# Network Analysis of Terrestrial Wetlands Identifies Five Classes of Climate Risk

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**Abstract**

Climate change puts the habitat functions of wildlife conservation areas at risk. Conservation areas managed for wetlands can be considered a network, permitting the tracking of current climate conditions within the network under projected future climates. A climate classification of the nodes in such a network can help the selection among multiple conservation management strategies based on their relative climate-connectedness. We examined wetlands in 48 US National Wildlife Refuges and mapped their climate networks to permit the incorporation of climate linkages. Using four climate projections, we found five climatic classes of wetlands: three are climatically stable; four are climate hubs, becoming climatically similar to current climate conditions of many other units; three whose current climate appear in many refuges; 8-16 whose climate conditions appear in only one other unit; and 10-25 are climatically isolated. The relative isolation of wetlands makes them particularly appropriate for network-based climate assessments.



# Introduction

Wetlands such as swamps, marshes, and bogs contain a wealth of biodiversity including many endemic and rare species (McLaughlin et al. 2017; Cartwright 2019). They also provide critical ecosystem services such as water quality improvement, flood damage reduction, and recreation and education opportunities (Randolph 2012). The unique features of wetland landscapes support unusual local environments and provide opportunities for species to survive in changing conditions, making them candidates for climate refugia (Morelli et al. 2016; McLaughlin et al. 2017). However, more research on the impacts of climate change and the conservation management of these unique ecosystems is needed (Cartwright and Wolfe 2016), in order to identify appropriate climate-change adaptation strategies. This need is pronounced for conventional reserve networks including protected wetlands, because these conservation areas have typically not been designated to address climate change (Araújo et al. 2011; Game et al. 2011; Schneider and Bayne 2015).

As climate conditions shift across continents, much conservation research has focused on tracking analog climates (Carroll et al. 2018; Parks et al. 2018; Fitzpatrick and Dunn 2019). Studies have examined landscape connectivity among reserves with climate change (Andrello et al. 2015), and projections of species future-ranges (Ramirez-Villegas et al. 2014; Choe et al. 2017) or vegetation shifts (Powers et al. 2018) to model theoretical networks of future conservation that incorporate climate change (Heller et al. 2015). However, there is a need for a more unified approach to analyzing climate connectivity across protected areas such as national parks, nature reserves, and multiple-use conservation areas (Belote et al. 2017) and for insular or rare ecosystems (Cumming et al. 2010; Cartwright 2019) to inform questions such as to which conservation areas might species need to move (Hannah et al. 2007; Lawler and Hepinstall-Cymerman 2010) and whether dispersal would result in species arriving at suitable, or analogous, climates to those being lost.

We used a discrete network-based analysis to examine climatically suitable arrival points for species being climatically dislodged from wetland nodes in a climatic network of conservation areas. We used wetlands in the United States National Wildlife Refuge System (NWRS) that span the California floristic region (Burge et al. 2016), part of the Pacific Northwest's temperate coniferous forest region, and parts of the desert ecosystems of Nevada to model analogous climates through time. We considered the wetland in each NWRS unit (hereafter refuge) a node within the network analysis, and the links are the climate relations between nodes. The NWRS administers a network of lands and waters for the conservation and management of wildlife species and their habitats (U.S. Code 1997). Currently, the refuges in USA provide habitats for over 700 bird species, 220 mammals, 250 reptiles and amphibians, and 1000 fish species (National Wildlife Refuge System, 2016). Refuges from the NWRS system are particularly suitable for a network analysis because they are spatially and environmentally isolated by large intervening areas.

Climate change impacts are expected to be significant (Rannow et al. 2014) and some refuges may become climatically unsuitable for the species the units were created to protect (Jewitt et al. 2017). This research was motivated by the question of whether suitable climate-conditions for dislodged protected species might occur or emerge at other nodes in the network, thereby making those nodes candidates for possible species relocations. In such cases, some nodes may lose their functions as habitats, but others may become more climatically suitable as species' habitats. Thus, developing a climate classification of nodes within a conservation network of wetlands is useful for conservation management.

We focused on the site-level climate conditions of refuges and examined the climate networks among 48 existing refuges (43 national wildlife refuges and 5 wildlife management areas) for present and future periods from the "climate-analog" point of view. Climate-analog analysis has the advantage that it does not need to make assumptions about the tolerances of species (Veloz et al. 2012), and can help to identify the most important or highly exposed areas among the refuges for resource management. For example, Parks et al. (2018) identified the climate-analog of mountainous ecoregions of the western US to evaluate how climate change may influence fire regime and vegetation shifts. The climate-analog approach can be applicable to other environments or regions (Veloz et al. 2012), but we have not seen the application of this approach to conservation area networks.

Here we ask how many types of temporal climate connections exist for a set of wetland conservation areas? We define the current climate conditions of each refuge and identify others with analogous climates. Then, we identify where each refuge's current climate can be found in the future using climate change projections to understand the climate network of each unit. Our objectives are to identify the temporal climate networks among the refuges under future climate projections, to classify the units using their relative climate importance based on their climate classes for efficient conservation management of the NWRS system, and to consider the utility of climate analog classifications within a conservation network.

# Material and methods

We examined the current-climate conditions of the 48 refuges in the NWRS Pacific Southwest Region of U.S. using two current-climate variables, annual average of minimum temperature and annual precipitation, to facilitate the understanding of climate change. Then, we identified the climate networks among the refuges for current and future time periods.

**Wildlife Refuges in the Pacific Southwest Regions of U.S.**

We used 48 units located in California, Oregon and Nevada, USA (Fig. 1). These comprise 47 refuges and one area of interest, the North Central Valley WMA (Wildlife Management Area), which is a generalized area in which the USFWS has interest but does not manage. The average refuge size is 99 $km^2$, leaving aside the unusually large North Central Valley WMA (19,128 $km^2$) and the Desert NWR (6,619 $km^2$) (see Table S1 in Supporting Information).

### Climate Space Shifts for each Wildlife Refuge

We calculated the ranges, from minimum to maximum value, of the two climate variables to define the two-dimensional current-climate space for each refuge using conditions from 1981-2010. We used the annual average of minimum temperature because it is expected to warm faster than maximum temperature at most locations (Hartmann et al. 2013).

We identified where the current-climate space of each refuge will be found among all the refuges for three future periods, 2010-2039, 2040-2069, and 2070-2099. For future-climate scenarios, we used four projections that bracket a range of possible future-conditions predicted by 12 Global Climate Models (GCMs) (Thorne et al., 2016; Thorne et al., 2017). The four futures are derived from two GCMs that respectively are hotter and drier (MIROC ESM), and warmer and wetter (CNRM-CM5) than current conditions; and two Representative Concentration Pathways (RCPs), which were defined by their total radiative forcing pathway and level by 2100 (IPCC 2014). We used the RCP8.5 emissions scenario, IPCC's highest rate of anthropogenic greenhouse gas emissions, already surpassed by current emissions (Hayhoe et al. 2017); and the RCP4.5 emissions scenario, representing an attempt to limit global warming to 2°C (Thomson et al. 2011). Each emission scenario was used with each GCM.

### Climate Networks among Wildlife Refuges



Network analysis investigates structures by identifying networks among component individuals (Otte and Rousseau 2002). Each individual is called a node and links are the relations between nodes (Cumming et al. 2010). Here, refuges are the nodes and we linked refuges using the relationships of climate space of each refuge. We used arrows to represent the directions of links. If an initial refuge node's current climate space is found in other refuge nodes, those nodes are final nodes and the arrowheads point to the final nodes. The density of vectors is an indicator of the connectedness in the network (Otte and Rousseau 2002). We calculated the levels of connections for each refuge unit and the number of nodes from which climate departs or arrives can be found under future projections.

After mapping the temporal climate networks among refuges for each climate projection, we asked how many distinct types of climate connections could be identified. For the future-climate connections among refuges, we report on 2070-2099 in the main text, and see Table S2 for other future periods results.

## Results

### Climate Change of Each Wildlife Refuge

The five refuges with the largest end-of-century increase in annual minimum temperatures under the CNRM-CM5 RCP8.5 are the Modoc NWR, Tule Lake NWR, Ash Meadows NWR, Klamath Marsh NWR, and Lower Klamath NWR. Under the MIROC ESM RCP8.5, the five refuges with the highest minimum temperature increases are Ash Meadows NWR, Tule Lake NWR, Ruby Lake NWR, Modoc NWR, and Fallon NWR (Table S1, Figures S1 and S2).

Under the CNRM-CM5 RCP8.5, annual precipitation is expected to increase in all refuges except Hopper Mountain NWR. Under the MIROC ESM RCP8.5, annual precipitation is expected to decrease in almost all refuges except Modoc NWR, Lower Klamath NWR, Humboldt Bay NWR, and Upper Klamath NWR (Table S1, Figures S3 and S4).

### Climate Networks among Wildlife Refuges

We identified five climate categories in the refuge network and ranked them from most- to least-at-risk for climate-change impacts: 1)*Disappearing climates* - refuges whose current climate conditions are not represented in any other refuges in the future; 2)*Isolating climates* - refuges whose current climate conditions appear in only one other refuge; 3) *Dispersing climates* - refuges whose current climate conditions appear in multiple other refuges in the future; 4) *Enduring climates* - refuges that retain their current climate conditions in the future; and 5) *Climate hubs* - refuges that meet the current climate conditions of other refuges in the future. See Table S3 in Supporting Information for the climate categories of each refuge under each climate scenario for three future periods, 2010-2039, 2040-2069, and 2070-2099.

*Disappearing climates* - The current climates of six of the smaller refuges are not found in any other refuges currently (Blue Ridge NWR, Seal Beach NWR, Coachella Valley NWR, Humboldt Bay NWR, Klamath Marsh NWR, and Sonny Bono Salton Sea NWR; Fig. 2 and Table S2). By end-of-century, there is no climatically isolated refuge in all four climate scenarios, but eight are climatically isolated under three climate scenarios (Fig. 3 and Table S2). They are Antioch Dunes NWR, Marin Islands NWR, Seal Beach NWR, Sutter NWR, Colusa NWR, Upper Klamath NWR, Klamath Marsh NWR, and Sonny Bono Salton Sea NWR. These represent the units that are most climatically at risk.

However, far more refuges are at this highest level of risk when each future climate is considered separately. Under the warmer and wetter future, CNRM-CM5 RCP4.5 scenario, the current climate space of 21 refuges are not found in any refuges by end-of-century (Fig. 3a). Among these 21 refuges, 10 contain arriving current climates of other units but the other 11 do not have any connections, which means the current climate conditions of these refuges did not appear elsewhere, nor did the current climate of other refuges appear in these refuges. Under the CNRM-CM5 RCP8.5, the current climate space of 32 refuges cannot be found in any others (Fig. 3b). Among these 32 refuges, 25 do not have any climate connections. Under the hotter and drier GCM, MIROC ESM RCP4.5 scenario, the current climate space of 25 refuges cannot be found in any others and 10 refuges do not have any connections (Fig. 3c). Under the MIROC ESM RCP8.5, the current climate space of 31 refuges cannot be found in any others and 20 do not have any connections (Fig. 3d).

*Isolating climates* - The current climate conditions of many refuges appear in only one other unit by end-of-century (Fig. 3 and Table S2), especially those of Don Edwards San Francisco Bay NWR and Pixley NWR, which appear in only a single refuge under three climate scenarios. Under the CNRM-CM5 RCP4.5 and RCP8.5, the current climate conditions of 14 and 10 refuges can be found in only one other refuge, respectively (Fig. 3a and 3b). Under the MIROC ESM RCP4.5 and RCP8.5, the current climate conditions of 16 and eight refuges can be found in only one other unit, respectively (Fig. 3c and Fig. 3d).

*Dispersing climates* - For refuges whose current climates appear in many other refuges, the climate space of three refuges, Desert NWR, North Central Valley WMA, and San Diego NWR, appear in many refuges in all four climate change scenarios (Fig. 3 and Table S2). Under the CNRM-CM5 RCP4.5, the current climate conditions of the Desert NWR and of the San Diego NWR can be found 15 and eight refuges, respectively (Fig. 3a). Under the CNRM-CM5 RCP8.5, the current climate conditions of the Desert NWR and of the North Central Valley WMA can be found in eight and five refuges, respectively (Fig. 3b). Under the MIROC ESM RCP4.5, the current climate conditions of the Desert NWR and of the San Diego NWR can be found in 24 and 13 refuges, respectively (Fig. 3c). Under the MIROC ESM RCP8.5, the current climate conditions of the Desert NWR and of the North Central Valley WMA can be found in 14 and four refuges, respectively (Fig. 3d).

*Enduring climates* - Taking all four climate change scenario outcomes into account three refuges, San Diego NWR, Desert NWR, and North Central Valley WMA, retain their current climate conditions by end-of-century (Fig. 3 and Table S2). Under the CNRM-CM5 RCP4.5, seven refuges (Blue Ridge NWR, Bear Valley NWR, Bitter Creek NWR, Ruby Lake NWR, San Diego NWR, Desert NWR, and North Central Valley WMA) retain their current climate conditions. Under the CNRM-CM5 RCP8.5, four refuges (Hopper Mountain NWR, San Diego NWR, Desert NWR, and North Central Valley WMA) retain their current climate conditions. Under the MIROC ESM RCP4.5 and RCP8.5, four refuges (Bitter Creek NWR, San Diego NWR, Desert NWR, and North Central Valley WMA) retain their current climate conditions.

*Climate hubs* - The North Central Valley WMA meets the current climate conditions of 23 other refuges and its current climate space can also currently be found in 23 other refuges, the highest number of current climate connections (Figure 2 and Table S2). Next, the Desert NWR meets the current climate conditions of 17 other refuges and its current climate space can currently be found in 24 other refuges. By the end-of-century, under the CNRM-CM5, the current climate conditions of many refuges are present in Bitter Creek NWR under both emission scenarios (Fig. 3a and 3b). The current climate conditions of many refuges can be found in North Central Valley WMA under both emission scenarios of the MIROC ESM (Fig. 3c and 3d). On the other hand, using the RCP4.5 scenario, the current climate conditions of many refuges can be present in Hopper Mountain NWR and San Diego NWR using the both GCMs (Fig. 3a and 3c), while the current climate conditions of many refuges can be found in Desert NWR in both of GCMs under the RCP8.5 emission scenario (Fig. 3b and 3d).

When we see the climate network outcomes using each climate scenario separately, the current climate conditions of six refuges exist in the Desert NWR including itself and of nine refuges can be found in San Diego NWR including itself under the CNRM-CM5 RCP4.5 (Fig. 3a). The current climate conditions of seven refuges can be found in Hopper Mountain NWR and Bitter Creek NWR, respectively. Under the CNRM-CM5 RCP8.5, the current climate conditions of 11 refuges exist in the Desert NWR including itself and of three refuges can be found in North Central Valley WMA including itself (Fig. 3b). The current climate conditions of six refuges can be found in Bitter Creek NWR. Under the MIROC ESM RCP4.5, the current climate conditions of four, five, 12 refuges exist in the Desert NWR, San Diego NWR, North Central Valley WMA including itself, respectively (Fig. 3c). And, the current climate conditions of seven refuges can be found in Hopper Mountain NWR. Under the MIROC ESM RCP8.5, the current climate conditions of eight refuges exist in the Desert NWR including itself and of six refuges can be found in North Central Valley WMA including itself (Fig. 3d). The current climate conditions of six refuges can be found in Blue Ridge NWR.

# Discussion

Conservation management plans that are based on current patterns of species distribution will become less effective under climate change (Carroll et al. 2017), so new approaches are needed for managing natural resources (Lawler 2009; Choe et al. 2018). We applied a climate network analysis to examine the climate links among 48 wetlands and found five climate-connection categories that can inform natural resource management strategies.

Wetlands lend themselves well to a network analysis because they are distinct landscape features occurring across multiple climates that are composed of different species at most nodes. While wetlands themselves are ecological islands that may have enhanced capacity to persist under climate change (Cartwright 2019), for conservation management of the vertebrate species using wetlands, climate dynamics will likely become an important challenge. Shorebirds in particular are largely dependent on the NWRS-managed network due to substantial wetland loss and their unique habitat requirements (Schaffer-Smith et al. 2018). Therefore, the five climate categories we found in the network analysis provide useful context for developing climate-adaptive management strategies for vertebrate species, particularly birds within the refuge network system, considering its unique ecosystem and management approach.

Most small-size refuges were climatically disappeared in the future time periods, or had only one other unit with a future analogous climate. For refuges with only one future unit, it may be beneficial to conduct further research into the resilience and species climate vulnerability at both the current and future locations. For climatically isolated units, some may have suitable climates in units beyond the boundaries of our study area (Choe and Thorne 2019), such as in northern refuges whose climates may shift into adjoining states (Lenoir and Svenning 2015). Alternatively, new refuges may need to be identified to account for species inhabiting these climatically isolated refuges, particularly if their climates do not appear anywhere in the larger network of protected areas.

The refuge network contains four climate hubs, where the current climate conditions of many refuges converge in the future (Bitter Creek NWR, North Central Valley WMA, Hopper Mountain NWR, and Desert NWR). These nodes could be targets for managed relocation (Schwartz et al. 2012), and target species lists can be developed from the species lists of those refuges whose climate conditions become unsuitable, but shift to these arriving node units in the future. Conversely, the climate in some nodes (Desert NWR, North Central Valley WMA, San Diego NWR) appears in many other refuges (dispersing climates), suggesting greater flexibility in species relocation for the species found in this class.

Not surprisingly, the three refuges with enduring climates include the two largest, whose range of climate conditions is broad enough to contain their own current climate conditions in the future. Although the North Central Valley WMA is only designated as a refuge area of interest and therefore the lands are mostly not under conservation management, its role as an important node in the climate networks shows the value that conserving this large area could provide. The third unit to retain its own climate, the San Diego NWR, is moderately sized (eighth largest). It is located in coastal southern California, and maritime influence may be a factor in the lower warming in this area than elsewhere in our study domain (Fig. S2). Management for this climate class of refuges, should focus on external threats such as invasive species, habitat fragmentation, and maintaining ecosystem functions.

This study could be considered a coarse filter approach (Groves et al. 2002; Khoury et al. 2011) to support wetland climate-conservation. Further research could consider wetland hydrological processes and additional climate variables to better define the climate conditions of each refuge. However, when we conducted a sensitivity analysis using up to nine climate variables, we found more variables narrowed the areas identified as climate analogs and rendered most refuge units climatically isolated. We decided to use the two most fundamental climate variables (temperature and climate). In addition, our study does not include projected shifts in species' ranges (Choe and Thorne 2017; Choe et al. 2017), or their sensitivity and adaptive capacity (Thorne et al. 2016) which are commonly used frameworks for understanding the vulnerability of individual species to climate change (Glick et al. 2011). These approaches have their own strengths and limitations, including assumptions about dispersal success and biotic interactions (Perez-Garcia et al. 2017). Instead this study focuses on the climate conditions that are part of the exposure metrics for species, but that are useful for describing the sites species occupy.

Our discovery of five classes of climate risk to existing wetland conservation features emphasizes the importance of including climate information when developing management strategies for protected area networks. It may be possible to quickly identify these classes for other conservation areas based on size, topographic complexity, and proximity to maritime influences. For example, the >2300 Ramsar wetlands which cover over 2.5 million km$^2$ globally (*https://rsis.ramsar.org/*), could be good candidates for climate network analyses. Finally, although some of the refuges we studied are very small, they intrinsically have a high adaptive capacity because the majority are managed wetlands into which additional waters could be pumped, which may offset climate impacts as projected here, at least to some degree. Although this study was limited to the refuge network, our next steps would be to explore the locations and time schedules for additional refuges.

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# References

Andrello M., Jacobi M.N., Manel S., Thuiller W., Mouillot D. (2015) Extending networks of protected areas to optimize connectivity and population growth rate. *Ecography* **38** , 273-282.

Araújo, M. B., Alagador, D., Cabeza, M., Nogués-Bravo, D. & Thuiller, W. (2011). Climate change threatens european conservation areas.*Ecology Letters* , 14, 484-492.

Belote R.T., Dietz M.S., Jenkins C.N. *et al.* (2017) Wild, connected, and diverse: building a more resilient system of protected areas. *Ecological Applications* **27** , 1050-1056.

Burge D.O., Thorne J.H., Harrison S.P. *et al.* (2016) Plant diversity and endemism in the California Floristic Province.*Madrono* **63** , 3–206.

Carroll C., Parks S.A., Dobrowski S.Z., Roberts D.R. (2018) Climatic, topographic, and anthropogenic factors determine connectivity between current and future climate analogs in North America. *Global Change Biology* **24** , 5318-5331.

Carroll C., Roberts D.R., Michalak J.L. *et al.* (2017) Scale-dependent complementarity of climatic velocity and environmental diversity for identifying priority areas for conservation under climate change. *Global Change Biology* **23** , 4508-4520.

Cartwright J. (2019) Ecological islands: conserving biodiversity hotspots in a changing climate. *Frontiers in Ecology and the Environment* **17** , 331-340.

Cartwright, J. M. & Wolfe, W. J. (2016). Insular ecosystems of the southeastern United States—A regional synthesis to support biodiversity conservation in a changing climate. Reston, VA: US Geological Survey.

Choe H., Thorne J.H. (2019) Climate exposure of east asian temperate forests suggests transboundary climate adaptation strategies are needed.*Climatic Change* **156** , 51-67.

Choe H., Thorne J.H. (2017) Integrating climate change and land use impacts to explore forest conservation policy. *Forests,* **8** , 321.

Choe H., Thorne J.H., Hijmans R., Kim J., Kwon H., Seo C. (2017) Meta-corridor solutions for climate-vulnerable plant species groups in South Korea. *Journal of Applied Ecology* **54** , 1742-1754.

Choe H., Thorne J.H., Huber P.R., Lee D., Quinn J.F. (2018) Assessing shortfalls and complementary conservation areas for national plant biodiversity in South Korea. *PLOS ONE* **13** , e0190754.

Cumming G.S., Bodin O., Ernstson H., Elmqvist T. (2010) Network analysis in conservation biogeography: challenges and opportunities.*Diversity and Distributions* **16** , 414-425.

Fitzpatrick, M.C., Dunn, R.R. (2019) Contemporary climatic analogs for 540 north american urban areas in the late 21st century. *Nature Communications,* **10** , 614.

Game, E. T., Lipsett-Moore, G., Saxon, E., Peterson, N. & Sheppard, S. (2011). Incorporating climate change adaptation into national conservation assessments. *Global Change Biology* **17** , 3150-3160.

Glick, P., Stein, B.A., Edelson, N.A. (eds.) (2011) Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment. National Wildlife Federation, Washington, DC, USA.

Groves, C. R., Jensen, D. B., Valutis, L. L., Redford, K. H., Shaffer, M. L., Scott, J. M., Baumgartner, J. V., Higgins, J. V., Beck, M. W. & Anderson, M. G. (2002). Planning for biodiversity conservation: Putting conservation science into practice: A seven-step framework for developing regional plans to conserve biological diversity, based upon principles of conservation biology and ecology, is being used extensively by the nature conservancy to identify priority areas for conservation. Bioscience, 52, 499-512.

Hannah, L., Midgley, G., Andelman, S., Araujo, M., Hughes, G., Martinez-Meyer, E., Pearson, R., Williams, P. (2007) Protected area needs in a changing climate. *Frontiers in Ecology and the Environment,* **5** , 131-138.

Hartmann D.L., Klein Tank A.M.G., Rusticucci M. *et al.*Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, Qin D, Plattner GK *et al.* (eds.)]. 2013, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Hayhoe K., Edmonds J., Kopp R.E. *et al.* Climate models, scenarios, and projections. In: Climate Science Special Report: Fourth National Climate Assessment. [Wuebbles DJ, Fahey DW, Hibbard KA *et al.* (eds.)]. 2017, U.S. Global Change Research Program, Washington, DC, USA.

Heller N.E., Kreitler J., Ackerly D.D. *et al.* (2015) Targeting climate diversity in conservation planning to build resilience to climate change. *Ecosphere* **6** , 65.

IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.

Jewitt D., Goodman P.S., Erasmus B.F.N., O'Connor T.G., Witkowski E.T.F. (2017) Planning for the Maintenance of Floristic Diversity in the Face of Land Cover and Climate Change. *Environmental Management***59** , 792-806.

Khoury, M., Higgins, J. & Weitzell, R. (2011). A freshwater conservation assessment of the upper mississippi river basin using a coarse-and fine-filter approach. Freshwat.Biol., 56, 162-179.

Lawler J.J. (2009) Climate Change Adaptation Strategies for Resource Management and Conservation Planning. *Annals of the New York Academy of Sciences* **1162** , 79-98.

Lawler J.J., Hepinstall-Cymerman J. (2010) Conservation Planning in a Changing Climate: Assessing the Impacts of Potential Range Shifts on a Reserve Network. In S.C. Trombulak & R.F. Baldwin (Eds.),*Landscape-scale Conservation Planning* (pp. 325-348). Springer Science & Business Media.

Lenoir J., Svenning J.C. (2015) Climate-related range shifts – a global multidimensional synthesis and new research directions. *Ecography***38** , 15-28.

McLaughlin, B. C., Ackerly, D. D., Klos, P. Z., Natali, J., Dawson, T. E. & Thompson, S. E. (2017). Hydrologic refugia, plants, and climate change. Global Change Biol., 23, 2941-2961.

Morelli, T. L., Daly, C., Dobrowski, S. Z., Dulen, D. M., Ebersole, J. L., Jackson, S. T., Lundquist, J. D., Millar, C. I., Maher, S. P. & Monahan, W. B. (2016). Managing climate change refugia for climate adaptation, 11, e0159909.

National Wildlife Refuge system (2016) Annual Performance Report FY2015. U.S. Fish & Wildlife Service

Otte E., Rousseau R. (2002) Social network analysis: a powerful strategy, also for the information sciences. *Journal of Information Science* **28** , 441-453.

Parks S.A., Holsinger L.M., Miller C., Parisien M.A. (2018) Analog-based fire regime and vegetation shifts in mountainous regions of the western US. *Ecography* **41** , 910-921.

Perez-Garcia N., Thorne J.H., Dominguez F. (2017) The mid-distance dispersal optimum, evidence from a mixed-model climate vulnerability analysis of an edaphic endemic shrub. *Diversity and Distributions***23** , 771-782.

Powers R.P., Coops N.C., Tulloch V.J., Gergel S.E., Nelson T.A., Wulder M.A. (2017) A conservation assessment of Canada's boreal forest incorporating alternate climate change scenarios. *Remote Sensing in Ecology and Conservation* **3** , 202-216.

Ramirez-Villegas J., Cuesta F., Devenish C., Peralvo M., Jarvis A., Arnillas C.A. (2014) Using species distributions models for designing conservation strategies of Tropical Andean biodiversity under climate change. *Journal for Nature Conservation* **22** , 391-404.

Randolph J. (2012) Environmental Land Use Planning and Management. Island Press, Washington, DC, USA.

Rannow S., Macgregor N.A., Albrecht J. *et al.* (2014) Managing Protected Areas Under Climate Change: Challenges and Priorities.*Environmental Management* **54** , 732-743.

Schaffer-Smith, D., Swenson, J. J., Reiter, M. E. & Isola, J. E. (2018). Quantifying shorebird habitat in managed wetlands by modeling shallow water depth dynamics. Ecol.Appl., 28, 1534-1545.

Schneider, R. R. & Bayne, E. M. (2015). Reserve design under climate change: From land facets back to ecosystem representation, 10, e0126918.

Schwartz, M. W., Hellmann, J. J., McLachlan, J. M., Sax, D. F., Borevitz, J. O., Brennan, J., Camacho, A. E., Ceballos, G., Clark, J. R. & Doremus, H. (2012). Managed relocation: Integrating the scientific, regulatory, and ethical challenges. Bioscience, 62, 732-743.

Thomson A.M., Calvin K.V., Smith S.J. *et al.* (2011) RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change* **109** , 77-94.

Thorne J.H., Boynton R.M., Holguin A.J., Stewart J.A.E., Bjorkman J. (2016) A climate change vulnerability assessment of California's terrestrial vegetation. California Department of Fish and Wildlife, Sacramento, CA, 331 pp

Thorne J.H., Choe H., Boynton R.M. *et al.* (2017) The impact of climate change uncertainty on California's vegetation and adaptation management. *Ecosphere* **8** , e02021.

U.S. Code (1997) National Wildlife Refuge System Improvement Act, 16 U.S.C. 668dd.

Veloz S., Williams J.W., Lorenz D., Notaro M., Vavrus S., Vimont D.J. (2012) Identifying climatic analogs for Wisconsin under 21st-century climate-change scenarios. *Climatic Change* **112** , 1037-1058.



## Supporting Information

Additional Supporting Information may be downloaded via the online version of this article at Wiley Online Library (www.ecologyletters.com).

Table S1. The area and current (1981-2010) climate information including annual average of minimum temperature and total annual precipitation of each refuge.

Table S2. The number of links of each refuge node based on climate directions. The number of "depart" refers to the number of other refuge nodes where a target refuge node's current-climate space will be found. The number of "arrive" means the number of other refuge nodes where their current-climate spaces will occur in a target node for the time period indicated.

Table S3. The climate categories of each refuge under each climate scenario for the time period indicated. Five climate categories are represented using five colors (red: disappearing climates; orange: isolating climates, yellow: dispersing climates, light green: enduring climates, green: climate hubs).

Figure S1. Current (1981-2010) average annual minimum temperature.

Figure S2. Changes in minimum temperature by 2070-2099 under four climate scenarios.

Figure S3. Current (1981-2010) average annual precipitation.

Figure S4. Changes in precipitation by 2070-2099 under four climate scenarios.

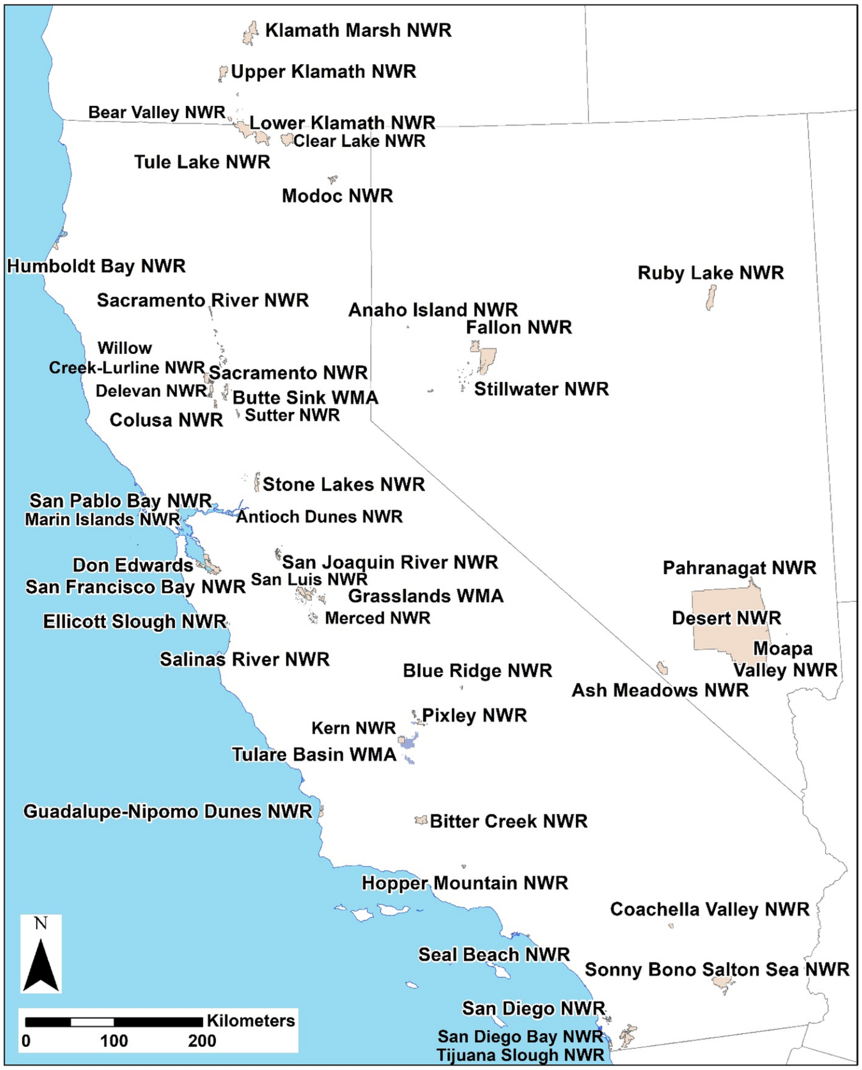


Figure 1. Locations of the NWRS (National Wildlife Refuge Systems) in the Pacific Southwest Regions of USA.

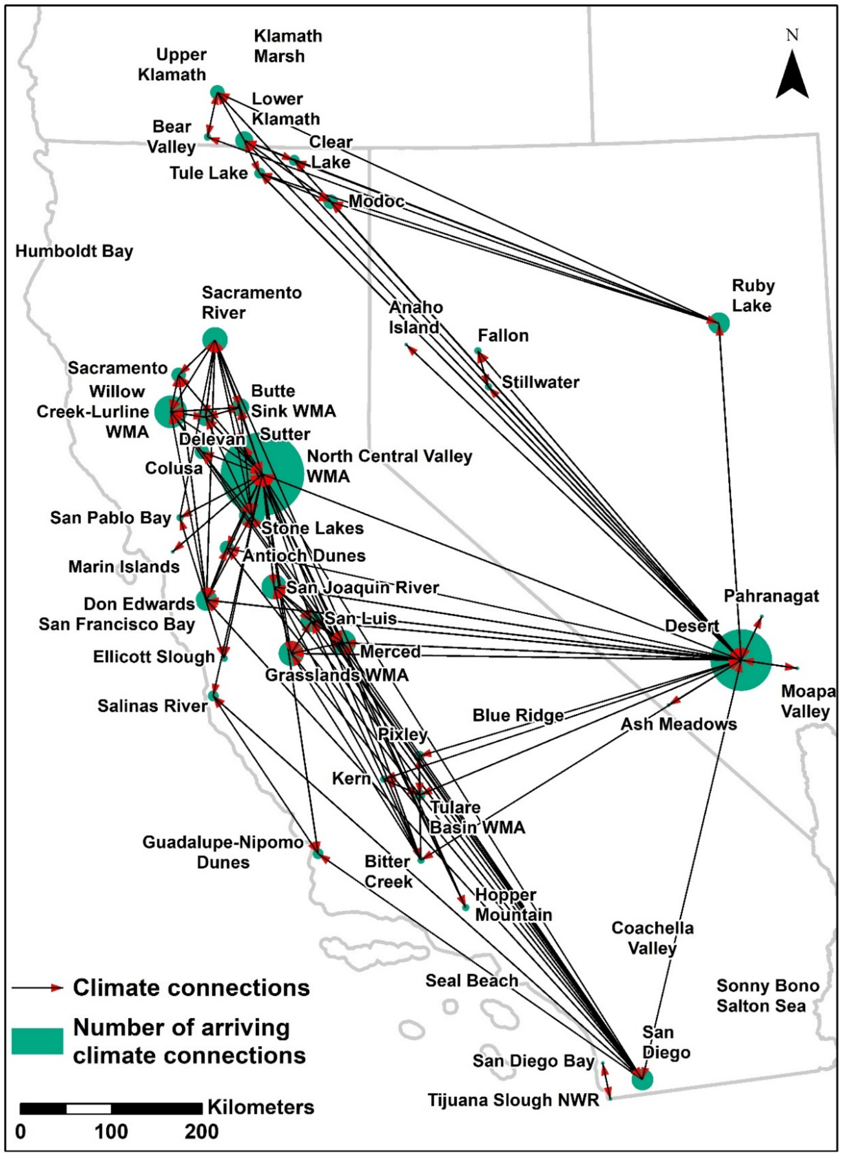


Figure 2. Current (1981-2010) climate connections among refuges. We used arrows to represent the directions of links. If an initial refuge node's current climate space is found in other refuge nodes, those nodes are final nodes and the arrowheads headed toward the final nodes. The size of the green circles represents the number of arriving climate connections to a unit or area.

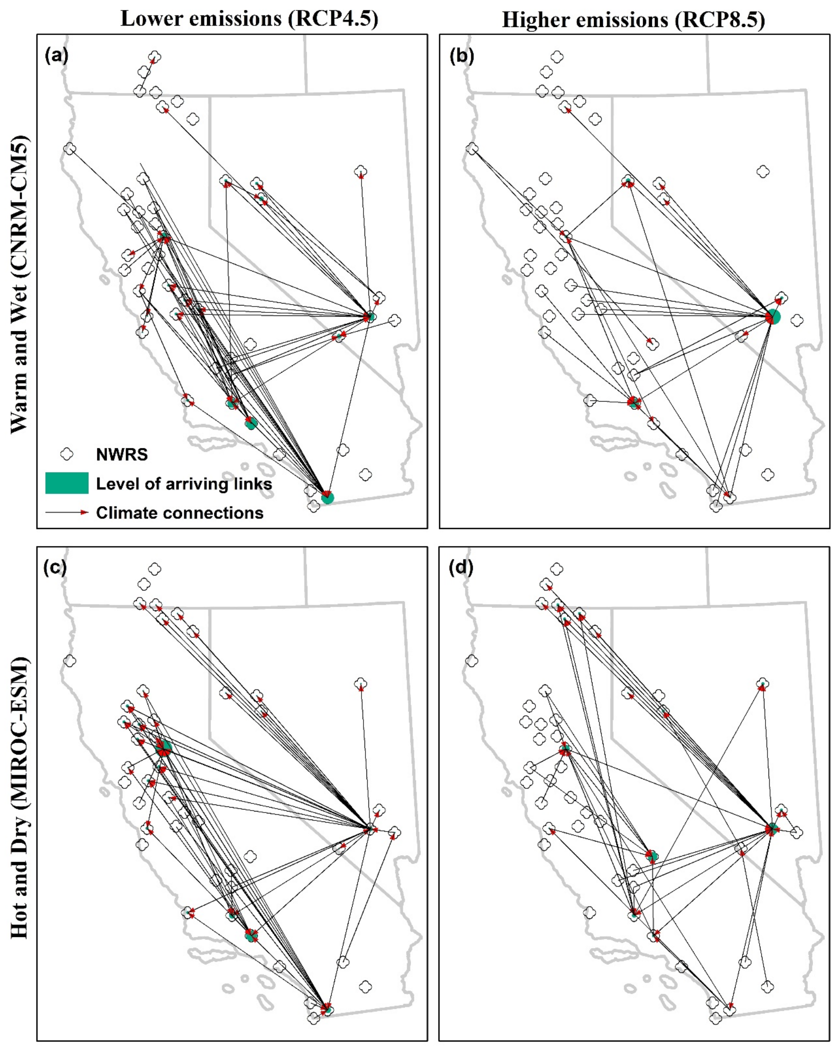


Figure 3. Climate connections among refuges by 2070-2099. If an initial refuge node's current climate space is found in other refuge nodes' future climate (2070-2099), those nodes are final nodes and the arrowheads headed toward the final nodes. We used projections of future climate using two GCMs that respectively are hotter and drier (MIROC ESM), and warmer and wetter (CNRM-CM5) than current conditions. For each GCM we used two emission scenarios (RCP 4.5 and RCP 8.5) that represent lower and higher levels of greenhouse gas concentration. The size of the green circles represents the number of arriving climate connections to a unit or area.