’s regional plan boundaries superimposed (DIP 2009), to guide the interpretation of regional variation in change.

An interpretive case study is presented in Section 4, presenting a preliminary synthesis of bioregional patterns of change.

4. METHODS

The analyses performed for Queensland were based on continental models developed in two recent Commonwealth environment department funded projects (Ferrier *et al.* 2010; Williams *et al.* 2010a; Williams *et al.* 2010b) assessing the extent to which change in climate is likely to drive ecological change in the species composition of plant communities. These projects employed generalised dissimilarity modelling (GDM: Ferrier *et al.* 2007), a statistical technique for modelling the compositional dissimilarity in biodiversity between pairs of geographical locations, for a given biological group (e.g., vascular plants), as a function of environmental differences between these locations (Box 1). Compositional dissimilarity is simply the proportion of species occurring at one location that do not occur at the other location (averaged across the two locations) – ranging from 0 if the two locations have exactly the same species through to 1 if they have no species in common. GDM uses data derived from observations of species recorded at a sample of locations across the region of interest to fit a model predicting the compositional dissimilarity between pairs of locations as a non-linear multivariate function of the environmental attributes of these locations. Another way of viewing this is that GDM effectively weights and transforms the environmental variables of interest such that distances between locations in this transformed multidimensional environmental space now correlate, as closely as possible, with observed compositional dissimilarities between these same locations.

Box 1: A brief description of generalised dissimilarity modelling.

Generalised Dissimilarity Modelling (GDM) is a statistical technique for modelling the compositional dissimilarity between pairs of geographical locations, for a given biological group (e.g., reptiles), as a function of environmental differences between these locations (Ferrier 2002; Ferrier *et al.* 2002; Ferrier *et al.* 2007). The measure of compositional dissimilarity (*d*) employed in this project is the Sorenson or Bray-Curtis, index:

$$d_{ij} = 1 - \frac{2A}{2A + B + C}$$

where *A* is the number of species common to both locations *i* and *j*
B is the number of species present only at location *i*
C is the number of species present only at location *j*

In other words, based on this measure, the compositional dissimilarity between a given pair of locations is the proportion of species occurring at one location that do not occur at the other location (averaged across the two locations) – ranging from 0 if the two locations have exactly the same species through to 1 if they have no species in common.

The GDM model of native vascular plants underpinning the analyses presented here is based on a stratified-random subsample of about 100,000 observations from more than 350,000 sites throughout the Australian continent, representing the historical occurrence of over 12,000 native species in 83 vascular plant families (Williams *et al.* 2010a; Williams *et al.* 2010b). These data were extracted from Commonwealth environment department's[1] Australian Natural Heritage Assessment Tool (ANHAT) database, based on the available data compilation and with data quality filters applied (e.g. spatial accuracy of location reference, collection date). The model was fitted by relating these observations to spatial (mapped) variables describing historical environmental conditions prior to the rapid onset of climate change (approximately centred on 1960).

Two future scenarios under the CSIRO mk3.5 general circulation model (GCM) were considered for 2030 and 2070; a high change scenario (A1FI, high climate sensitivity) in line with current observations

[1] Commonwealth Department of Environment, Water, Heritage and the Arts; now the Department of Sustainability, Environment, Water, Population and Communities.

and a more conservative A1B, moderate climate sensitivity scenario (GCM emission scenarios are described in Appendix A - Williams & Crimp 2012). These projections used regional outputs (monthly rainfall, temperature, relative humidity) from the CSIRO mk3.5 climate model (Gordon *et al.* 2010) downloaded as 25km (0.25º) interpolated grids from OzClim (CSIRO 2007; Ricketts & Page 2007), that were expanded and rescaled (Salathé Jr 2005) to 1km (0.01º) grid resolution using 1960-centred long-term average monthly climate surfaces (Hutchinson & Kesteven 1998), a digital elevation model (Hutchinson *et al.* 2008) resampled to 0.01° and ANUCLIM beta-version 6.0 (Hutchinson *et al.* 2000), described in Harwood *et al.* (2010). Average annual climatic variability in 1960, 2030 and 2070 was expressed through a range of predictors describing minimum, maximum and seasonal conditions (for details see Williams *et al.* 2010a; Williams *et al.* 2010b). Non-climatic environmental predictors captured spatial variation in substrate and topography through derivatives of soil (Bureau of Rural Sciences 2000; McKenzie *et al.* 2000; Raupach *et al.* 2001a; Raupach *et al.* 2001b; Western & McKenzie 2004), geoscience (Bacchin *et al.* 2008; Laurie *et al.* 2008; Raymond 2009; Milligan 2010) and land (Gallant & Dowling 2003; Geoscience Australia 2006; Hutchinson *et al.* 2008) datasets (for details see Williams *et al.* 2010a; Williams *et al.* 2010b).

The continental vascular-plant GDM is used here to ecologically scale the two projected scenarios of climate change for Queensland (Figure 1). This scaling is based on the assumption that the potential for change in species composition at location *A* as a result of climate change, will be equivalent to the compositional dissimilarity currently observed between location *A* and another location *B* with a current climate matching that projected for the future at location *A*. However, the actual change in biological composition resulting from climate change is likely to be shaped by many factors and associated sources of uncertainty, beyond those considered in this modelling – for example, biotic interactions, indirect effects of changed fire regimes, dispersal ability, lag effects, adaptation capacity and plasticity. The projected level of compositional change assessed using the outputs of a GDM model is therefore best interpreted as no more than a relative indicator of the potential (or the pressure) for such change, rather than as an expectation of the actual change that will occur at any given location.

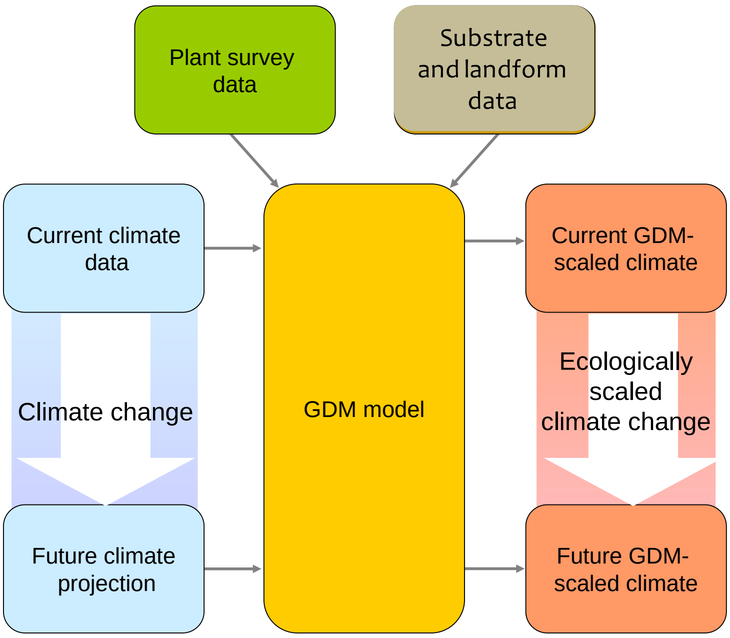

Figure 1: Ecological scaling of environmental change. Biological survey data (e.g., vascular plants) are combined with current climate data, along with data on substrate (e.g., soils, geology) and landform (e.g., topography), to generate a GDM model for current conditions (e.g., 1960 equilibrium climates). This model is then used to scale both current and future environmental conditions.

5. RESULTS

5.1 Potential for ecological change

The predicted dissimilarity between the current composition of each grid cell and its future composition under a given climate scenario is a general indicator of potential environmental pressure on a cell-by-cell basis. This was estimated and mapped for each of the two climate change scenarios (A1B emission scenario with medium climatic sensitivity; A1FI with medium climatic sensitivity) and two time periods (2030 and 2070).

In Figure 2 the continental GDM modelling of vascular plants has been used to scale environmental change expected for Queensland in 2030 and 2070 under the two climate scenarios (an enlargement of the A1B 2070 map is also provided in Figure 3). The colours depict a range from green for locations (1km grid-cells in this analysis) with least potential for change in vascular plant species composition currently occurring at that location, through to reddish-brown for locations with most potential for change in vascular plant species composition. Two aspects of these results are worth noting:

- The potential for compositional change is not evenly distributed across the State. Some regions and environments exhibit greater potential for change than others. These patterns arise from a combination of differences in the amount of change predicted for climate itself (i.e., annual mean and seasonal ranges in minimum and maximum temperature, precipitation, evaporation, relative humidity and solar radiation) across different parts of the State (from the CSIRO mk3.5 climate model) and of differences in the amount of change in species composition expected for a given change in climate in different environments (from the GDM).

- The overall potential for compositional change is high, particularly by 2070. If the ‘dissimilarity’ values depicted in these maps are interpreted literally (see caveats above) then, even under the moderate-emissions / medium-sensitivity scenario, most of the State will have experienced sufficient environmental change by 2070 to result (over the longer term) in more than 60% change in the composition of plant species occurring at any given location (Figure 3). Under the high-emissions / high-sensitivity scenario, most of the State will experience even higher levels of environmental change, potentially resulting in more than 90% change in plant species composition for a large proportion of locations.

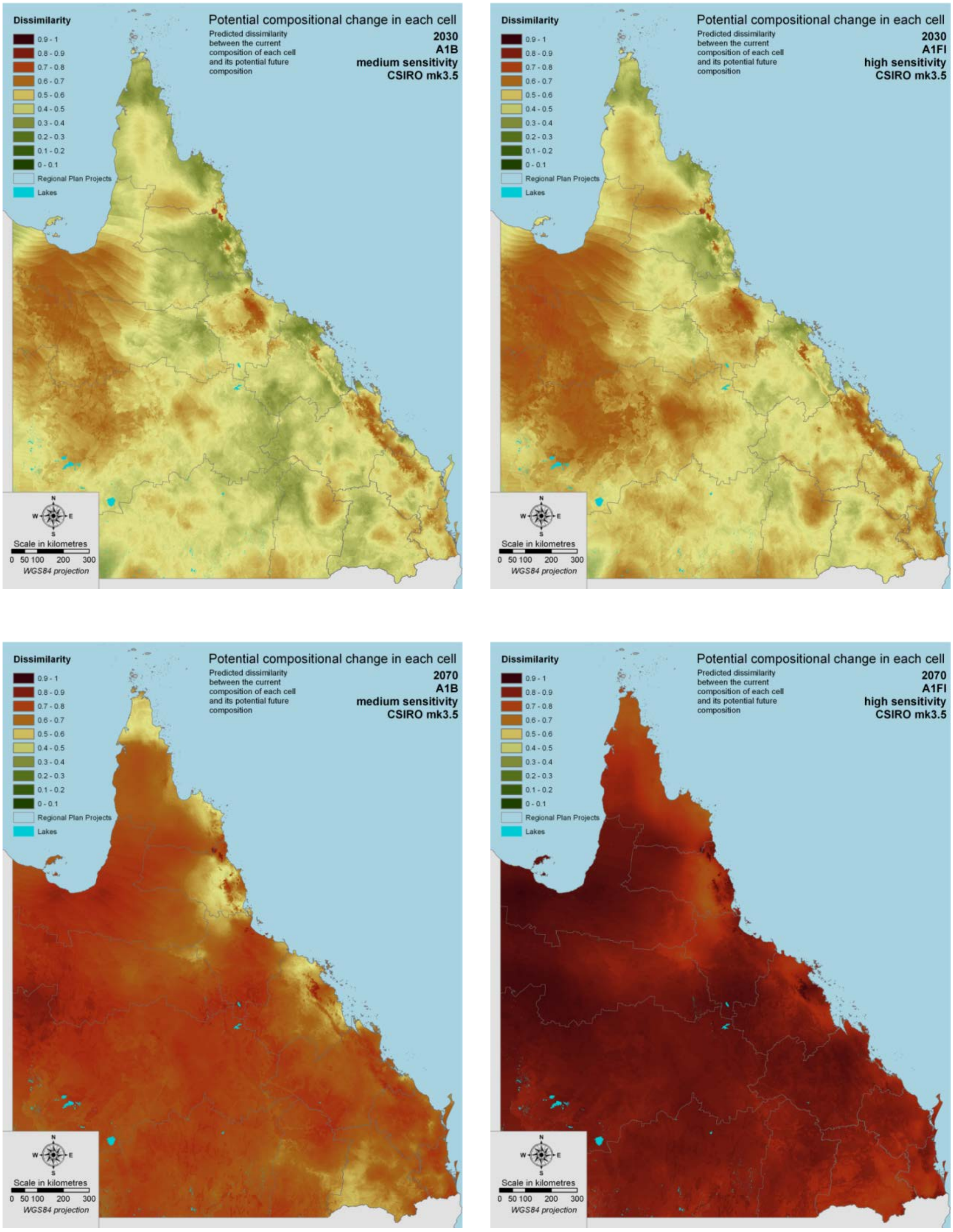

Figure 2: Potential ecologically-scaled environmental change, in 2030 and 2070, for two climate-change scenarios, based on modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). Green areas are those with least potential for change, while reddish-brown areas have highest potential for change in composition. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

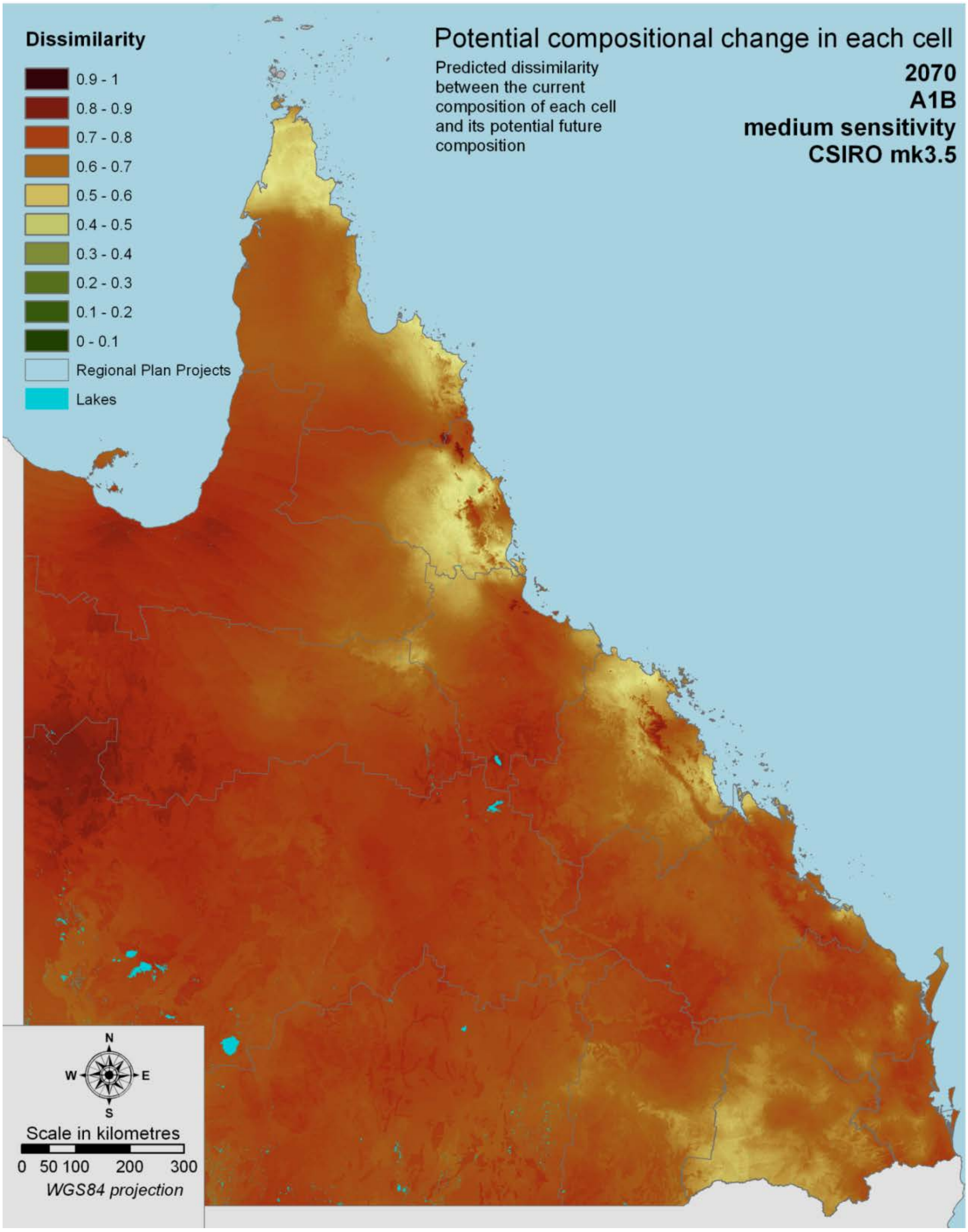

Figure 3: Potential ecologically-scaled environmental change for 2070, A1B climate scenario (enlarged map from Figure 2), based on modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). Darker reddish-browns indicate higher levels of potential environmental change. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

5.2 Disappearing and novel environments

Our perspective on the ecology of past and future climates is largely limited to comparison with observed present climates and communities according to the principle of “uniformitarianism” (Williams & Jackson 2007). That is, "the present is the key to the past" and is functioning at the same rates. Under projected CO_2-induced climatic change there is the strong possibility that some future climates will lie outside the range of known climatic combinations (novel climates), whilst some present climates will no longer exist (disappearing climates). Williams and Jackson (2007) present a compelling argument for the existence and distribution of these novel and disappearing climates couched in terms of the Standardised Euclidean Distance (SED) of a suite of climatic variables. However, this measure is limited in its explanatory power in that it assumes a linear relationship between biological responses and the chosen suite of climatic variables. It tells us how different the distribution of climates is expected to be from the present but not how different the resultant ecological communities would be.

Working with our GDM-scaled environmental change, we are able to make predictions of the extent to which biologically, rather than purely physically, scaled climates might be different under climate change. Whilst the distributions of novel and disappearing climates of Williams *et al*. (2007) will undoubtedly highlight the areas which will undergo the greatest climatic stress, our approach adds value by assessing the extent to which future climates are ecologically novel and which current ecologically-scaled climates are likely to disappear. Disappearing ecologically-scaled environments were calculated for any reference cell by locating the most environmentally similar cell to the current state of the reference cell within a sample of cells from the future. Three spatial domains or contexts, were used for the analysis – 1) all cells lying within a 50km radius of the reference cell (7845 cells); 2) a stratified random sample of 1 in 200 cells in Queensland (7500 cells); and 3) a stratified random sample of 1 in 500 cells in Australia (14000 cells). Selected results of these analyses are presented (Figure 4, Figure 5 and Figure 6).

Figure 4 depicts disappearing environments mapped for the three spatial domains: 50km radius, Queensland context, Australia-wide context. The middle map shows current environments which are disappearing within Queensland. This is superficially similar to the Australia wide analysis (on the right) but shows environments likely to be lost at the State level. The dark brown areas in the left-most map show those cells where the current environment is disappearing within a 50km radius. This shows qualitative differences to the Australia wide map (on the right), and the Queensland-context is influenced by the jurisdiction boundary highlighting the importance of choosing an appropriate spatial context. If a similar environment will be found in a distant location in the future, it is likely to be of less benefit to the species currently occurring in a cell than a more accessible location.

Novel ecologically-scaled environments are defined in a similar manner but in this case we look back from each reference cell in the future to find the most similar cell in the present. Selected results of these analyses (only for the Australia-wide context) are presented in Figure 7 and Figure 8. Comparison of the maps of disappearing and novel environments reveals some interesting patterns. For example, the higher peaks in the Queensland Wet Tropics are, quite understandably, mapped as disappearing environments. But the environments expected to replace these are not novel (i.e., they are probably environments that already occur at lower elevations in this region). On the other hand, much of Queensland’s semi-arid and arid country is mapped as supporting both disappearing and novel environments; that is, the environments currently occurring in these regions are unlikely to be found anywhere else in the future and will probably be replaced by environments unlike anything occurring elsewhere at present.

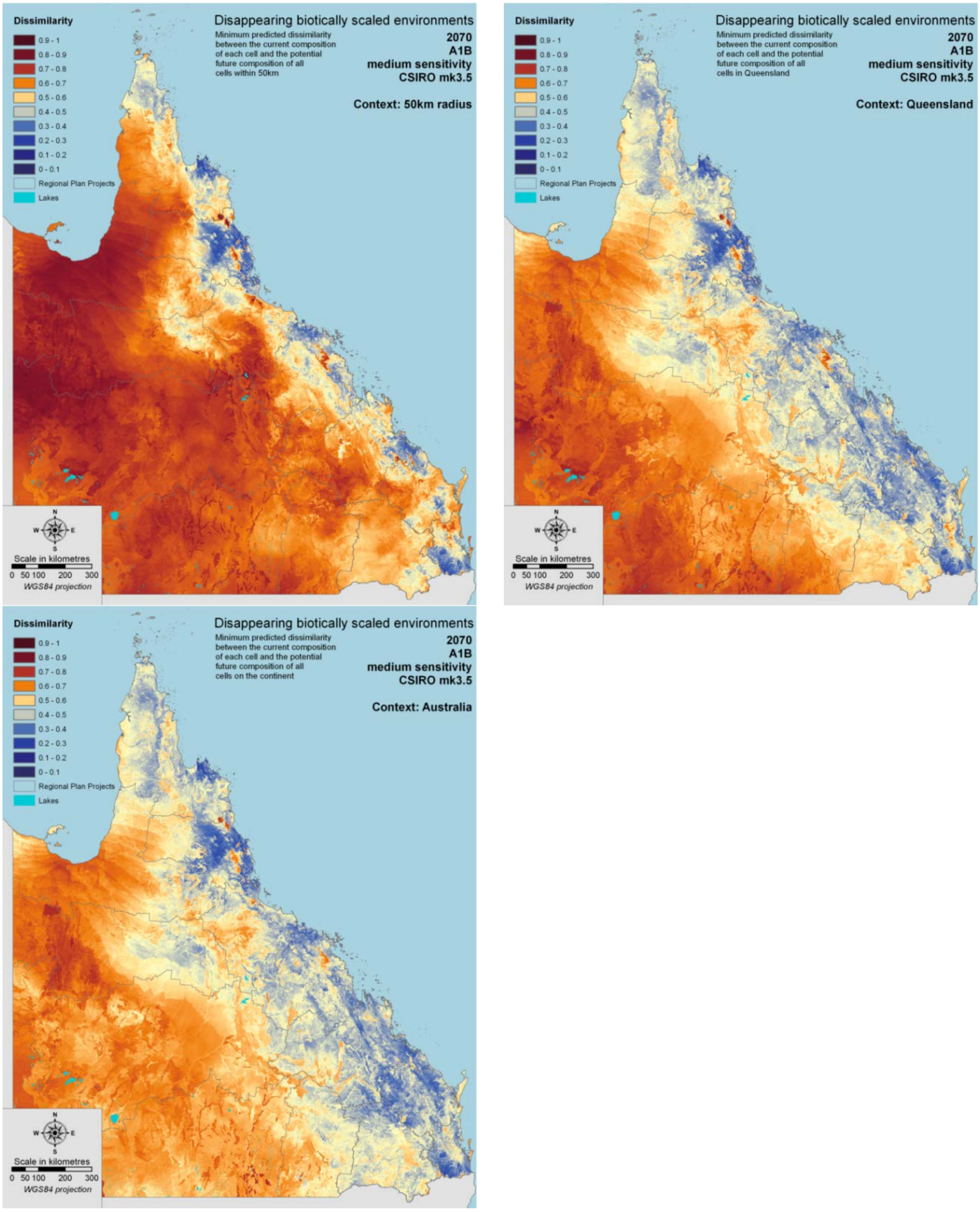

Figure 4: Potential distribution of disappearing environments under A1B climate scenario, for 2070 (scaled using modelling of species composition of vascular-plant communities, benchmarked using 1960-centred average climates), relative to three different spatial domains or contexts:1) a 50 km radius around each location; 2) all of Queensland; and all of Australia. Reddish-brown areas are those with current environments that are least likely to occur anywhere in a 50km radius (or in Queensland or in Australia, depending on the spatial domain employed) under this climate scenario, while environments in the blue areas are those most likely to be retained somewhere in the spatial domain. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

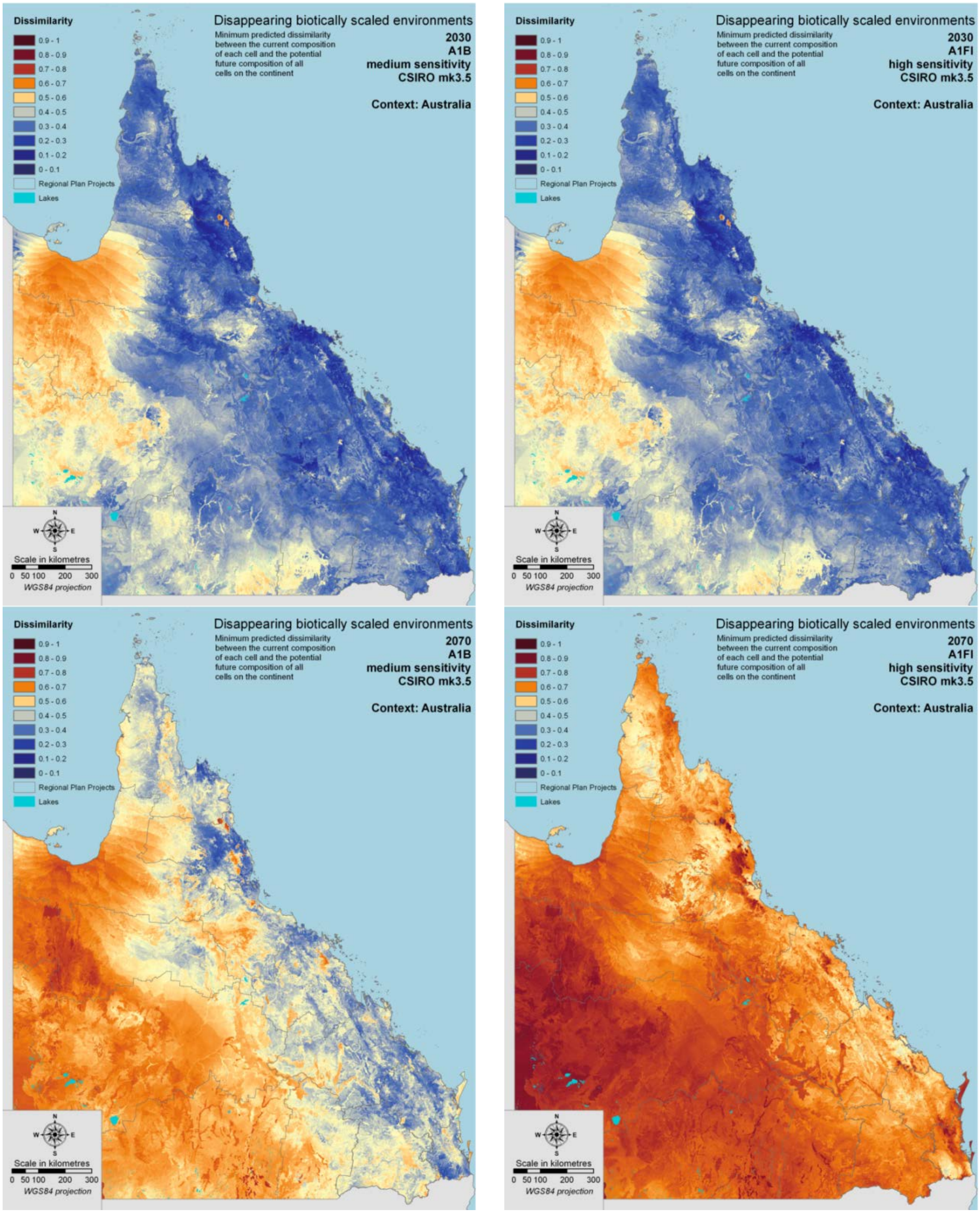

Figure 5: Potential distribution of disappearing environments for all climate scenarios in 2030 and 2070; scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). Brown areas are those with current environments that are least likely to occur anywhere in Australia under this scenario, while environments in the blue areas are those most likely to be retained somewhere on the continent. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

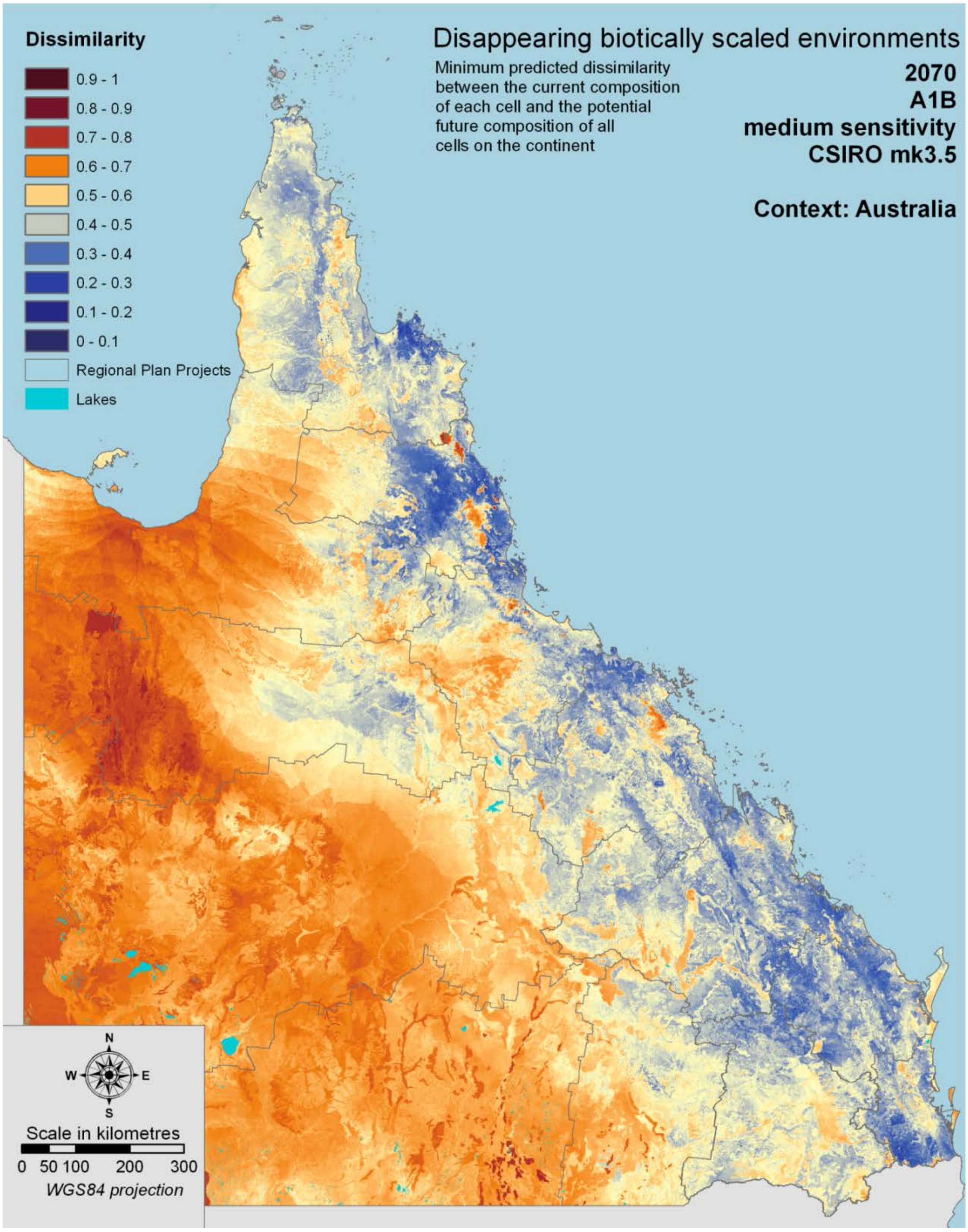

Figure 6: Potential distribution of disappearing environments under A1B scenario, in 2070 (enlarged map from Figure 5). Scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). Brown areas are those with current environments that are least likely to occur anywhere in Australia under this scenario, while environments in the blue areas are those most likely to be retained somewhere on the continent. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

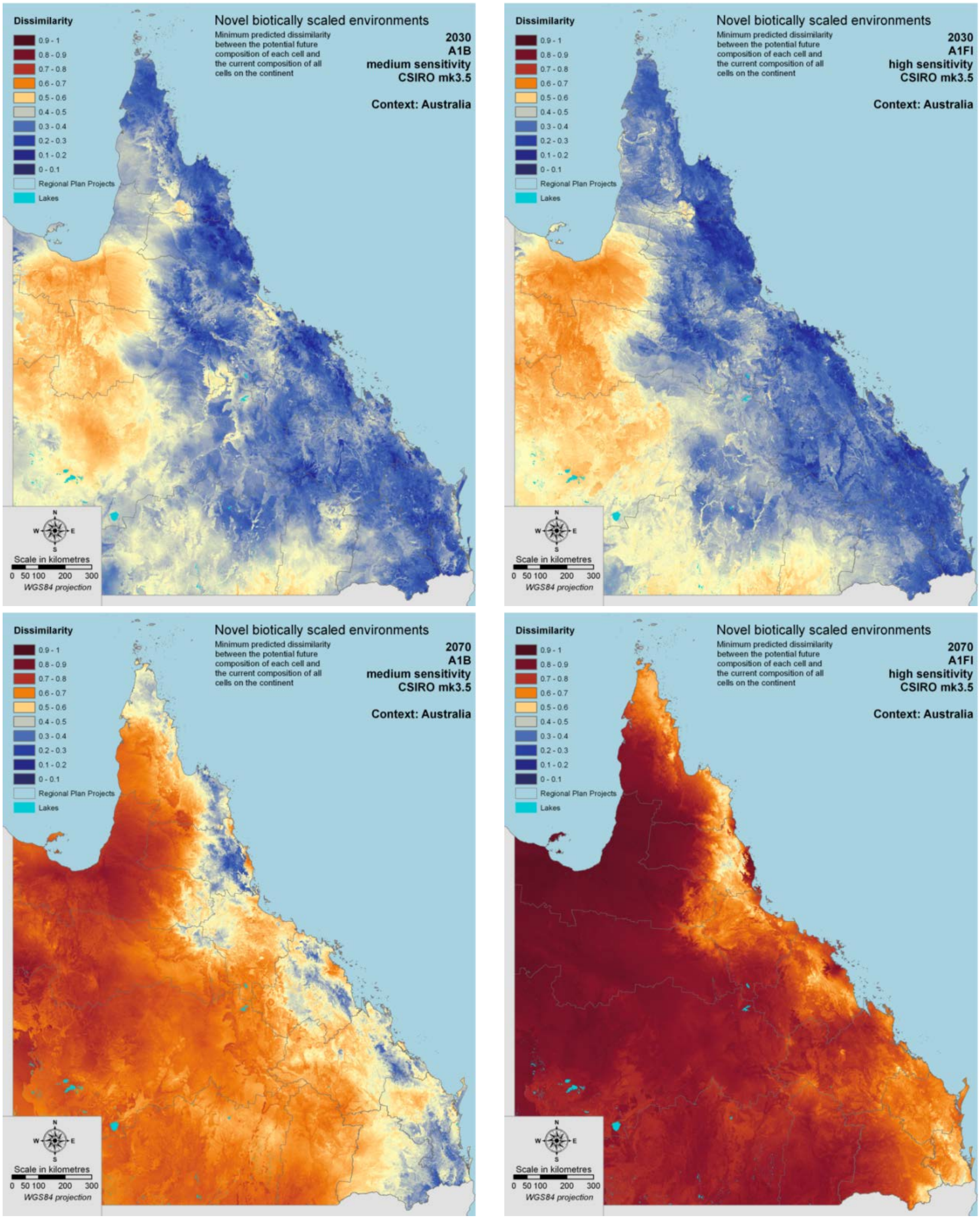

Figure 7: Potential distribution of novel environments for all climate scenarios in 2030 and 2070; scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). Brown areas are those most likely to support environments without any current analogue throughout Australia, while environments in the blue areas do have current analogues. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

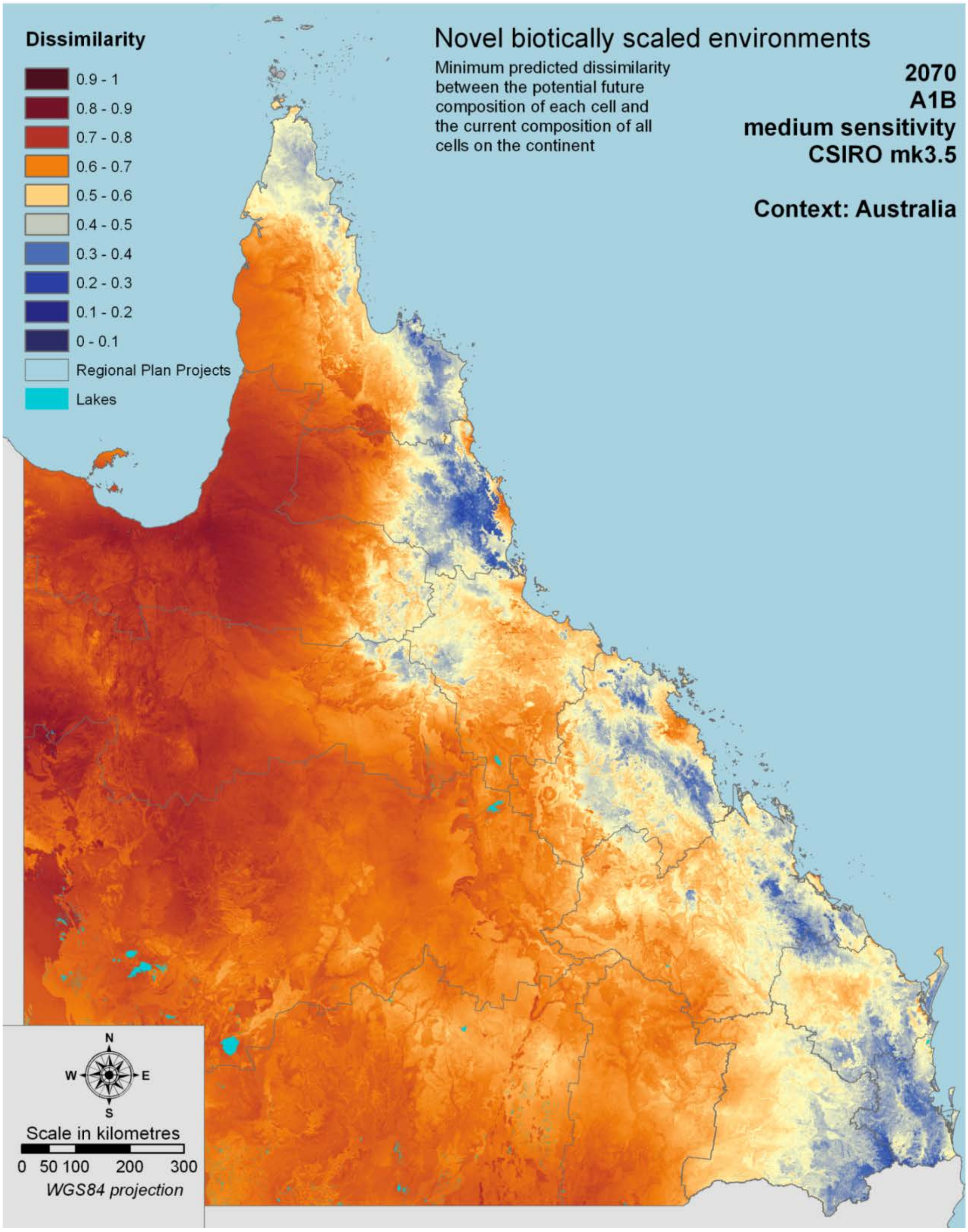

Figure 8: Potential distribution of novel environments under A1B climate scenario, in 2070 (enlarged map from Figure 7). Scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates)Brown areas are those most likely to support environments without any current analogue throughout Australia, while environments in the blue areas do have current analogues. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

5.3 Potential change in 'effective habitat area'

The assessment of disappearing ecological environments described in the previous section provides an indication, for each reference (or focal) cell, of how similar that cell's current environment is to the most similar environment projected for a given climate scenario, anywhere within a specified spatial domain; that is, either a 50km radius around the focal cell, all of Queensland or the entire continent. Here, we extend this assessment to consider change in the total extent (area) of environments similar to the focal cell, initially assuming intact environments (i.e., in "pristine" ecological condition). In the next section we consider the combined effect of environmental change and variation in ecological condition.

In this analysis the 'effective habitat area' for a given focal cell under present climatic conditions is simply a weighted sum of the areas of all cells within the specified spatial domain, where each of these cells is weighted according to the predicted similarity (the complement of dissimilarity: $s_{ij} = 1\text{-}d_{ij}$) between this cell and the focal cell (see Ferrier *et al.* 2004 for a detailed explanation of this concept; Allnutt *et al.* 2008). Thus, focal cells with environments similar to that of many other cells will be scored high, while cells that are relatively unique will be scored low. The effective habitat area for this same focal cell under a changed climate is derived by replacing the similarity values of s_{ij} used in this calculation with predicted levels of similarity between the future composition of cells within the specified domain and the current composition of the focal cell. This future effective habitat area is then expressed as a proportion of the current effective habitat area.

We conducted this analysis using two different spatial domains: 1) the whole of Queensland (Figure 9 and Figure 10); and 2) a 50 km radius around each focal cell (Figure 11). Note that in most cases, there is a greater magnitude of change in effective habitat area within a 50km radius around each focal cell than for the whole of Queensland. It is also worth noting the general similarity in spatial pattern between these maps and those of potential change within each cell (Figure 2 and Figure 3), although there are some important differences at finer spatial scales.

Most regions contain moderate areas of similar habitat up to 2030 for both scenarios but the two emission scenarios show sharp departures by 2070. Overall, there exist some hotspots of buffered habitat in coastal upland regions of the wet tropics, desert uplands, central Queensland and pockets of the elevated Scenic Rim in southern Queensland (a group of mountain ranges forming part of the Great Dividing Range), that are likely to retain their general character; but, under a high emissions scenario all habitats are becoming rare by 2070.

Some spatial artefacts are apparent in the underlying climatic predictor data associated with the monthly cut-off in rainfall, for example, that appear like dunes radiating out from the coast around the Gulf region.

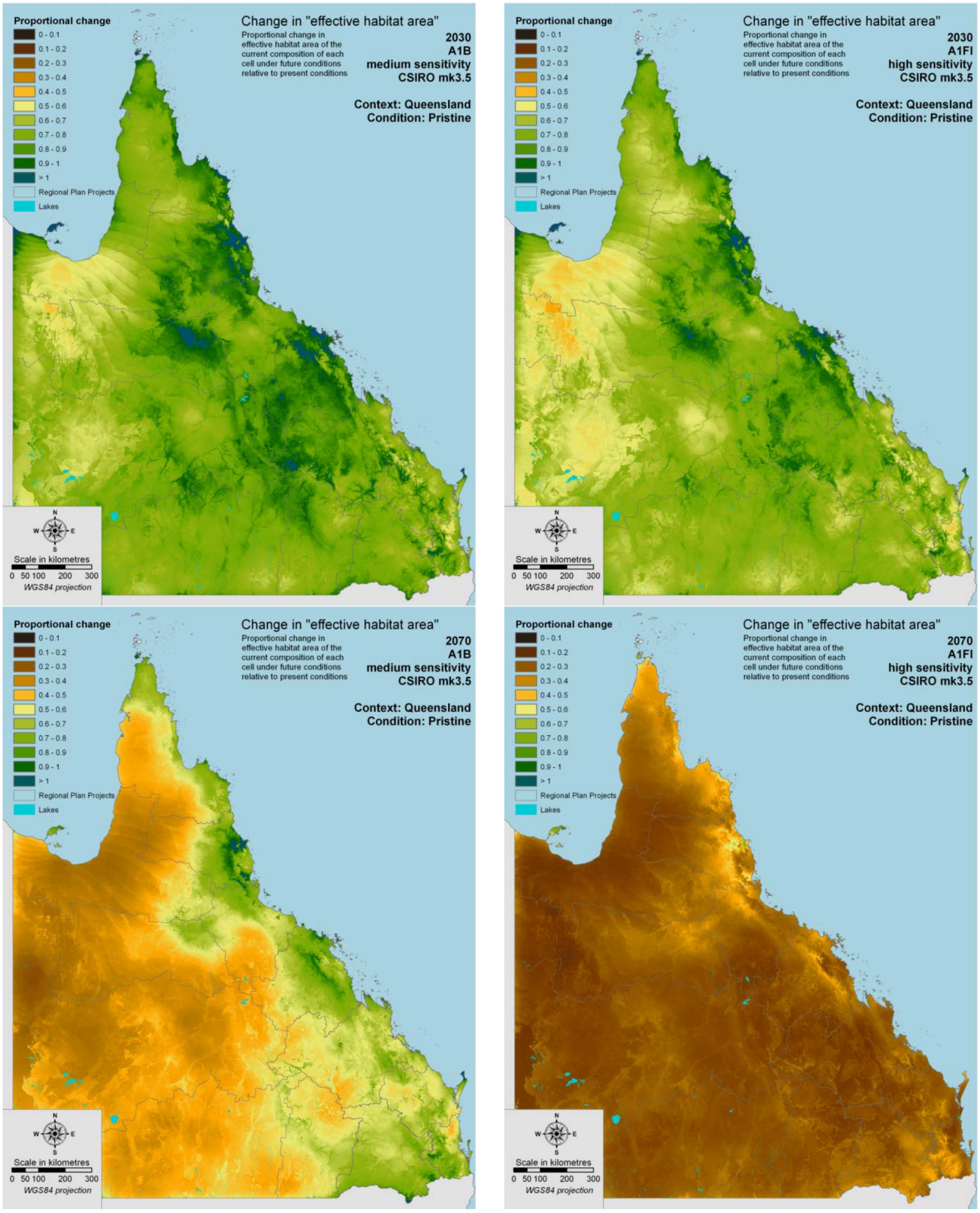

Figure 9: Potential change in effective habitat area, of ecologically-scaled environments, anywhere in Queensland, that are similar to the current environment of each focal grid-cell, for all climate scenarios. “Proportional change” is future effective habitat area expressed as a proportion of current effective habitat area. Green areas therefore show little change and brown areas a greater reduction in effective habitat area. Scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

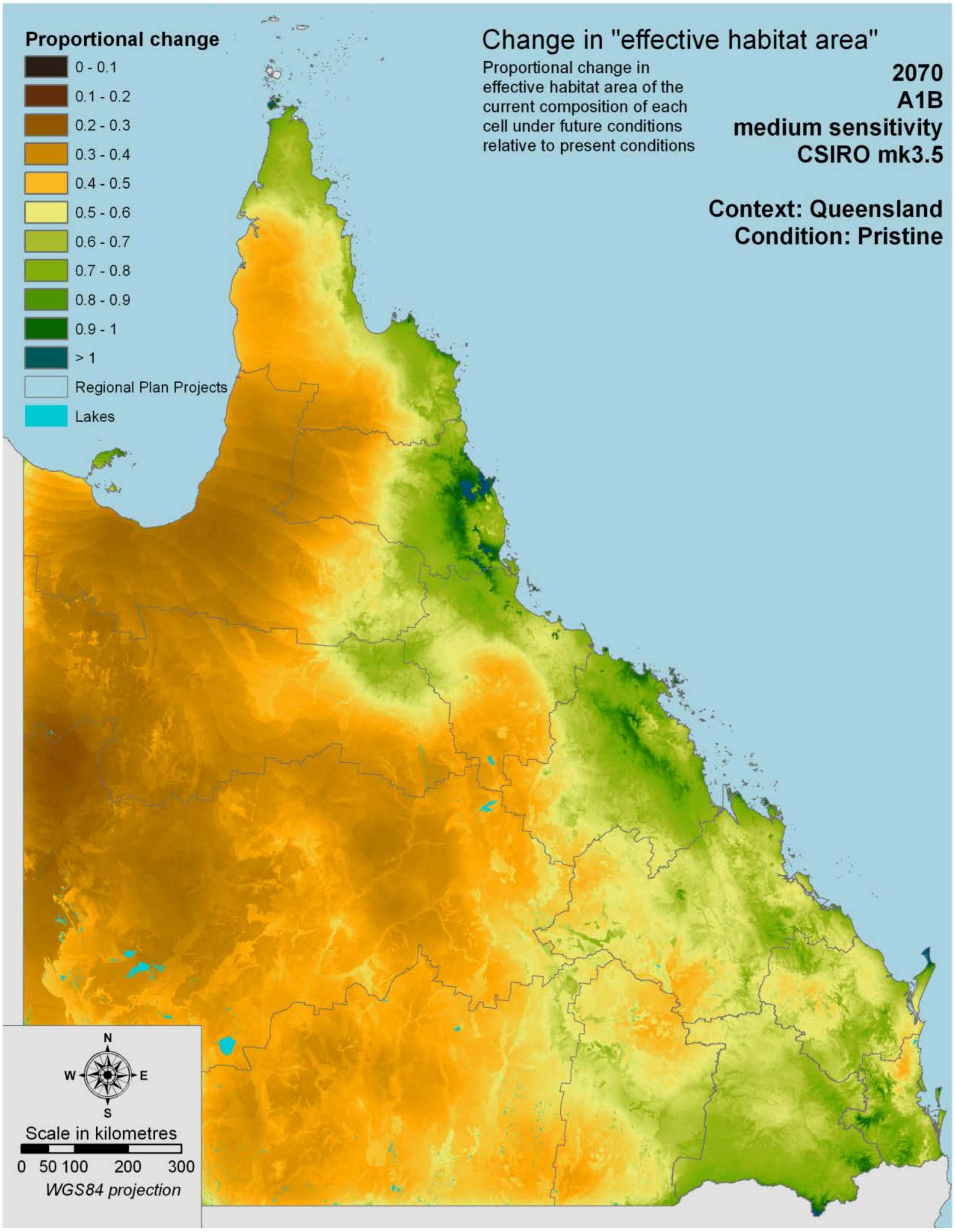

Figure 10: Potential change in effective habitat area, of ecologically-scaled environments, anywhere in Queensland, that are similar to the current environment of each focal grid-cell, for the 2070 A1B scenario. “Proportional change” is future effective habitat area expressed as a proportion of current effective habitat area. Green areas therefore show little change and brown areas a greater reduction in effective habitat area. Scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates).). This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

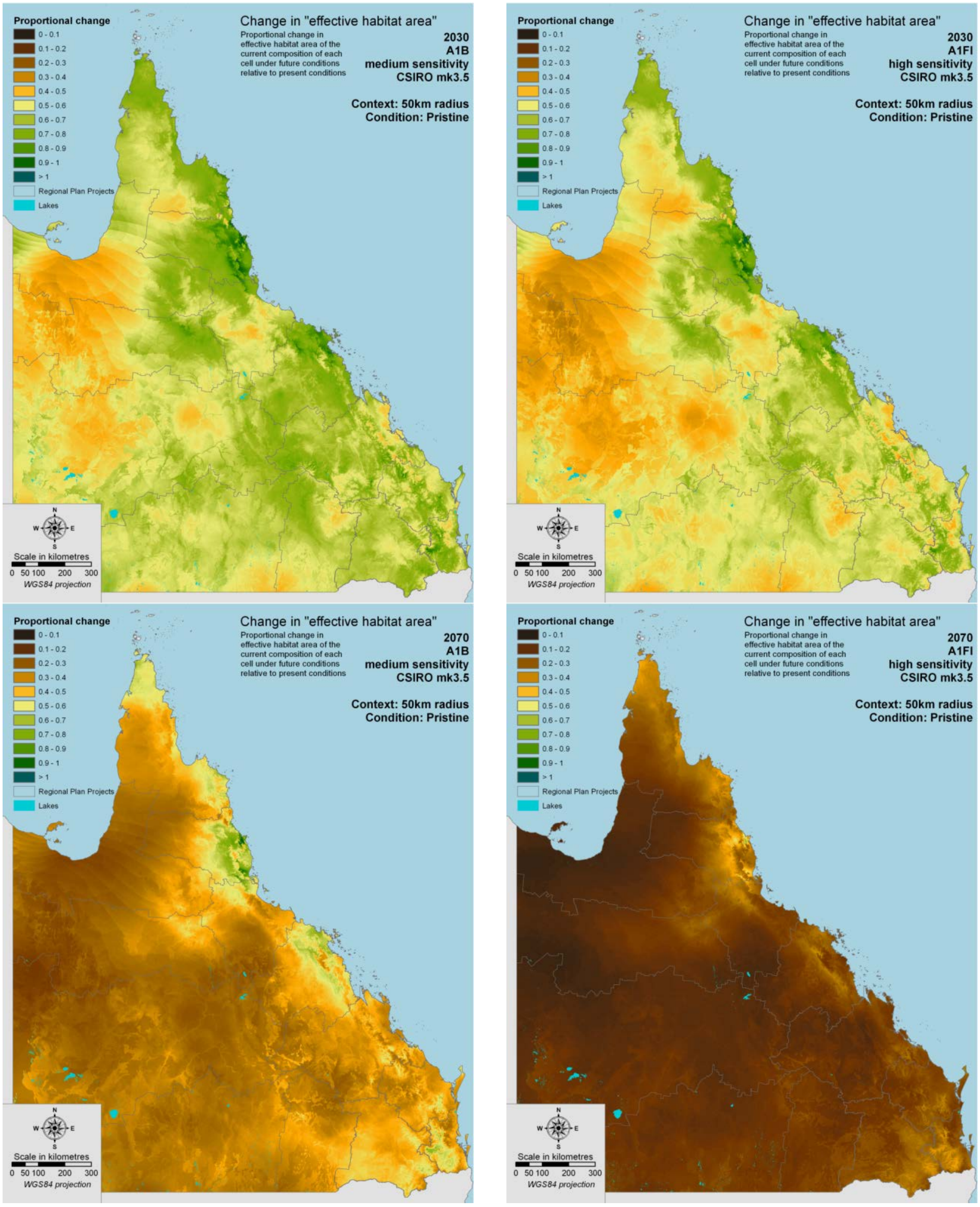

Figure 11: Potential change in effective habitat area, of ecologically-scaled environments—cells within 50km of the focal grid-cell that are similar to the current environment of that cell—for two climate scenarios in 2030 and 2070; scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). “Proportional change” is future effective habitat area expressed as a proportion of current effective habitat area. Green areas therefore show little change and brown areas a greater reduction in effective habitat area. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

5.4 Distance to the closest compositionally similar cell

In a further variant of the assessment of disappearing environments (Section 1.4.2) we estimated the distance from each focal cell to the nearest location in Queensland with a predicted compositional similarity of at least 0.5 (under a specified climate scenario), relative to the current environment of the focal cell. This provides an indication of how far species occurring in a given focal cell may need to move (disperse or migrate) to "find" an environment reasonably similar to the present environment of that cell. Whether or not these species actually need to move; or are capable of moving; will, however, depend on a range of additional factors not considered here (e.g., dispersal ability, biotic interactions, capacity for evolutionary adaptation).

The analysis was applied in two different ways: 1) by measuring the distance to the nearest similar location (under climate change), regardless of the land use of that location (i.e., assuming pristine vegetation condition throughout the State); and 2) by measuring the distance to the nearest similar location with remnant native vegetation (i.e., excluding cleared areas; see Figure 12). In some cases, the potential environmental change is so great that it is not possible to find a location with 0.5 predicted similarity to the focal cell anywhere within Queensland and these cells are therefore left blank in the mapped results presented here (Figure 13, Figure 14 and Figure 15).

Accessible similar habitat is almost non-existent for the high emission scenario (A1FI) by 2070 (Figure 13 and Figure 15). By 2030, the Gulf region, channel country and arid regions quickly become inaccessible and the pattern of accessible habitats moves eastwards toward the coastal mountain fringe of the Great Dividing Range to the tip of Cape York (Figure 13, Figure 14 and Figure 15). These effects are exacerbated when current levels of clearing are considered (Figure 15).

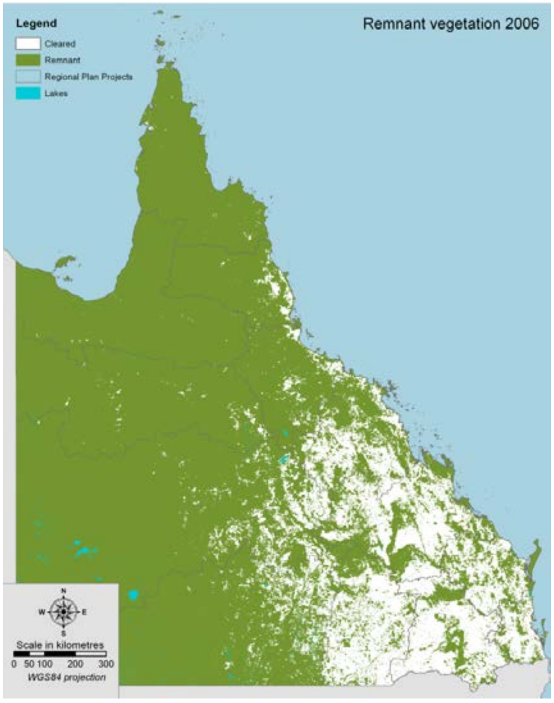

Figure 12: Remnant native vegetation (green) and cleared land (white) mask (0.01° grid) derived from 2006 Vegetation Cover of Queensland, Version 6.0b (Queensland Herbarium 2009). This mask was used to examine the current and future effects of land clearance and the potential outcomes of revegetation (see Figure 15, Figure 19, Figure 20 and Figure 25).

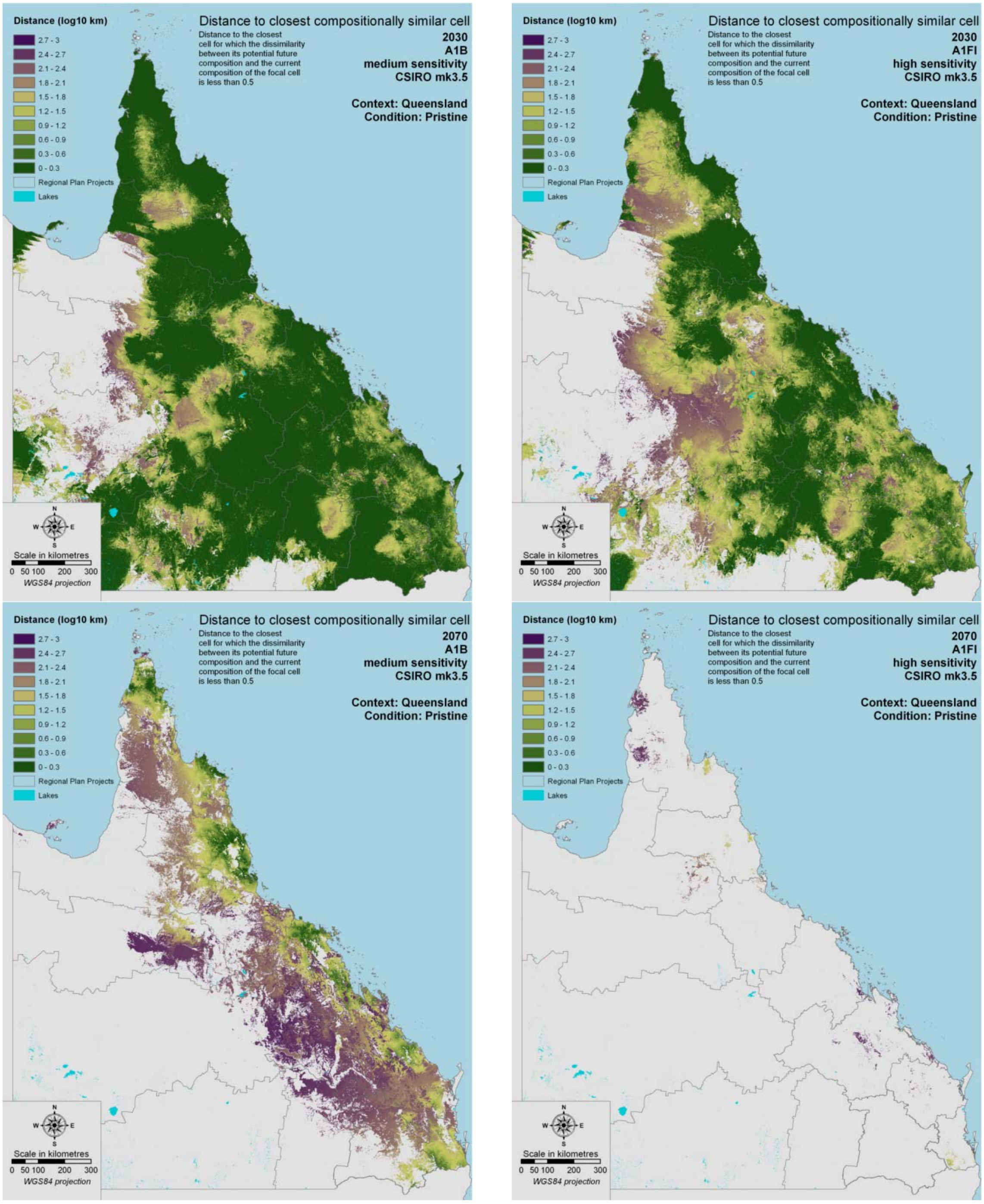

Figure 13: Distance to the closest location predicted to have a similar bioclimate in the future to the current bioclimate of the focal grid-cell (greater than 50% potential compositional similarity), for all climate scenarios in 2030 and 2070; scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). Note use of a log10 scale, such that a value of 1, 2 or three is equivalent to 10, 100 and 1000 km respectively. Where no similar bioclimate could be located anywhere in Queensland, the map is shaded pale grey. Green areas are those with similar bioclimates within 10km. Darker pink indicates longer distances to a similar bioclimate. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

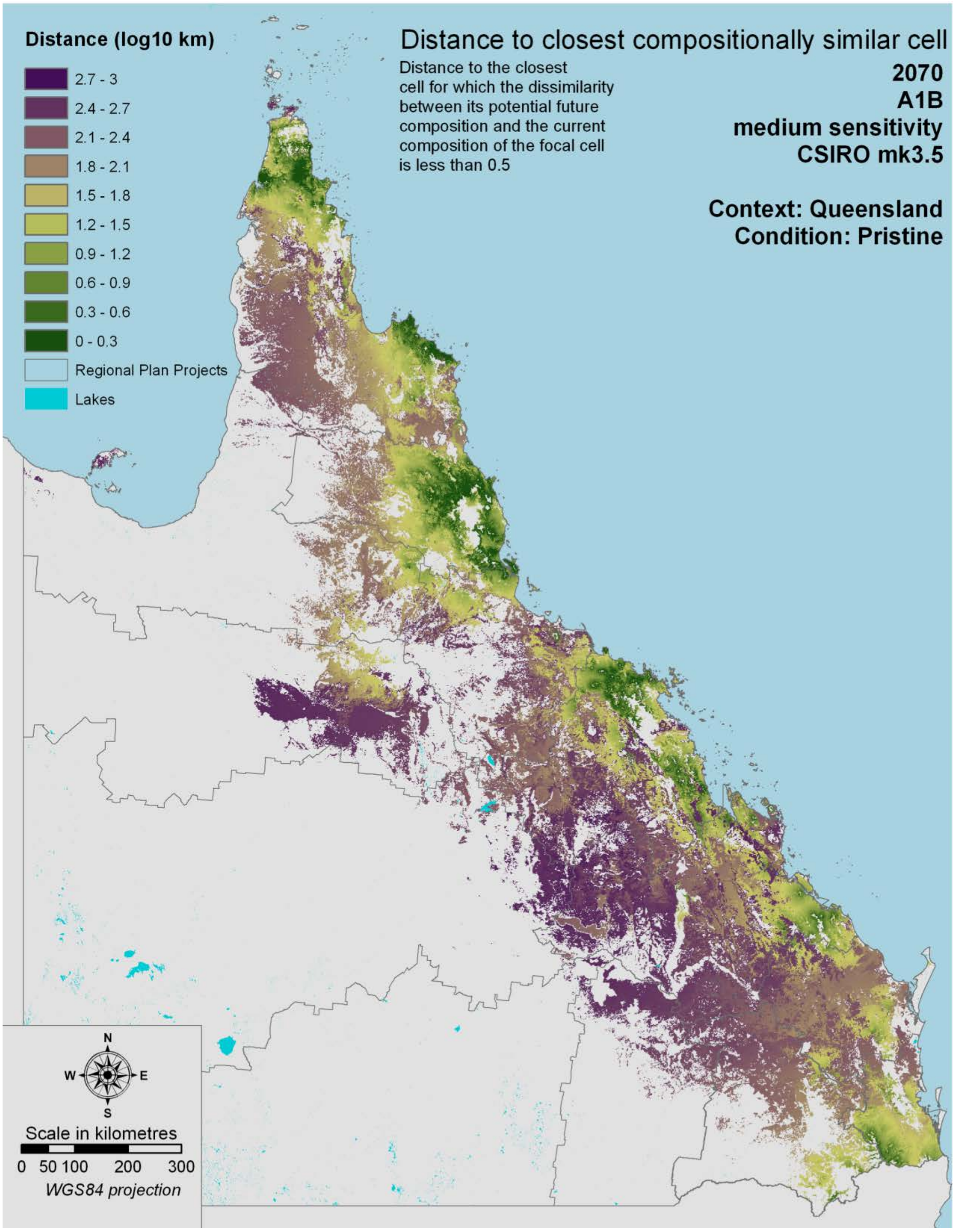

Figure 14: Distance to the closest location predicted to have a similar bioclimate in the future to the current bioclimate of the focal grid-cell (greater than 50% potential compositional similarity), for the 2070 A1B scenario; scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). Note use of a log10 scale, such that a value of 1, 2 or three is equivalent to 10, 100 and 1000 km respectively. Where no similar bioclimate could be located anywhere in Queensland, the map is shaded pale grey. Green areas are those with similar bioclimates within 10km. Darker pink indicates longer distances to a similar bioclimate. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

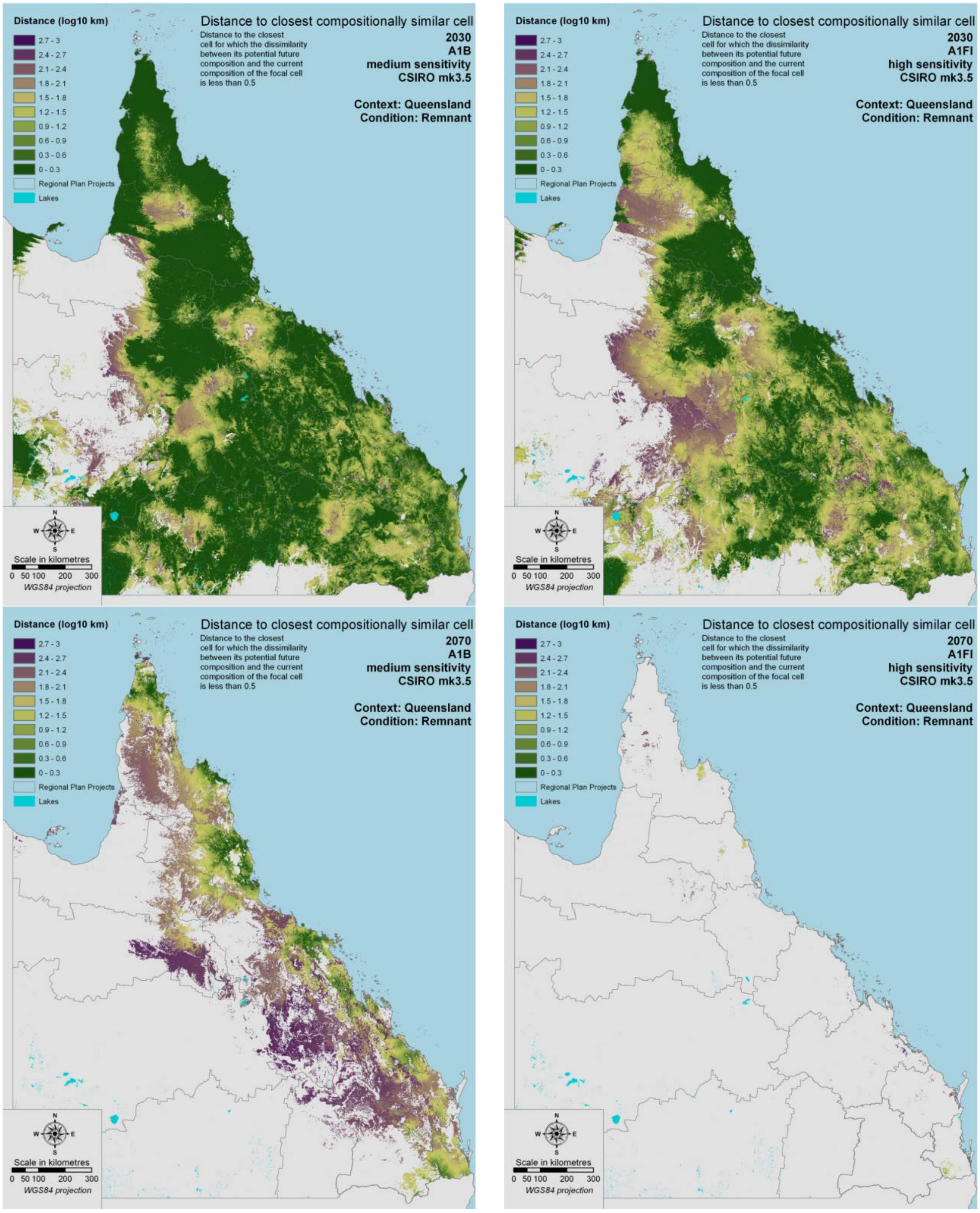

Figure 15: Distance to the closest location, *with uncleared (extant) natural vegetation*, predicted to have a similar bioclimate in the future to the current bioclimate of the focal grid-cell (greater than 50% potential compositional similarity), for all climate scenarios in 2030 and 2070; scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). Note use of a log10 scale, such that a value of 1, 2 or three is equivalent to 10, 100 and 1000 km respectively. Where no similar bioclimate could be located anywhere in Queensland, the map is shaded pale grey. Green areas are those with similar bioclimates within 10km. Darker pink indicates longer distances to a similar bioclimate. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

5.5 Potential benefit of adaptation management actions enhancing or assisting, long-distance migration / colonisation

We are also trialling two new GDM-based indices designed to more directly inform thinking about priorities for applying different types of adaptation management in different parts of the continent. These indices are at an experimental stage of development but the initial results presented here for Queensland aim to provide an indication of the potential value that could be derived through further refinement and application of this general approach.

The first of these two "adaptation indices" aims to assess the potential benefit of adaptation management actions aimed at enhancing or assisting, long-distance migration / colonisation. For example, actions, such as establishment of large-scale (long-distance) habitat corridors or assisted colonisation (translocation). This index is derived by integrating two variants of the "disappearing environments" measure described in Section 3.2: the dissimilarity (0 to 1) between the present ecologically-scaled environment of the reference (or focal) cell and the most similar future environment, under a given climate scenario, of any cell within a 50km radius of the focal cell (this dissimilarity is here denoted as D_{R50}); and 2) the dissimilarity between the present environment of the focal cell and the most similar future environment anywhere in Queensland (here denoted as D_Q). The index is then calculated as:

$$(D_{R50} - D_Q)D_{R50}$$

This analysis was applied in two different ways: 1) by measuring D_{R50} and D_Q in relation to the most similar cell to the focal cell, regardless of the present or future land use of that location (results presented in Figure 16 and Figure 17); and 2) by measuring D_{R50} and D_Q in relation to the most similar cell with remnant native vegetation (i.e., excluding cleared areas; results presented in Figure 18). Remnant vegetation in this context follows the Queensland definition (Neldner *et al.* 2005) and applies a mask generated from the 2006 vegetation cover dataset (Queensland Herbarium 2009) (Figure 12).

Places (focal cells) with low values for the index (the darker green areas in Figure 16, Figure 17 and Figure 18) are those that either have a low value for D_{R50} (i.e., there is at least one location within a 50km radius with a future environment similar to that of the present environment of the focal cell) or have a low value for D_{R50} - D_Q (i.e., there is little difference between the dissimilarity of the focal cell's present environment and the future environment of the most similar location in a 50km radius *versus* the most similar location anywhere in Queensland) or both.

Places with high values for the index (the darker pink areas in Figure 16, Figure 17 and Figure 18) are those that have a relatively high value for D_{R50} (i.e., no location within a 50km radius has a future environment similar to that of the present environment of the focal cell) and a relatively high value for D_{R50} - D_Q (i.e., there is at least one location elsewhere in Queensland, beyond 50km, with a future environment more similar to that of the present environment of the focal cell). These places are indicative of the most potential benefit to be gained from adaptation management actions aimed at enhancing dispersal.

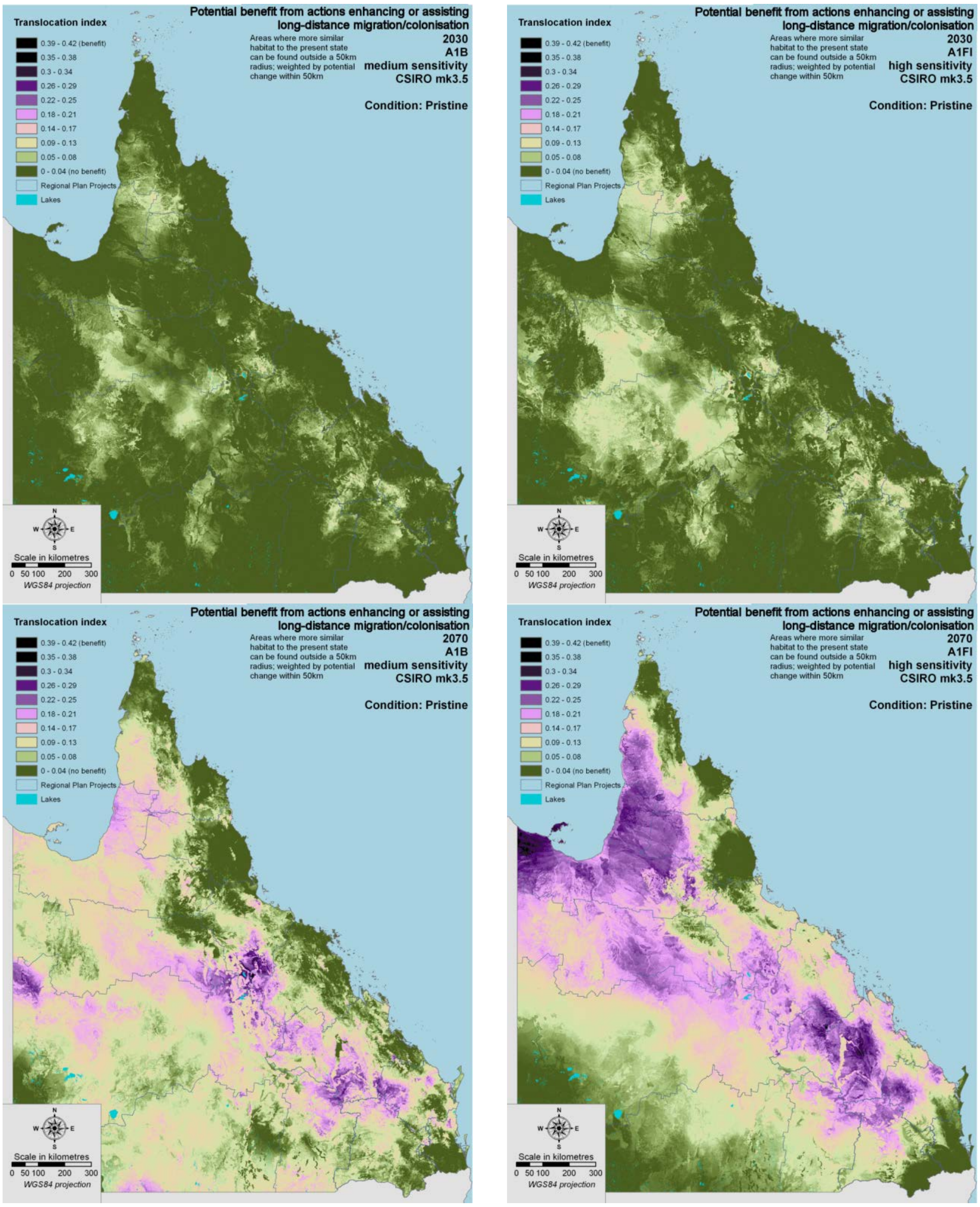

Figure 16: Index of potential benefit of adaptation management actions enhancing or assisting, long-distance migration / colonisation, for two climate scenarios in 2030 and 2070; scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). Benefit here assumes all ecosystems are in “pristine” or original, intact condition. This is a *trial approach* to identifying areas likely to benefit from actions, such as enhancement of broad-scale (long-distance) habitat connectivity or assisted colonisation. See text for detail on the derivation of this index. Green areas are those which are likely to benefit least from actions enhancing or assisting long-distance, migration / colonisation, while pink areas those likely to benefit most. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

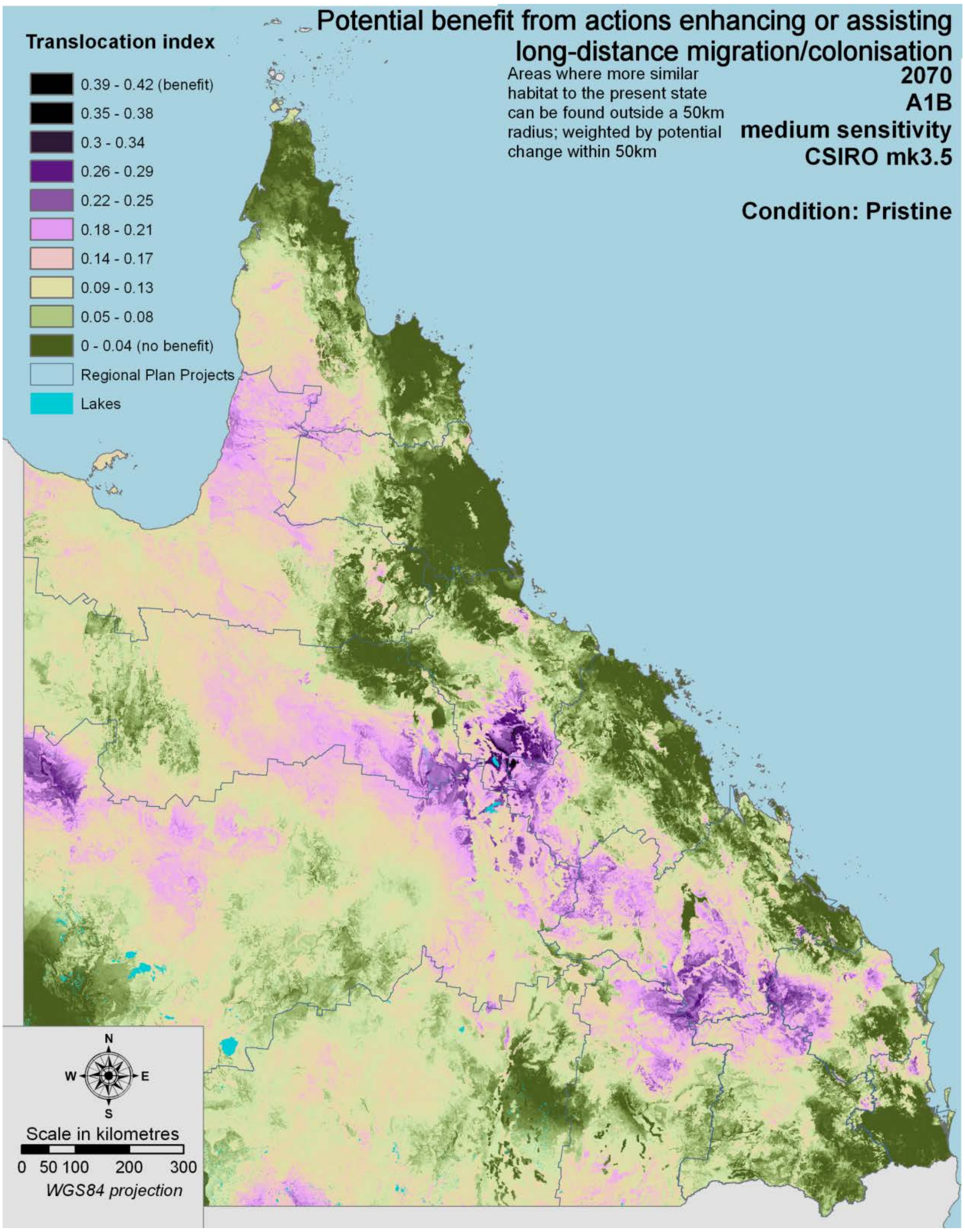

Figure 17: Index of potential benefit of adaptation management actions enhancing or assisting, long-distance migration / colonisation, for the 2070 A1B scenario; scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). Benefit here assumes all ecosystems are in "pristine" or original, intact condition. This is a *trial approach* to identifying areas likely to benefit from actions, such as enhancement of broad-scale (long-distance) habitat connectivity or assisted colonisation. See text for detail on the derivation of this index. Green areas are those which are likely to benefit least from actions enhancing or assisting long-distance, migration / colonisation, while pink areas those likely to benefit most. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

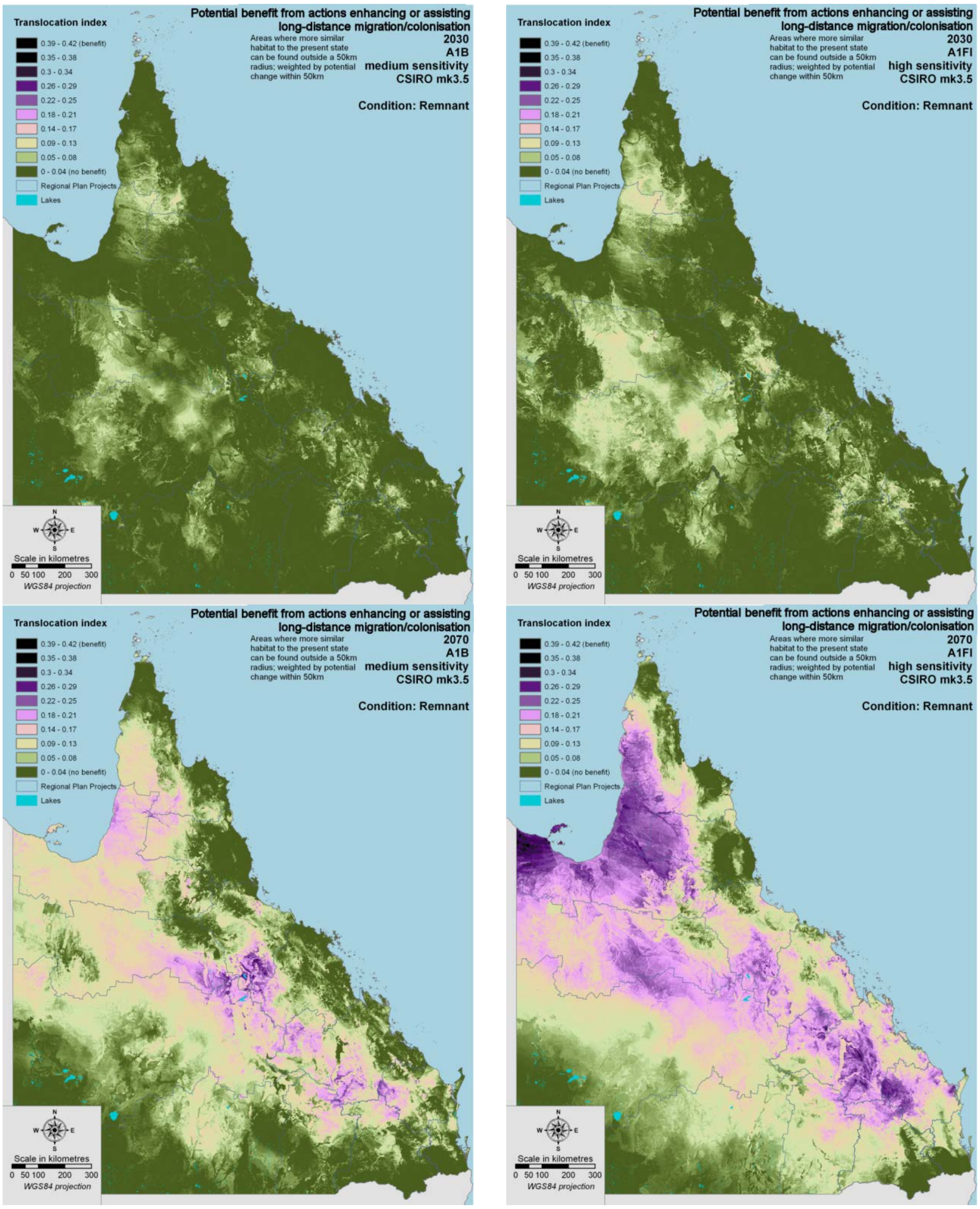

Figure 18: Index of potential benefit of adaptation management actions enhancing or assisting, long-distance migration / colonisation, for two climate scenarios in 2030 and 2070; scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). *Here (unlike Figure 16 and Figure 17) the index has been derived using only those grid-cells with uncleared (extant) native vegetation.* This is a *trial approach* to identifying areas likely to benefit from actions, such as enhancement of broad-scale (long-distance) habitat connectivity or assisted colonisation. See text for detail on the derivation of this index. Green areas are those which are likely to benefit least from actions enhancing or assisting long-distance, migration / colonisation, while pink areas those likely to benefit most. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

5.6 Potential benefit of adaptation management actions restoring cleared or degraded native habitat in local landscapes

The second of the two “adaptation indices” trialled here for Queensland aims to assess the potential benefit of adaptation management actions in restoring cleared or degraded native habitat in local landscapes; for example, activities enhancing the extent, condition and local (short-distance) connectivity of native vegetation. This index is derived by integrating two variants of the D_{R50} measure introduced in Section 3.5: a “pristine” version estimating the dissimilarity between the present environment of the focal cell and the most similar future environment within a 50km radius, regardless of land use and a “remnant” version estimating the dissimilarity in relation to the most similar future environment only for those cells with remnant native vegetation (i.e., excluding cleared areas as shown in Figure 12). The index is then calculated as:

$$\left(D_{R50}^{\mathrm{Re}\,mnant} - D_{R50}^{\mathrm{Pr}\,istine}\right) D_{R50}^{\mathrm{Re}\,mnant}$$

In Figure 19 and Figure 20 the index is mapped only for focal cells that are themselves covered by remnant native vegetation. Focal cells with low values for the index (the whiter areas in Figure 19 and Figure 20) either have a present environment similar to the future environment of a remnant vegetation cell somewhere within the 50km radius or this similarity is not increased by including non-remnant (i.e., currently cleared) cells in the analysis or both. Focal cells with high values for the index (the redder areas in Figure 19 and Figure 20) are those that have a relatively high value for the remnant version of D_{50} (i.e., no vegetated location within a 50km radius has a future environment similar to that of the present environment of the focal cell) and a relatively high value for the difference between the remnant and pristine versions of D_{50} (i.e., there is at least one currently-cleared location within 50km, with a future environment more similar to that of the present environment of the focal cell).

The index presently distinguishes cleared and remnant habitats and could be extended to include levels of degradation of remnant habitats and, likewise, the capacity to establish native vegetation given different intensities of land use; both, where suitable data exist. Other criteria related to existing land use and the practical realities of restoration ecology will help determine the relative cost/benefit of different locations; thereby narrowing the scope for action.

This index can therefore be used, in conjunction with other information, to indicate where the most potential benefit can be gained from adaptation management actions aimed at restoring degraded native habitats.

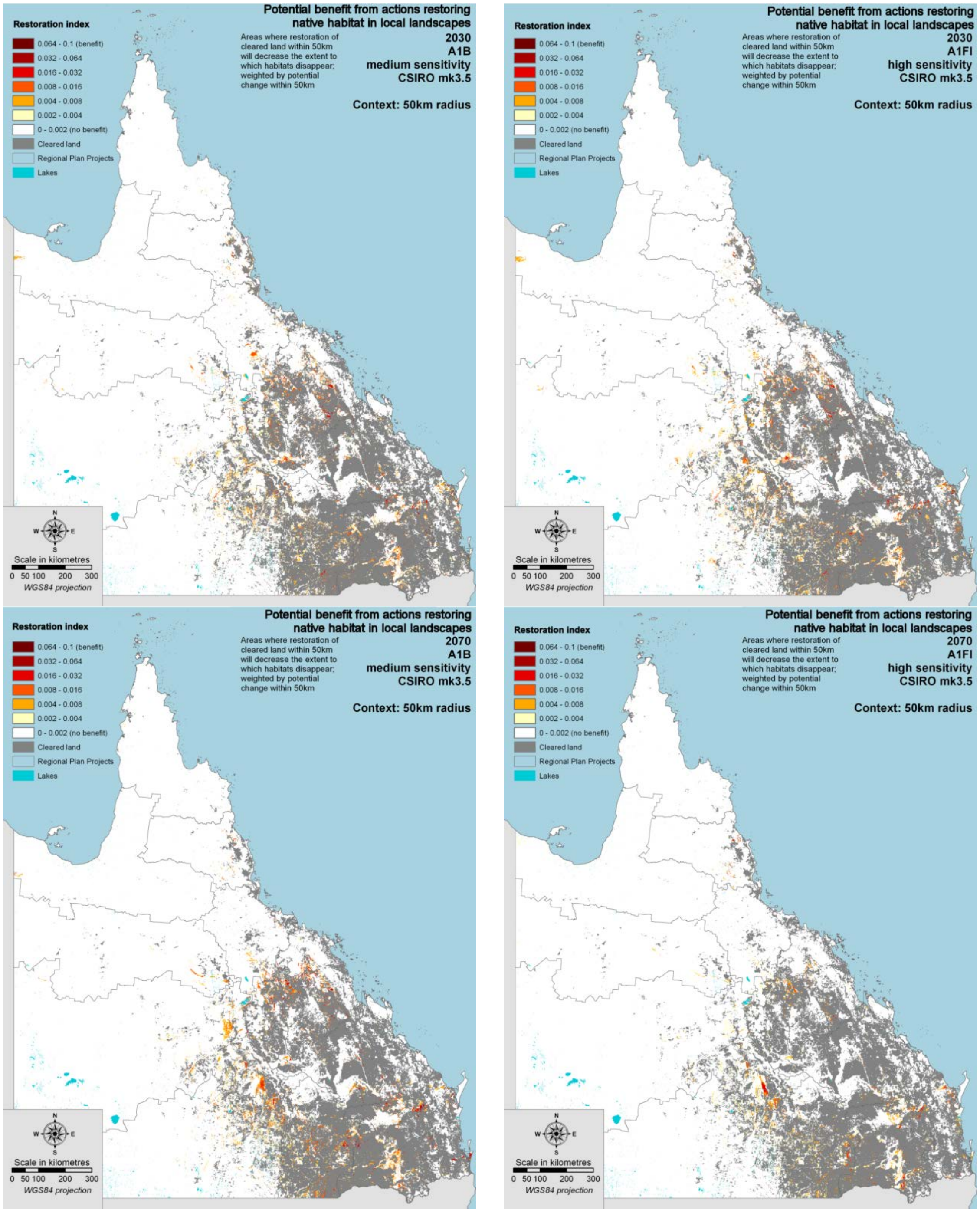

Figure 19: Index of potential benefit of adaptation management actions restoring cleared or degraded native habitat in local landscapes, for all climate scenarios in 2030 and 2070; scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). This is a *trial approach* to identifying areas of remnant native vegetation that are likely to benefit most from restoration of cleared land in the surrounding landscape (50km radius). These areas are depicted in orange and red on the map, with cleared land shown in grey. See text for detail on the derivation of this index. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

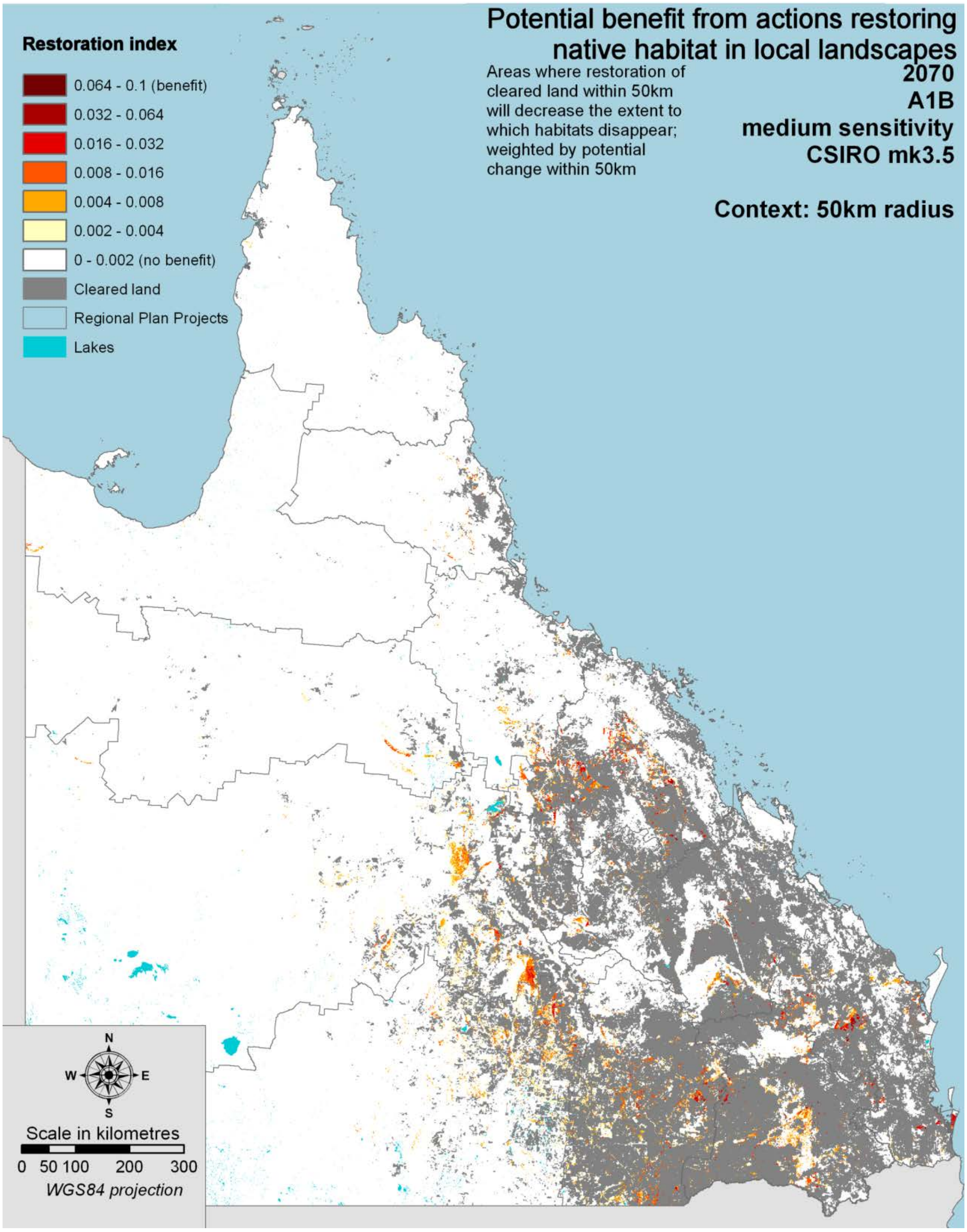

Figure 20: Index of potential benefit of adaptation management actions restoring cleared or degraded native habitat in local landscapes, for the 2070 A1B scenario; scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). This is a *trial approach* to identifying areas of remnant native vegetation that are likely to benefit most from restoration of cleared land in the surrounding landscape (50km radius). These areas are depicted in orange and red on the map, with cleared land shown in grey. See text for detail on the derivation of this index. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

5.7 Projected change in the distribution of ecologically scaled environments – an example

Most of the analyses presented in earlier sections of this report provide information on how much change might be expected in ecologically-scaled environments and how far these environments might move geographically but shed little light on precisely where a given environment will move to or where there are present environments similar to that projected for a given place under climate change. Here we trial a new variant of our GDM-based analysis aimed at addressing these questions and illustrate the approach using a single Queensland bioregional sub-region (SEQ2, the Moreton Basin), derived from the *Interim Biogeographic Regionalisation for Australia* (IBRA version 6.1, DEWHA 2004). This approach could, in the future, be applied to any Queensland region or sub-region (or, indeed, any other defined place; for example, a particular mapped ecosystem type).

The bioregion classification includes a strong biophysical component so we should expect a degree of homogeneity of environmental conditions within a small sub-region. Our analysis compares each and every cell throughout the continent to each cell within the Moreton Basin. The similarity to the most similar cell within the study region is recorded for each cell on the continent. Low values (pale colours) indicate that there are no similar cells within the Moreton Basin. Higher values (greens) indicate that there is at least one cell within the Moreton Basin which is similar. Several points should be noted here. First, the value gives no indication of the extent (area) of similar environment within the Moreton Basin. Second, it must be stressed that this analysis depicts only similarities in and potential shifts in the distribution of, ecologically-scaled environments or "bioclimates". This analysis could be coupled with the analysis of effective habitat areas shown in Section 3.3. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation).

Use of different time combinations enables visualisation of different aspects of potential change in the bioclimate of the Moreton Basin subregion. Figure 21 shows the distribution of environments similar to the Moreton Basin (SEQ2) in the present (based on modelled dissimilarity of vascular-plant composition, benchmarked using 1960-centred average climates). The green areas on the map become visible at a similarity of 0.4, implying around 40% species in common. Moving to Figure 22, which shows the distribution of these same bioclimates in the projected state of 2070 (A1B, medium climatic sensitivity), we can first note a contraction of the total area of similar climates. Figure 22 may also be interpreted as providing an indication of where suitable bioclimates for species and ecological communities presently found in the Moreton Basin may occur in the future. The final analysis (Figure 23) depicts areas with current environmental conditions similar to those projected for the Moreton Basin in the future.

While the rate and extent of the effect of regional climate change on biodiversity is difficult to predict, this can be visualised with the aid of ecological models showing how regional environmental conditions may change, in light of their past and future analogues. More specific ecosystem scenarios could usefully test ecological understanding and provide a framework for identifying hotspots of change over time and where monitoring could provide early warning signals for adaptive management responses.

These figures provide context for describing the possible ways species and ecosystems may respond to climate change (Box 1). For example, looking forward (Figure 22), one might consider whether the distance and direction of change over time is within the capacity of species to migrate – tracking their envelope of suitable conditions. If barriers exist (such as land clearing or mountain ranges), one might consider the ethics of appropriate translocation and explore custom analyses that account for the limits to dispersal under natural (non-climate change) conditions. Looking backward (Figure 23), one might consider the potential for invasion by migrating species—native or alien—and whether these may negatively influence local natural heritage values. Ethical considerations again determine which goals of management apply to balance competing values and continuing change. More specific species- or ecosystem-focussed scenarios, visualised in this way, could support the testing of ecological understanding in developing a framework for identifying hotspots of change over time, where monitoring could provide early warning signals for adaptive management responses.

Box 2: Projected environmental analogues – a narrative of how regional environmental conditions may lead to observable ecological change.

Here we provide a commentary on what types of ecological responses might be observed if we were living in the Moreton Basin subregion of South East Queensland. The current suite of environmental conditions associated with the subregion has occurrences with varying levels of similarity that radiate geographically in close proximity (e.g., Figure 21). By 2070, these environmental conditions could have shifted and contracted southward and to higher elevations. They appear spread across the New England Tableland and Nandewar bioregions of northern New South Wales (e.g., Figure 22). The future environmental conditions are less similar to the current environments because the available combinations of future climate, and existing substrate and terrain in this new region are different. Higher levels of similarity characterise places more like the Moreton Basin subregion and lower levels of similarity indicate places less like that subregion. These upland plateau and mountain regions of northern New South Wales, in part connected to Moreton Basin through the Border Ranges, appear to offer habitats that are potentially within the range of environmental conditions of migrating species, assuming capacity for movements of 100km or more over the 100 years since 1960. For some species the rugged terrain represents a significant barrier to movement and assisted migration may be necessary for the species to persist. Cleared areas occupied by other land use (not shown in the figures) may also preclude establishment by species once they arrive at a destination.

By 2070, the environment of the Moreton Basin subregion has changed. These new conditions appear to be similar to those today in northern parts of the South East Queensland bioregion and the northern and coastward parts of the Brigalow Belt subregions (e.g., Figure 21). The future combination of environmental conditions associated with the Moreton Basin subregion is not completely unlike the present combination of environments (e.g., compare Figure 21 and Figure 23). Many species that presently make up the ecosystems of Moreton Basin may be expected to remain, if also able to tolerate the generally drier and warmer conditions or find refuge in cooler microhabitats. However, some species abundances and geographic ranges will have contracted sharply, and species dominance may also have changed. These changes will affect the appearance, structure and function of ecosystem. Some species will not be able to survive *in situ* and, if they are unable to migrate with the decadal drift in climatic conditions, may need intervention or be allowed to go extinct. Remaining species will also need to contend with competition from formerly low density co-occurring species that sharply increase in abundance and begin to dominate. These may be species that previously were at the southern margins of their geographic ranges that now find themselves located in more suitable habitat. Refuges become contested locations for establishment and survival. Increasing numbers of vagrants, moving southward from their northern habitats, are starting to occupy spaces that are now only loosely held by the former resident species. Some of these invading species may be alien to Australia, expanding from nearby gardens and farmlands and naturalising in the surrounding hills. While others are natives, potentially displaced by the relatively inhospitable environment of their normal habitat, but only a few have the capacity to reach new places and establish in more suitable habitats.

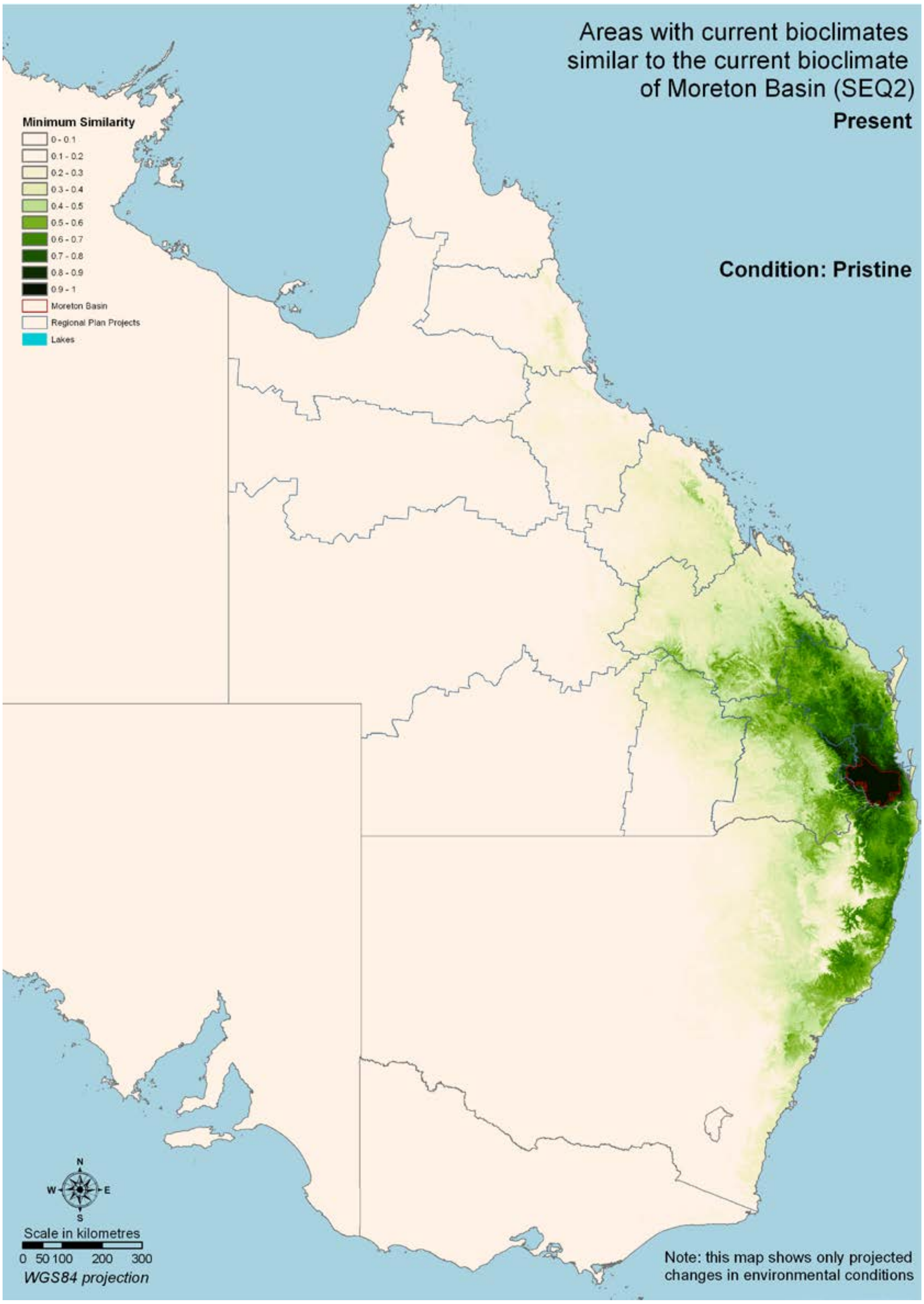

Figure 21: Areas with current bioclimates similar to the current bioclimate of the Moreton Basin (based on modelled dissimilarity of vascular-plant composition benchmarked using 1960-centred average climates). Darker green areas have increasingly similar environments. Compare with Figure 22 and Figure 23.

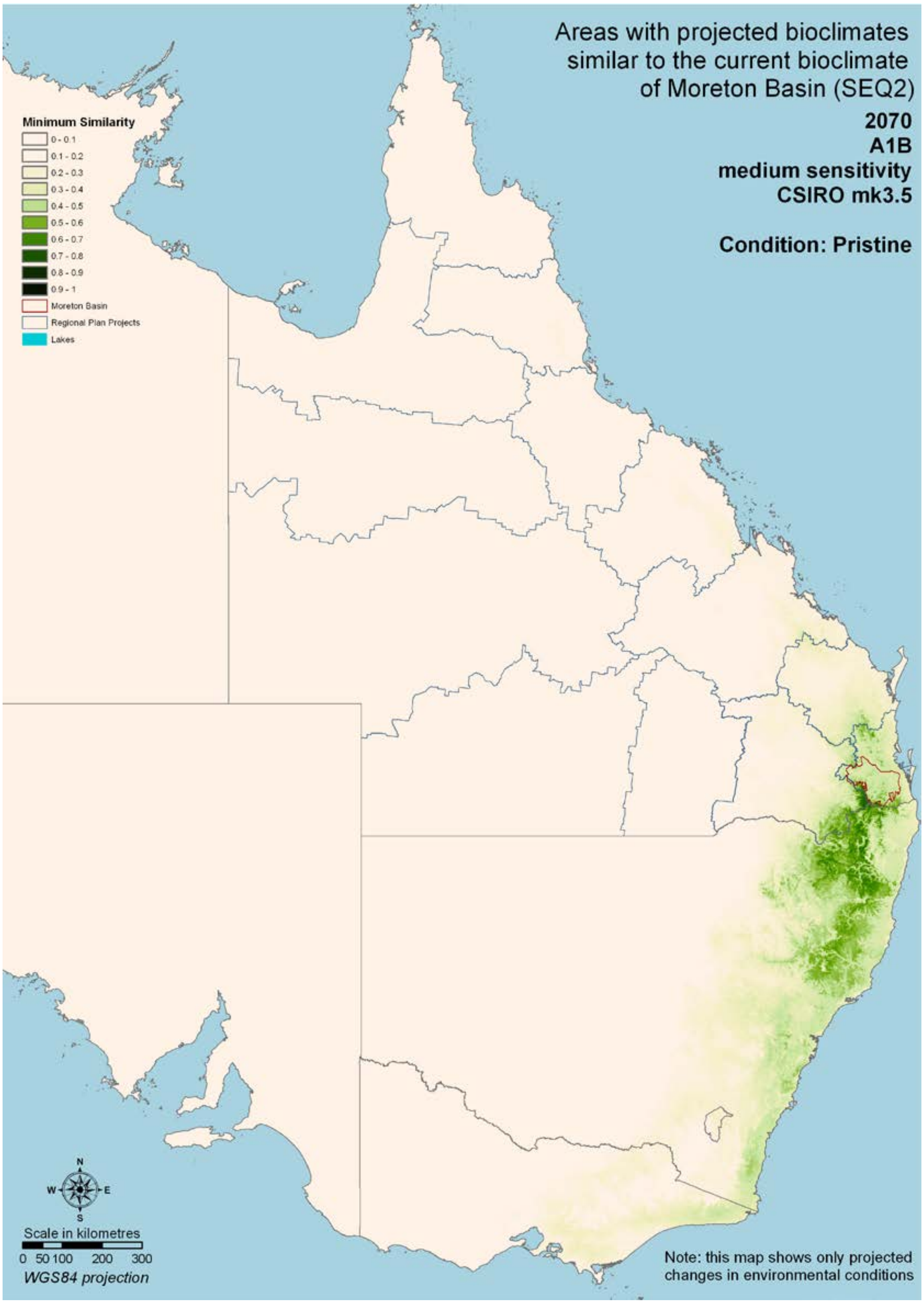

Figure 22: Areas with projected bioclimates (A1B climate scenario, 2070) similar to the current bioclimate of the Moreton Basin (based on modelled dissimilarity of vascular-plant composition benchmarked using 1960-centred average climates). Darker green areas have increasingly similar environments. NOTE: This map shows only projected changes in environmental conditions. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation). Compare with Figure 21 and Figure 23.

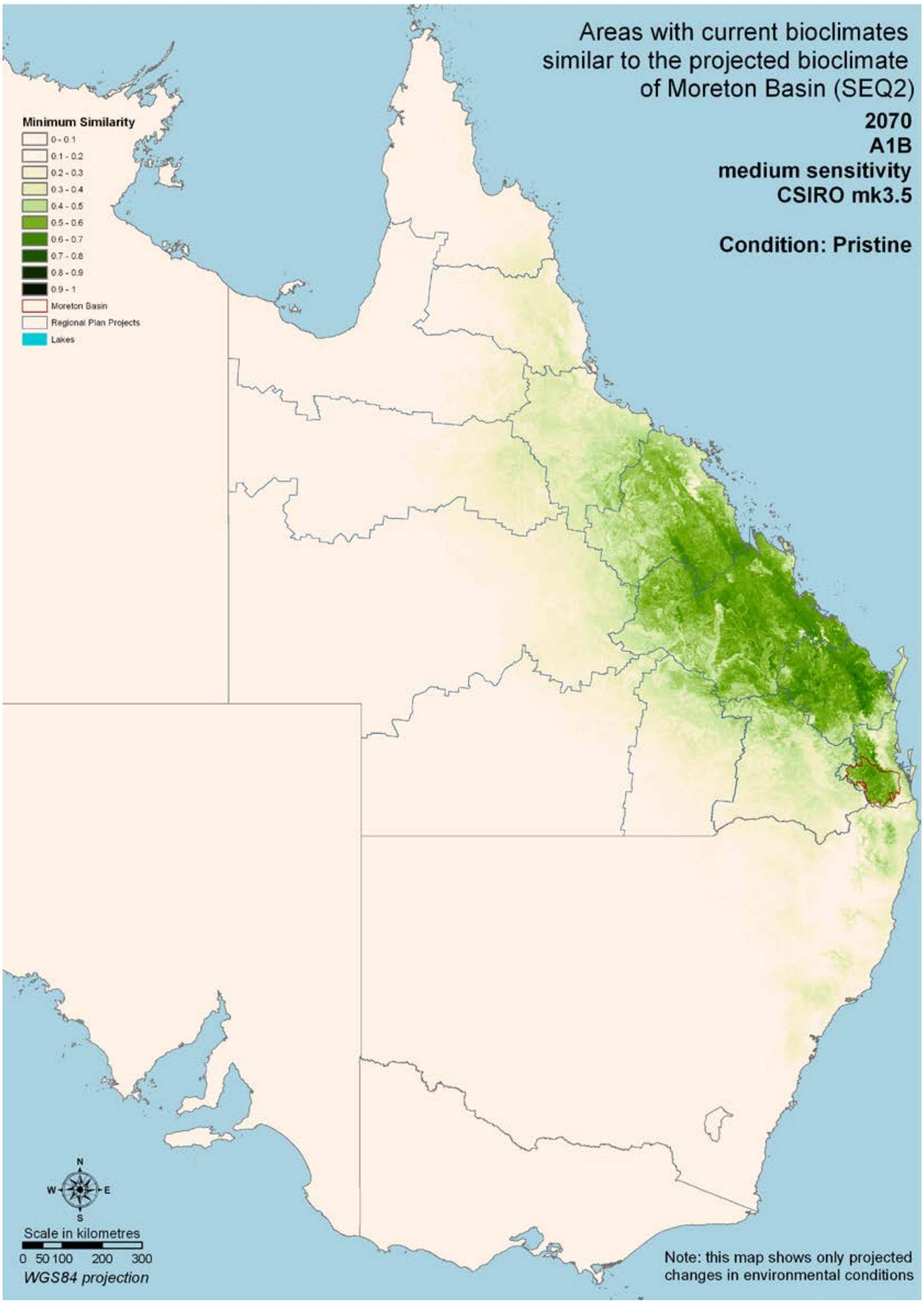

Figure 23: Areas with current bioclimates similar to the projected bioclimate (A1B climate scenario, 2070) of the Moreton Basin (based on modelled dissimilarity of vascular-plant composition benchmarked using 1960-centred average climates). Darker green areas have increasingly similar environments. NOTE: This map shows only projected changes in environmental conditions. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation). Compare with Figure 21 and Figure 22.

6. CASE STUDY: A PRELIMINARY SYNTHESIS OF BIOREGIONAL PATTERNS

6.1 Introduction

Here we present a preliminary synthesis of selected GDM-based outputs within the context of the 18 of Australia's 85 bioregions in Queensland (based on IBRA version 6.1, DEWHA 2004). The bioregions shown in Figure 24 are superimposed over examples of projected ecological change for the 2070 A1B climate scenario, shown in Figure 25. Each of these maps was presented in preceding sections with Queensland's regional plan boundaries (DIP 2009) superimposed. However, an ecological synthesis of change requires the use of ecologically-consistent geographic units, such as bioregions, subregions or regional ecosystems. In Figure 25, the bioregion boundaries are shown over results from selected GDM-based analyses – "disappearing environments" and "novel environments" (from Section 3.2), "potential benefit from actions enhancing or assisting long-distance migration / colonisation" (from Section 3.5) and "potential benefit from actions restoring native habitat in local landscapes" (from Section 3.6). An indicative, qualitative analysis of variation in bioregional patterns of ecological change is presented in Table 1, which summarises levels of potential change between the baseline 1960 current and the selected 2070 future climate scenario. The purpose of this synthesis is to demonstrate how the projections of ecological change can be summarised to inform policy.

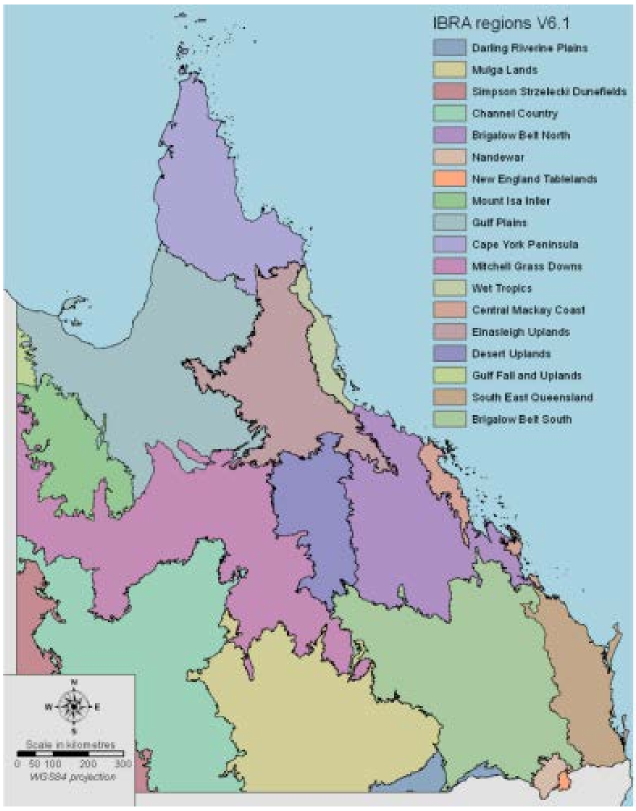

Figure 24: Queensland extent of Australia's bioregions (DEWHA 2004).

6.2 Likelihood of existing environments disappearing from the continent

By 2070, eight of the bioregions show consistently high levels of environmental change potentially leading to changes in the composition of species (top left in Figure 25, Table 1). Although not modelled here, these changes in environmental conditions and possibly species composition (e.g., presence, richness, abundance) may cause serious disruption to ecological function, that will likely result also in changes to the structure and characteristics or appearance of component ecosystems, as they are currently known. That is, these ecosystems may no longer exist as the same recognisable units, as species adjust to the changed conditions and reassemble.

Four bioregions are classed in the medium to high likelihood of containing biotic environments that will disappear from the continent. These are: Gulf Falls and Uplands; Simpson Strzelecki Dunefields; Channel Country and; Mulga Lands (Table 1). A further four bioregions, with relatively more natural heterogeneity or large extents, are classed in the low to high likelihood of containing biotic environments that will disappear from the continent. These bioregions are: Wet Tropics; Central Mackay Coast; Gulf Plains; and Mitchell Grass Downs (Table 1). The potential disappearance of mountain top habitats, for example, from the Wet Tropics bioregion is well established as a likely outcome of climate change (see Murphy *et al.* 2012). Much less is known about the likely outcome for ecosystems under the wider range of environmental pressures occurring in these other bioregions; although Low (2011) presents examples and evidence for how climate-change may mediate ecological change through a range of mechanisms affecting species in Queensland’s bioregions.

6.3 Likelihood of appearance of novel environments

By 2070, new types of ecosystems may begin to appear with ecological characteristics (i.e., structure, function and composition) that are unlike anything currently extant. Several bioregions show consistently high levels of environmental change potentially leading to new combinations of species, reassembling from surrounding regions under a new environmental regimen (top right in Figure 25, Table 1). Some species may have become locally extinct or rare and isolated in small pockets of buffered conditions and other species are likely to establish in vacated niches or out-compete species that now find themselves in more marginal conditions (see discussion in Murphy *et al.* 2012).

Seven bioregions are classed with a medium to high likelihood of containing environments that are novel to Australia (and therefore novel ecosystem characteristics). These are: Gulf Plains; Gulf Falls and Uplands; Mt Isa Inlier; Mitchell Grass Downs; Simpson Strzelecki Dunefields; Channel Country; and Mulga Lands (Table 1). Upland regions, such as the New England Tablelands, Desert Uplands and Einasleigh Uplands, show less change overall (top right in Figure 25, Table 1). Some of these environments may change in ways that enable them to maintain the majority of their character by adopting the characteristics of surrounding regions, from where species—those that are able to—may migrate from less suitable to more favourable conditions.

6.4 Potential benefit of actions enhancing long-distance dispersal

Assuming the current extent of vegetation clearing and pattern of land use remains much the same in the future as today, two bioregions in particular may be focal points for adaptation management actions leading up to 2070 (bottom left in Figure 25). The Gulf Plains and the Mitchell Grass Downs are likely to benefit the most (medium to high potential benefit, Table 1) from actions aimed at enhancing or assisting, long-distance migration / colonisation; for example, through establishment of large-scale (long-distance) habitat corridors or assisted colonisation (translocation). Four other bioregions also contain locations that may be focal points where such actions may be beneficial (low to high potential benefit, Table 1). These are the Brigalow Belt (North and South), Cape York Peninsula and the Desert Uplands.

This analysis illustrates the potential benefit of actions to enhance the long-distance dispersal capability of species, relative to capacities to track suitable habitat by up to 50km over 100 years (i.e., between the c.1960 benchmark conditions and a 2070 future scenario) as climates change. The indicative results show focal locations where original bioclimates have shifted by more than 50km (e.g., by 2070) and where populations may be at risk of extinction because of their inability to track the rate of change in their preferred climatic habitat. Species at these locations are therefore likely to benefit from earlier adaptation management actions that enhance their capacity for long-distance migration / colonisation; for example, through establishment of large-scale (long-distance) habitat corridors; or through assisted colonisation (translocation). There are two reasons why some locations in Figure 25 (bottom, left) appear to benefit little from such actions: 1) analogous bioclimates exist within 50km; 2) analogous climates (in this case within Queensland) do not exist beyond 50km—some of these may be classed as disappearing bioclimatic environments if they also do not exist anywhere on the continent (see Figure 4, far right). In this context, bioclimates among the more dissected terrain of the eastern bioregions are more likely to have analogies within 50km; and bioclimates among the more subdued terrain of the western arid regions may have no analogies beyond 50km and within Queensland. As some bioclimates disappear completely, there may be no options of analogous conditions and assisted migration will be of limited benefit.

Between the two extremes described above are bioregions in which analogous bioclimates exist beyond 50km (pink areas in Figure 25, bottom left). Locations most likely to benefit from adaptation management actions are those that contain future analogous bioclimates in Queensland beyond 50km of their original location (i.e., suitable habitat may not exist close by but may exist at a distance). Original populations requiring dispersal assistance would be those for which the rate of environmental change is likely to exceed their dispersal capacity or where landscape configurations create dispersal bottlenecks or sinks, such as cleared or disjunct, isolated suitable habitat and natural biogeographic barriers. A complementary analysis could be used to identify, for each orphaned location, the array of potential analogous locations where suitable habitat for these species might continue to exist. The example of projected change in the distribution of ecologically scaled environments (Section 3.7), shows how supplementary analyses could be used to investigate the location of potential adaptation pathways, for example where large-scale corridors and translocation might be of benefit. Thus, a number of different analyses might be used to identify the location of specific adaptation options and landscape pathways with particular functions.

However, careful choices need to be made about the facilitated movement of species to ensure invasion mistakes of the past are not repeated (Thomas 2011; Webber *et al.* 2011). Target species for translocation or facilitated dispersal will require careful screening and clear objectives before such actions can be promoted (Minteer & Collins 2010; Webber & Scott 2012). The process of developing these maps helps to highlight those exceptions, where different climate-landscape interactions require different management approaches and a greater depth of thinking is required in developing information products for adaptation planning and in designing tactics for management. For example, if there is no suitable habitat to move to, then adaptation management actions other than assisted dispersal need to be considered.

6.5 Potential benefit of actions restoring native habitat in local landscapes

By 2070, the potential benefit of adaptation management actions aimed at restoring cleared or degraded native habitat in local landscapes is apparent across five bioregions that are presently extensively cleared (bottom right in Figure 25). With medium to high potential benefit (Table 1), these bioregions are: South East Queensland, Brigalow Belt (North and South); Desert Uplands and the Darling Riverine Plains. The extensive Mitchell Grass Downs bioregion also contains locations that may be focal points where such actions may be beneficial (low to high potential benefit, Table 1), near the boundary with these eastern bioregions. Areas with identified medium to high potential benefit represent places where enhancement of the extent and condition of native vegetation is likely to improve local (short-distance) connectivity.

This preliminary analysis assumes a connectivity distance of 50km between locations with environments that are compositionally similar (over the period from 1960 average climates to a 2070 projected climate) and aims to fill key gaps in landscape pathways to enhance the effectiveness of climate change corridors for biodiversity (e.g., see this objective in (DERM 2009a; DERM 2009b; DERM 2010b; DERM 2010a). Because this analysis takes into account current and future environments, it automatically accounts for pathways of change where vegetation enhancement and reinstatement are most likely to accrue biodiversity benefits. Places with low values for the index (the whiter areas in bottom right Figure 25) either have a present environment similar to the future environment of a remnant vegetation cell somewhere within the 50km radius or this similarity is not increased by including non-remnant vegetation (i.e., currently cleared) cells in the analysis or both.

6.6 Discussion

Considering the combined high likelihood of change (disappearing or novel environments) and high likelihood of benefit from adaptation management actions across the four GDM-based analyses summarised here, it would appear that the Mitchell Grass Downs and the Gulf Plains represent "hotspots" of initial concern and opportunities for positive action (Table 1). However, the actual nature of concern and action may not necessarily be aligned and will need to be investigated in more detail. By way of contrast, places that appear to be prospects for the retention or persistence of regional biodiversity with a combined generally low likelihood of change and low likelihood of benefit from adaptation management actions are the New England Tablelands and the adjacent Nandewar bioregion (Table 1). These heterogeneous upland regions may contain sufficient intact vegetation and vertical complexity that require less lateral movements by species in order to track their suitable habitats or retreats to buffered habitat crevices and refugia.

The two analyses of change – disappearing and novel environments – highlight subtly different but important facets of change. Disappearing environments represent the possibility of change among species that have limited capacity to adapt or disperse, where as the novel environments represent the capacity for *in situ* adaptation and the likely establishment of species from adjacent locations, potentially finding more suitable habitat than in their former location. Likewise, the two analyses of possible adaptation management actions related to translocation and vegetation enhancement, each to facilitate species movements and ecosystem reassembly through climate change corridors, are subtly different ways of combining information to address specific landscape planning questions.

The selected A1B emission scenario with medium climatic sensitivity represents a relatively modest amount of change (e.g., increased global average temperatures of 2°C by 2050) compared with the potential for change assuming current emissions levels continue into the foreseeable future (currently tracking around the upper range of the A1FI scenario, see Le Quere *et al.* 2009; Dolman *et al.* 2010), which could lead to a warming of 4°C relative to pre-industrial during the 2070s. In this latter case, adaptation decisions that have long lead times or that have implications playing out over many decades become more uncertain and complex (Stafford Smith *et al.* 2011). That is, adaptation to global warming of 4°C will be a more substantial, continuous and transformative process (Stafford Smith *et al.* 2011), requiring the generation of a wide range of scenarios and information products to support the thinking around management feasibility and to plan for robust adaptation pathways, operationally and in terms of outcomes for biodiversity persistence.

Clear objectives, time-series analyses and information products that consider an array of ecological change consequences are needed to inform adaptation strategies and pathways, including an assessment of knowledge gaps and uncertainty. The examples of adaptation management actions presented here represent a decision time slice and just a few objectives that would need to be coupled with analyses that show possible trajectories of change for different ecological circumstances. For example, focal areas for adaptation management attention may change location in the landscape as climate change deepens. Adaptation management will need to investigate the appropriate timing and location of particular actions, taking into account different waves of change that are likely to propagate across the landscape with increasing intensity over the next few decades. Target locations and target species would need to be identified and adaptation management will need to be flexible in the scheduling of actions, shifting from one location to another—as efficiently and effectively as possible, enhancing and supporting the natural adaptive capacity of species and ecosystems (further details are given in Dunlop *et al.* 2012).

The trial analyses presented here are preliminary and demonstrative of possible information products that may be generated and are indicative of the potential to design and generate other custom information products to support the thinking and planning around adaptation management and its operational foci. In addition to new types of analyses, the analyses presented here can be further customised in their parameters, such as the 50km radius used to simulate dispersal distances (over the period from 1960 average climates to, say 2070), so that these represent feasible ecological outcomes. We presented results for vascular plants but could equally model the consequences for other biological groups, such as birds, reptiles, amphibians and mammals. For example, GDM models were developed for 11 biological groups, including invertebrates, for the continent of Australia (Williams *et al.* 2010a; Williams *et al.* 2010b).

The analyses presented here can also be coupled, in order to distinguish different facets of change and appropriate management responses, by focussing on specific objectives. For example, the analyses presented in Section 3.2, show how much change might be expected in ecologically-scaled environments and how far these environments might move geographically but shed little light on precisely where a given environment will move to or where there are present environments similar to that projected for a given place under climate change. The supplementary analysis in Section 3.7 therefore shows how with a particular focus on a region, subregion, regional ecosystem or a particular species' habitat (e.g., architectural dominant trees), the shift of environmental conditions can be visualised. This visualisation can support the development of hypotheses about the capacity of species to move or adapt and impute the possible nature of ecosystem change. The local outcomes of change could be investigated through a deeper understand of individual species ecology and with knowledge of the components of ecosystems that are most likely to change (i.e., elements of structure, function and composition). For example, Low (2011) provides an overview of bioregional differences in the vulnerability of Queensland's biodiversity to climate change. That review of the literature, coupled with personal ecological insights, represents an example of how projections of change and ecological understanding may be coupled in future, in order to come up with propositions of the likely outcome of different climate change scenarios, with scoping of management implications. A more general overview of regional change is provided in Murphy *et al.* (2012).

It is important to recognise, however, that these particular GDM-based analyses represent projected changes in ecologically-scaled environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation). Current research is investigating ways to model and integrate these different facets of change in the context of climate change forecasting of biodiversity distribution responses.

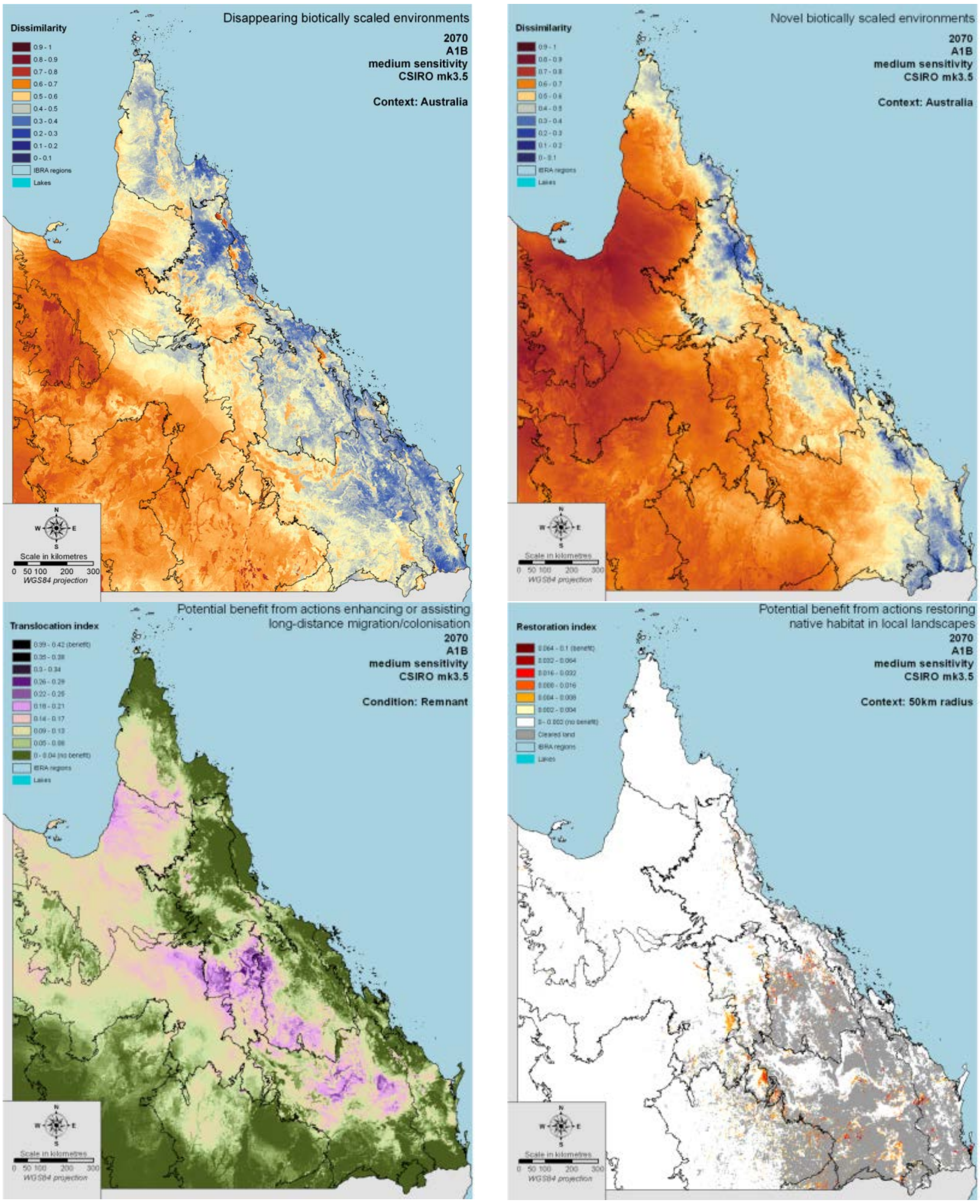

Figure 25: Boundaries of IBRA bioregions superimposed over results from selected GDM-based analyses (all for the 2070 A1B emissions scenario with medium climate sensitivity) – "disappearing environments" (top, left), "novel environments" (top, right), "potential benefit from actions enhancing or assisting long-distance migration / colonisation" (bottom, left) and "potential benefit from actions restoring native habitat in local landscapes" (bottom, right). Scaled using modelling of species composition of vascular-plant communities (benchmarked using 1960-centred average climates). See text for detail on the derivation of each index. This map shows projected changes in environmental conditions only. Realised changes in the distribution of species and communities will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation). These maps were used to generate the synthesis of bioregional patterns presented in Table 1.

Table 1: Synthesis of bioregional patterns (IBRA version 6.1, DEWHA 2004) based on interpretation of mapped results of GDM-based analyses presented in Figure 25, depicting levels of potential ecological change between the models applied to the baseline 1960 current climate and the selected A1B 2070 future climate scenario (with medium sensitivity). Measures of "likelihood" and "benefit" – low, medium and high – are qualitative estimates of the continuous range in conditions derived from the respective GDM-based analyses presented in Figure 25.

Bioregion	Likelihood of existing environments disappearing (from the continent)	Likelihood of appearance of novel environments	Potential benefit of actions enhancing long-distance dispersal	Potential benefit of actions restoring habitat in local landscapes
South East Qld	Low-Medium	Low-Medium	Low-Medium	Medium-High
New England Tablelands	Medium	Low	Low	Low
Nandewar	Low-Medium	Low-Medium	Low	Low-Medium
Brigalow Belt South	Low-Medium	Low-Medium	Low-High	Medium-High
Central Mackay Coast	Low-High	Low-High	Low-Medium	Low
Brigalow Belt North	Low-Medium	Low-Medium	Low-High	Medium-High
Wet Tropics	Low-High	Low-High	Low-Medium	Low-Medium
Einasleigh Uplands	Low-Medium	Low-Medium	Low-Medium	Low-Medium
Cape York Peninsula	Low-Medium	Low-High	Low-High	Low
Gulf Plains	Low -High	Medium-High	Medium-High	Low
Gulf Falls and Uplands	Medium-High	Medium-High	Medium	Low-Medium
Mt Isa Inlier	Medium	Medium-High	Low-Medium	Low
Mitchell Grass Downs	Low -High	Medium-High	Medium-High	Low-High
Desert Uplands	Low-Medium	Medium	Low-High	Medium-High
Simpson Strzelecki Dunefields	Medium-High	Medium-High	Low	Low
Channel Country	Medium-High	Medium-High	Low-Medium	Low
Mulga Lands	Medium-High	Medium-High	Low-Medium	Low-Medium
Darling Riverine Plains	Low-Medium	Medium	Low	Medium-High

7. CONCLUSIONS

The projections of terrestrial ecological change presented in this report are GDM-based scalings of environmental change. The GDM method (generalised dissimilarity modelling – Ferrier *et al.* 2007) is a powerful way of assessing the ecological significance of environmental changes projected to result from climate change, to inform policy and management responses. GDM is here used to analyse distributional data for many thousands of vascular-plant species to develop a measure of the ecological implications of environmental variation in terrestrial ecosystems. Applying this measure to two different climate change scenarios at 2030 and 2070 suggests the potential for ecologically-significant environmental changes in many parts of Queensland. However, the actual level of change eventuating in any particular place will be determined by a range of additional processes not considered here (e.g., dispersal, biotic interactions, capacity for evolutionary adaptation). Current research (lead by S. Ferrier in CSIRO) is investigating ways to model and integrate these different facets of change in the context of climate change forecasting of biodiversity distribution responses, to more realistically represent possible trajectories of ecosystem change.

In Section 3.5 and 3.6, we presented two new GDM-based indices designed to more directly inform thinking about priorities for applying different types of adaptation management in different parts of the continent. Applied to Queensland environments, these experimental indices aim to provide an indication of the potential value that could be derived through further refinement and application of this general approach. In Section 4, we present preliminary interpretations of these analyses through a synthesis of bioregional patterns. These results, however, are not intended to represent a prioritisation of management actions, rather, this information should be used as part of a comprehensive methodological framework giving due consideration to distributional information for individual species or ecological communities of particular conservation concern and to other key factors, such as threats, costs, opportunities and ecological processes, of relevance to climate change, such as persistence and dispersal (Ferrier & Drielsma 2010). We would envisage these spatial biodiversity forecasting outputs being used in conjunction with other sources of information supporting the development of regional and state-wide biodiversity conservation plans; integrated with other land use plans aimed at enhancing landscape resilience (Ferrier & Wintle 2009).

While we have focussed here on a GDM-based model of vascular plants; these analyses could readily be applied to other terrestrial biological groups, such as birds, reptiles, amphibians, mammals and invertebrate groups, for which we have developed similar models for the continent of Australia (Williams *et al.* 2010a; Williams *et al.* 2010b). GDM-based models of compositional patterns in biodiversity have also been developed for freshwater (Leathwick *et al.* 2011) and marine habitats (Leaper *et al.* 2011) and for more refined understanding of evolutionary potential, using taxonomic or phylogenetic-species based indices (Rosauer *et al.* 2009) and genetic characteristics of species (Thomassen *et al.* 2010; Thomassen *et al.* 2011). These latter applications will likely be useful in deciding on biodiversity conservation efforts to maximise retained levels of evolutionary potential under climate change (DERM 2010b). GDM-based applications could equally be applied to the functional or structural composition of ecosystems (where comprehensive observational or interpreted data exist), as alternative ways to visualise degrees of landscape change or ecological function change related to ecosystem processes, in relation to climate change (DERM 2010a).

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CONTACT US

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

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FOR FURTHER INFORMATION

Climate Adaptation Flagship
Dr Kristen J Williams
t +61 2 6246 4213
e kristen.williams@csiro.au
w www.csiro.au/ca