Minimum Required Migration Distances: A New Tool for Estimating Climate Change Impacts

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Abstract

We describe a new technique to quantify and map the impact of any specified scenario of climatic change on terrestrial communities at equilibrium and adapted to living within the affected area. The analysis is based on a determination of the minimum straight-line distance that each affected community would have to move geographically after the climatic shift in order to return to a combination of environmental conditions similar to those it had before the change. This Minimum Required Migration (MRM) distance is used as an analog of the likelihood of extinction of that local community. The MRM direction for each local community is also mapped.

MRM analysis also indicates geographic locations that serve as MRM destinations for large areas. These destinations, which represent the closest future refuges for communities currently covering large areas, maximize the likelihood of survival for these communities, and therefore should be preserved. Thus, MRM analysis can be used for conservation planning as well as for mapping severity of impact, given a particular climatic change scenario. Standard GIS tools can be used to perform the MRM severity analysis.

Introduction

While the development of global climate simulations is an active area of research, there has been relatively little investment in tools that can estimate the ecological consequences or severity of predicted changes. Tools that can rapidly evaluate the risk of extinction of existing communities facing predicted scenarios of climatic change would be of particular value, yet are uncommon. No standardized approach yet exists for evaluating the ecological impact of climate change scenarios in terms of likelihood of extinction.

In what functionally represents a meta-analysis, Thomas et al. (2004) made projections of the geographic ranges of 1,103 plant and animal species using many different climate envelope modeling methods in order to provide coarse estimates of extinction probabilities associated with mid-range climate change scenarios for 2050. Two dispersal extremes were modeled: complete and none. Probability of extinction followed a power law relationship with range size. They predicted that 15–37% of the species in their sample of regions and taxa would be "committed to extinction." Minimal warming scenarios produced lower projections of species committed to extinction than mid-range and maximum-change scenarios.

Both the approach and results of Thomas et al. (2004a) were controversial, generating three literature responses and a rebuttal. Thuiller et al. (2004) maintained that combining assessments from different models was likely to introduce unquantified model effects. They found that differences between models were as large as differences between scenarios. Thuiller et al. (2004a) questioned the ability to translate range reduction directly into species losses. Buckley and Roughgarden (2004) asserted that the summation method across species used by Thomas et al. (2004a) invalidated the species-area relationship, and also disputed the claim that extinction risk is evenly distributed with respect to range size.

Harte et al. (2004) were concerned about the assumption that all individuals within a species are adapted to the same climate envelope. If population-level adaptations to sub-ranges of climate exist, then Thomas et al. (2004a) may greatly underestimate the threat to biodiversity from climate change. They also suggested that deriving extinction predictions for a community by applying the same exponent for all species can yield poor results.

In their response, Thomas et al. (2004b) maintained that their overall estimates of area loss and extinction risk for communities were not sensitive to model details, although predictions for individual species could be. They defended use of the mean range-change per species for calculating expected extinction across multiple species. While acknowledging the possibility of populations with specialized adaptations, Thomas et al. (2004b) point out that species have typically responded to past climate changes by shifting range rather than by evolving *in situ*. Moreover, if population-level adaptation to sub-ranges exists, Thomas et al. (2004b) point out that their original shocking predictions of extinction risks are conservative. The interest sparked by this high-profile, multi-author paper indicates both the importance and the difficulty of predicting the ecological consequences of climatic change. Many of the criticisms center on the methods used to integrate individual species responses up to the community level.

Saxon et al. (2004) used a common ecoregionalization to create 500 unique domains across both current and projected conditions in the year 2100 under two contrasting emission scenarios. They were able to map locations affected least and affected most under each scenario. They identified areas at lowest risk as potential present refugia, and areas at highest risk as potential sentinel ecosystems that could be monitored for signs of stress. Saxon et al. (2004) used the quantitative degree of environmental change as their risk metric.

While the method used by Saxon et al. (2004) identified areas where there was little projected change, it did not identify areas that would become important in the future because of the projected changes that they would undergo. We distinguish here the term refugium (plural refugia), a word of modern origin denoting an area of relatively unaltered climate, from the older term refuge (plural refuges), meaning a place that provides shelter or protection from danger or distress. A refugium provides protection because it remains the same, but a refuge may provide shelter because of what it becomes under a particular climate change scenario. Conservation under climatic changes will require an ability to identify and discriminate both unchanging refugia and changing refuges.

We have conceived a new type of climate change impact analysis: the Minimum Required Migration (MRM) distances and directions which will be needed for communities to return to the same environmental conditions following predicted climate change. This analysis assumes that communities are in equilibrium with the current climate, and is based on the question, “Following a climatic change, how far would a specialized community have to successfully disperse in order to reach the geographically closest example of its preferred former environment?”

Consider a plant community that is adapted to growing in cold mountaintop ecoregions. Under climatic warming, this community will be forced to move to higher elevations until it runs out of proper local habitat. If the closest mountaintop conditions which still remain are geographically distant, the likelihood that this plant community will successfully complete the migration and survive these climatic changes will depend on (1) the MRM distance, and (2) the dispersal mechanisms of the component populations.

MRM distance may be a better potential indicator of the probability of extinction for specialized local communities than habitat loss *per se*. Assuming comparable dispersal abilities, specialized communities will have a higher extinction risk in areas where long, straight-line Euclidean dispersal distances would be required to find the same pre-change environmental conditions. If the same initial conditions are available only a short geographic distance away, then the risk of extinction for the local community will be much lower.

MRM analysis is ecoregion-based. In a given change-through-time scenario, all geographic locations that undergo an environmental change are considered in the MRM analysis. At each location, the ecoregion classification is known, both before and after climate change. The straight-line distance required to reach the closest future occurrence of the former ecoregion is designated and mapped as the MRM distance. Locations changing from an ecoregion type that ceases to exist have an infinite MRM distance, by definition. Locations that do not change in climate have an MRM distance of zero. These communities are probably not at risk, and may also provide refugia.

MRM analysis uniformly applies a single model at the community level, rather than building up from predictions of multiple independent species or populations. Rather than using the extremes of either a perfect dispersal model or no dispersal at all, our method applies an assumption of an equal dispersal ability across functional species assemblages.

Two maps can be produced per change scenario, one indicating MRM distance, and one indicating the compass direction of the MRM. For climatic warming, the direction of MRM will usually be toward the poles, but may, in some locations, be mediated by strong local physiographic effects or prevailing wind or water circulation.

In this paper, we calculate MRM distances and directions within the lower 48 United States of America under both the Canadian Climate Centre (CCC) and the Hadley United Kingdom Meteorological Office (UKMO) forecasts for the year 2099. The same two alternative future scenarios were selected, downscaled to finer spatial resolution, and used as the basis for the 2001 U.S. National Assessment of climate change impacts. The objective of MRM analysis is to show the relative severity of each climatic prediction, and to indicate the degree to which biota in particular geographic regions will be affected by each scenario. These two scenarios were selected as examples only; the MRM analysis method is general, and can be applied to any predicted scenario of climatic change.

Methods

MRM utilizes a multivariate statistical clustering technique to generate the before- and after-change ecoregions upon which the analysis is based (Hargrove, Hoffman and Sterling 2001, Hargrove et al. 2003, Hargrove and Hoffman 2004a, 2004b). This ecoregionalization method begins with GIS layers describing conditions both before and after a climatic shift. These conditions are used as multivariate descriptors of the climatic environment at each location in the map. Using a supercomputer, all cells in the before and after maps are subjected to an iterative clustering procedure. The number of ecoregions is specified by the user. When fewer than a specified number of map cells changes assignment from the last iteration, the process converges on an ecoregion classification for every map cell. Since the geographic coordinates are not used in the classification procedure, ecoregions may be spatially disjunct when the map cells are re-positioned in geographic space.

When used on a chronosequence of maps, we call this technique Multivariate Spatio-Temporal Clustering (MSTC) (Hargrove and Hoffman 2003, Hargrove and Hoffman 2004a). Used in this way, MSTC divides both the before- and after-change maps into a single, common set of ecoregions. This common assignment of ecoregions makes it possible to determine where the geographically closest conditions are in the future to those formerly in this location in the past.

The quantitative ecoregions represent community types in MRM analysis. The sensitivity of the MRM analysis to environmental change can be controlled by the level of division within the before- and after-change ecoregion maps upon which it is based. The MSTC method can divide a map into many more ecoregions than are typically produced by human experts, thus describing environments much more specifically (Hargrove and Hoffman 2004a). Borders between adjacent ecoregions can also be characterized as sharp or gradual (Hargrove and Hoffman 1999).

Ecoregions used in MRM analysis should be created such that they closely correspond to the geographic ranges of communities of interest. That way, the environmental variance within the defined ecoregion will match the ability of those communities to tolerate climatic variability. MRM distances for communities that are specialized for geographically rare and restricted habitats are best predicted using maps divided into many finely specified ecoregions, while MRM distances for generalist communities occurring over broad areas are best predicted using maps divided into only a few broadly defined ecoregions.

Using MSTC, we produced a single, common ecoregionalization within synoptic present conditions and both alternative future U.S. maps. We divided the lower 48 United States of America under present conditions, and under the CCC and Hadley UKMO forecasts for the year 2099 into 100 quantitative ecoregions. Because all spatial cells from each of the three maps in the chronosequence were submitted to a single MSTC clustering analysis, the particular unique combination of conditions represented by each ecoregion group was retained across all maps in the time series. After the cells are geographically re-assembled into the maps, a particular clustered combination of environmental conditions may be present in all, a few, or only one map in the chronosequence.

Across maps in the time sequence, ecoregions representing a particular environmental combination may change in size, shape, and location. Even though they may grow or shrink in area, or even appear and disappear during the chronosequence, each of the ecoregions represents a discrete and unique clustered combination of conditions which can be tracked across space and through time.

We characterized environments in terms of the combination of 25 variables listed in Table 1. The factors included elevation, maximum, mean, and minimum annual temperature, monthly precipitation, several soil parameters, number of frost-free days, and solar aspect and input. Each of these layers represents a data map which was developed for the continental United States, at a resolution of 1 km^2. Over 7.8 million map cells are present in each of the 25 layers. Each layer was developed in a unique way. For a more detailed description of the data development methods, see Hargrove and Hoffman (2004b).

The Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) made downscaled yearly results from these models available for the period between 1994 and 2099 at 0.5 degree spatial resolution for the continental United States. Sixteen of the 25 environmental conditions shown in Table 1 were altered to represent the conditions forecast to occur within the United States in the year 2099 by each model. We subtracted 0.5 degree resolution maps of each environmental characteristic according to the future scenario from present maps to create a set of difference maps for each scenario, and then applied these differences to the present 1 km^2 data. Relative difference maps were used for precipitation changes. In this way, high-resolution local climatic features were retained in the predictions. MSTC was then used to find the 100 most-different common environmental combinations across this set of three maps (Figure 1).

Standard GIS tools intended for aspect and allocation calculations can be adapted to perform MRM analysis without extensive custom programming. Most modern GIS systems include a function to calculate the Euclidean distance from each raster cell to a set of source locations. By looping through each ecoregion common to both maps, setting the future ecoregion locations as sources, and then "clipping" the distance layer by the present ecoregion locations, the MRM distance from each present location to the closest location in the future can be calculated. When these Euclidean distances are viewed as an elevation layer, the aspect of that elevation surface will give the direction of the MRM. Using these standard aspect tools, MRM directions can be calculated from the final MRM distances map in a single step.

While MRM distance and direction maps are based on present-day ecoregions, the MRM destination map is based on future ecoregion locations. Working backwards, Euclidean allocation functions present in many GIS systems can be used to determine the closest discrete patch of each present ecoregion for every cell in the future map. A zonal sum of the area within each discrete patch of present ecoregion, assigned by allocation zone to each separate patch of the same ecoregion in the future, shows the number of present cells for which each patch of future ecoregion represents the MRM destination. For communities presently located within this much area, this future ecoregion patch represents the geographically closest occurrence of a return to pre-change environmental conditions.

The more cells for which a patch of a future ecoregion represents the closest environmental haven, the more important it will be to preserve that patch for the future. Future ecoregion patches that potentially represent sanctuary endpoints for MRM dispersers from large areas are important to identify from a conservation perspective. If such areas were not available, the MRM distance would increase for a large number of cells, increasing the likelihood of community extinction within large areas of the present map. Such common MRM destinations are important not because of the conservation value of their present biota today, but because of the potential value that they will have as both unaltered refugia and refuges under the altered conditions in the future.

Results

Figures 2 and 3 show MRM results for the Hadley and CCC 2099 predictions, respectively. MRM distances for the Hadley prediction are longest in the mountains of WV, but there is a large area of long MRM distances in the southeast (Figure 2A). Northern IA also shows long MRM distances. MRM distances for the CCC prediction are longest in a vertical corridor including TX, OK, and KS, but are also long in northern IA, WI, and parts of SD, as well as the southeastern Piedmont (Figure 3A). This scenario also produced long MRM distances along the west coast.

MRM distances follow a negative exponential frequency distribution, with many short MRM distances and only a few very long MRM distances (locations with infinite MRM distances under the CCC scenario were excluded; the Hadley UKMO scenario had no such locations). When graphed as a cumulative frequency distribution (Figure 4), the curve of CCC 2099 MRM distances rises faster, indicating that the impact of the CCC scenario is more severe (*i.e.*, more longer MRM distances and therefore higher likelihood of extinction of local communities) than the Hadley 2099 scenario. The curve for the CCC scenario also reaches a higher cumulative plateau, showing that it predicts changes over a greater area than does the Hadley prediction. Such a graphical depiction makes clear the relative severity of impact of multiple scenarios over a particular geographic area.

MRM direction is mapped as aspect when illuminated from the east in Figures 2B and 3B. The frequency distribution of MRM directions (Figure 5) indicates a positive north or northwest bias in both CCC and Hadley climate scenarios, with a corresponding negative bias in southern and southwestern MRMs. A northward trend is expected, since these are both warming scenarios. The standard deviation of MRM direction across the 48 States is nearly equal for these two scenarios (115 and 117 degrees, respectively). The fact that directional variance is equal across both scenarios may suggest that directional variance is a feature of the geographic area rather than the scenarios or the model predictions themselves.

Ecoregions adjacent to areas experiencing climatic shifts are the major potential destinations of MRM dispersers. For both scenarios, ecoregions in MT, ND, MN, IA, IL, IN, OH, and the northeast potentially receive the most MRMs. In addition to these, the Mississippi Valley ecoregion is predicted potentially to receive many MRM dispersers in the CCC scenario, while FL and the coastal plain potentially receive many MRMs in the Hadley UKMO scenario. These regions flank significant areas of change in each case. Of course, the MRM distance is measured only to the cells along the nearest edges of these regions.

Large discrete portions of ecoregions are likely to receive more migrant communities than smaller areas, especially ones with longer shared borders. The metric of conservation interest is value per unit area, since this often determines the cost of protection effort, restoration effort, and acquisition. We divided the number of cells whose communities are potentially ending up in each discrete portion of each ecoregion by the number of cells in that portion of the region in order to get a value per unit area. To use a hydrologic analogy, these areas “drain” communities from larger source areas than themselves. Spatial areas potentially receiving dispersing communities from large source areas are of particular value, since they represent important future refugia or refuges for large areas experiencing climatic changes.

Future ecoregion areas whose cells potentially receive dispersing communities from large areas are very localized, and differ substantially between the two scenarios (Figures 2C and 3C). According to the Hadley scenario (Figure 2C), several areas within the Piedmont will become significant refugia, along with isolated areas in the Mississippi valley and Sabine River valley. The northern Ozarks are identified as a large potential future refugium, as are several areas in northern WI. In the western U.S., the Hadley prediction results in future refugia scattered throughout the eastern Rockies, the arable parts of UT, and western WY. The central valley of CA becomes an important refugium under the Hadley scenario, as does the Olympic peninsula of WA.

Under the CCC scenario, parts of the NC and VA mountains, the southern Smoky Mountains, part of southern WV, and areas flanking Chesapeake Bay will become important future refugia, among others (Figure 3C). In the western U.S., the CCC scenario predicts numerous localized future refugia in the CO Rockies, western UT, and Northeast WY/Southeast MT, as well as others. Future refugia are absent from several gray areas of the map (Figure 3C) which, under this scenario, change dramatically into ecoregions that have no counterpart in the present U.S.

Discussion

Although whole communities are not usually thought of as capable of migrating, their locations obviously shift over time. Most of these community changes occur slowly, as with continental drift. Whether the “same” community can be said to migrate or whether a slightly different new community composition re-assembles is a matter of degree. In MRM analysis, each quantitative ecoregion is taken to represent a distinct community or set of communities. If the combination of environmental conditions comprising a particular ecoregion shifts geographically, presumably the community or communities formerly living within that ecoregion must either adapt or also undergo a geographic shift.

MRM distance is not the only component of extinction risk — another is migration ability. Although individual species vary widely in their vagility, MRM analysis assumes that adapted communities have comparable dispersal abilities. It would be necessary for most of the major components of a specialized community to successfully complete the MRM dispersal for that community to regain the functionality in the new location that it displayed at the original location. The species component of the community having the least ability to disperse may limit the rate of community dispersal, and this dispersal-limiting value may indeed be similar across all communities. The assumption that all adapted communities have similar dispersal abilities makes the continental-scale geographic comparison of extinction risk possible.

With an assumption of equivalent dispersal ability, a map of MRM distances quantifies the risk of extinction of communities currently present in every location following particular scenarios of environmental change. MRM analysis assumes that communities are less likely to successfully complete longer MRM dispersals than shorter ones, and that failure to complete MRM migration means extinction of the community that originated from that location. The community currently in a location with a changing ecoregion assignment is assumed to become locally extinct due to the climatic shift. The MRM distance shows whether this community is likely to successfully reach the closest similar new location.

MRM considers straight-line shortest migration distances only. There is no consideration of potential connectivity or the actual route required for such a migration, although this has been shown to be important (Hargrove et al. 2005, Jepsen et al. 2005). Nor is there consideration of minimum patch sizes (although patches are generally large due to the continental scale of the analysis). Thus, MRM analysis probably underestimates the risk of extinction in some cases.

MRM analysis assumes that communities are at selective equilibrium with the environmental conditions in their current locations, and that they are adapted to find these conditions optimum. MRM analysis also assumes that communities will have little ability to adapt to climatic change, and that their geographic range will continue to be restricted to the ecoregion where they originally occurred.

Particular communities may experience significant losses in total area of habitat without necessarily having long MRM distances. Communities presently found in many cells may be forced into a handful of future cells as an MRM destination. Indeed, this is the mechanism by which we identify future parcels that are valuable for conservation. However, this collapse of inhabited area may represent a type of extinction risk that is not explicitly considered in MRM analysis. Concentration of a community type into a smaller area likely increases susceptibility to predation and disease and reducing resilience.

We do not intend to downplay such risks. But prior efforts have been criticized for trying to estimate extinction risk exclusively from habitat loss (Thuiller et al 2004, Buckley and Roughgarden 2004). MRM analysis should be paired with analysis of changes in habitat area for a particular change scenario. The maps shown in Figure 1 provide a convenient means of estimating those area changes (Hargrove and Hoffman 2003, Hoffman et al. 2004).

Existing communities under future climate change scenarios show a gradual increase in MRM distance from the edges toward the middle within most large areas of climatic change, resulting in a central ridgeline where the MRM distances are the greatest when depicted as elevation aspects (Figures 2B and 3B). MRM dispersers move away in all directions from the central portions of most changed locations. Central ridgelines suggest that the three maps were divided into a sufficiently large number of clustered ecoregions initially. If MRM distance changed abruptly at borders, and MRM directions were unidirectional, it might mean that the three maps had been divided into too few initial ecoregions. Division into more ecoregions might result in a substantial geographic shift in the edges. The smoothly tapering distance elevations suggest that this is not the case, and that a sufficient number of initial ecoregions were used.

One exception is the border in northern IA, which appears as an abruptly ending incline sloping in uniformly northern directions under both change scenarios. The sharp edges in IA and central TX may have resulted from the largely homogeneous nature of these areas. Ecoregions delineated in these areas are large, and borders between them are likely to be gradual, not distinct (Hargrove and Hoffman 1999). Under these circumstances of uniformity, ecoregion borders placed in particular geographic locations may shift substantially if more ecoregions are created initially, and the emphasis placed on a border in a particular geographic location may be somewhat arbitrary. A long strip running parallel with the MRM direction might make a safer planned refuge in such gradually changing areas.

The MRM aspect maps show many examples of localized pits or cones which have unchanged remnant regions at the bottom. If these pits descend to an MRM distance of zero, then these locations represent habitat remnants that serve as future refugia. Many of these small pits can be seen on the CCC map in central KY (Figure 2B) and in the Hadley map in central GA and northern LA (Figure 3B). Many of these same small future refugia can be seen colored red in Figures 2C and 3C.

Not all of the red areas in Figures 2C and 3C are important because they are unchanged remnants, however. Some of these areas are important MRM destinations even though they have themselves undergone ecoregion changeover, making them future refuges. Their importance is because of what they are projected to become. Locations of such future refuges and refugia will be particularly sensitive to the downscaling methods that are used as well as to the scenario of change. Some areas indicated as important future refuges and refugia may be artifacts of the differences in resolution between the downscaled predictions and the original 1 km^2 environmental data sets.

Both MRM distance maps and locations of predicted future refugia and refuges are of potential conservation significance. Areas with long MRM distances may represent conservation opportunities in the form of transplantation interventions. Such manually assisted species displacements would reduce the chance of extinction of communities presently in these locations, and would mitigate the impact of the climate change scenario. Locations of predicted future refugia and refuges are potential targets for preservation. Such preservation, however, differs substantially from the usual sense of this term. It is not the current environmental conditions or current biota that make such parcels valuable, but their geographic location and the predicted future environmental conditions. Thus, such preservation will not entail the protection of the biota currently inhabiting these parcels. After all, the preservation plan is for the current biota to go extinct locally, and to be replaced by incoming MRMs. This kind of protection amounts to ensuring that the parcel is left available for the new biota, and is not urbanized or used for agricultural or forestry purposes. Such protection might incorporate a periodic disturbance, like plowing or burning, to encourage invasion and stimulate the desired community change.

With sufficient computational capacity, one could use MSTC to examine the predictions of a particular scenario at multiple points in the future, examining the locations of future refugia and refuges as they migrate through time. The movement of future refugia and refuges through time could be steady and stepwise, or they could suddenly jump across geographic space in a discontinuous way. Communities would be better able to keep up with stepwise geographic movement of future refugia and refuges, since such movement would only require a sequence of short MRMs. In any case, the risk of extinction of each local community, shown by the MRM distances analyzed at each time interval, would accurately reflect such differences. From this perspective, locating lands to be acquired and preserving them is not properly viewed as a static problem, but rather as a dynamic process.

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Table 1. Environmental characteristics used in the Multivariate Spatio-Temporal Clustering (MSTC) procedure. Each of the 25 characteristics represents a 1 km^2 resolution map of the continental U.S. containing more than 7.8 million cells. Asterisks indicate characteristics spatially altered under two alternative climate change scenarios.

Environmental Characteristic	Changed for Scenarios
elevation	
maximum annual temperature	*
mean annual temperature	*
minimum annual temperature	*
mean monthly precipitation (12)	*
soil Kjeldahl nitrogen	
soil organic matter	
soil plant-available water capacity	
frost-free days	*
depth to water table	
soil bulk density	
depth of mineral soil	
solar aspect	
mean solar insolation	

Figure Legends

Figure 1. Comparison of a common set of quantitative ecoregions within the present-day synoptic U.S. (A) and environments predicted for the year 2099 by the Canadian Climate Centre (CCC) Global Climate Model (GCM)(B), and by the Hadley United Kingdom Meteorological Office (UKMO) GCM (C) for the VEMAP program. One hundred common environmental combinations were identified across three versions of the U.S., the present and two alternative future scenarios for 2099, using Multivariate Spatio-Temporal Clustering. Random colors of the regions are consistent across the triad of maps. Comparison of any color across maps indicates how that environmental combination will change in size and shift geographically according to this future climate scenario. Substantial changes are predicted for the southeastern United States.

Figure 2. Minimum Required Migration (MRM) impact analysis of the Hadley United Kingdom Meteorological Office (UKMO) Global Climate Model for the continental United States for the year 2099.

(A) Map of MRM distances. Locations shown in green are unchanged, or require short migrations to find conditions similar to those present in these locations today. Biota growing in locations shown in red must successfully migrate long distances to reach locations having the same conditions in the future. Locations in yellow will require intermediate MRM distances.

(B) Map of MRM directions, colored as aspect when the MRM distance map is viewed as an elevation surface that is illuminated from the east. Ridge lines in this map are locations where the environment has changed that are far from similar conditions in the future. Large “watersheds” and pits can be seen in some locations which “drain” MRM dispersers to unchanged areas, shown in green.

(C) Map of future refugia, indicating how many cells will have potential MRM dispersers using this spatially distinct patch as a migration endpoint. Numbers of cells contributing MRM dispersers are divided by area of the migration endpoint patch, so that the importance of each destination patch per unit area is mapped. Areas whose cells potentially receive MRMs from less than one cell are colored green; areas whose cells receive MRMs from about one cell are colored yellow. Areas whose cells receive MRMs from more than one cell are colored darker red, and will be important future refugia. These areas will provide the closest environmental havens for MRM dispersers coming from large areas. Without these future refugia, the MRM distances would increase within large areas of the map.

Figure 3. Minimum Required Migration (MRM) impact analysis of the Canadian Climate Centre (CCC) Global Climate Model for the continental United States for the year 2099.

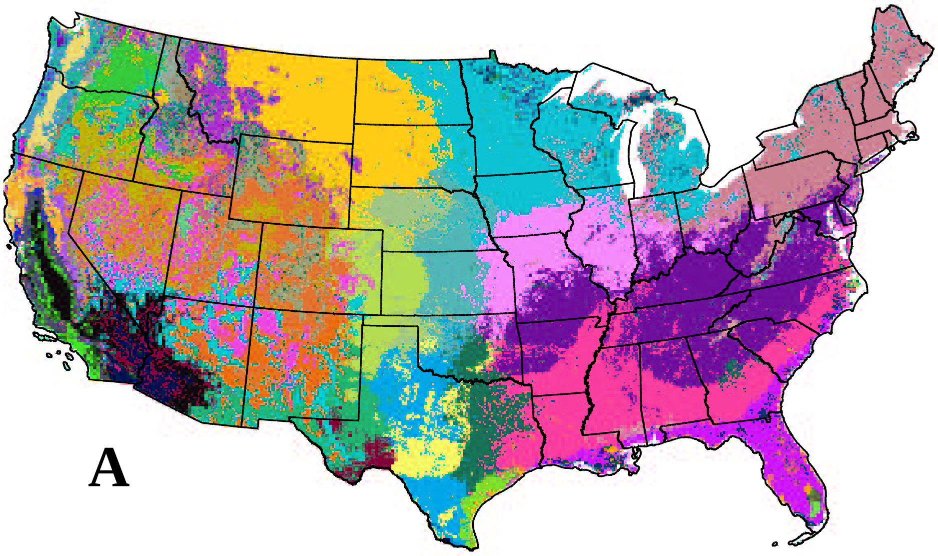
(A) Map of MRM distances. Locations shown in green are unchanged, or require short migrations to find conditions similar to those present in these locations today. Biota growing in locations shown in red must successfully migrate long distances to reach locations having the same conditions in the future. Locations in yellow will require intermediate MRM distances.

(B) Map of MRM directions, colored as aspect when the MRM distance map is viewed as an elevation surface that is illuminated from the east. Ridge lines in this map are locations where the environment has changed that are far from similar conditions in the future. Large "watersheds" and pits can be seen in some locations which "drain" MRM dispersers to unchanged areas, shown in green.

(C) Map of future refugia, indicating how many cells will have potential MRM dispersers using this spatially distinct patch as a migration endpoint. Numbers of cells contributing MRM dispersers are divided by area of the migration endpoint patch, so that the importance of each destination patch per unit area is mapped. Areas whose cells potentially receive MRMs from less than one cell are colored green; areas whose cells receive MRMs from about one cell are colored yellow. Areas whose cells receive MRMs from more than one cell are colored darker red, and will be important future refugia. These areas will provide the closest environmental havens for MRM dispersers coming from large areas. Without these future refugia, the MRM distances would increase within large areas of the map. Gray areas represent unique new ecoregions whose combination of environmental conditions has no analog in the present.

Figure 4. Cumulative frequency distribution of Minimum Required Migration (MRM) distances calculated from predictions from two leading Global Climate Models for the continental United States for the year 2099. The steeper climb of the cumulative curve for the Canadian Climate Center (CCC) scenario shows that it has more cells with longer MRM distances, and has a greater impact. The higher plateau of the CCC scenario indicates that it affects a larger area as well.

Figure 5. Direction of Minimum Required Migration under predictions from two leading Global Climate Models for the continental United States for the year 2099, in terms of percentage of map cells with changed environments. Both scenarios show a bias for northerly or northwestern MRMs, and against southerly MRMs.



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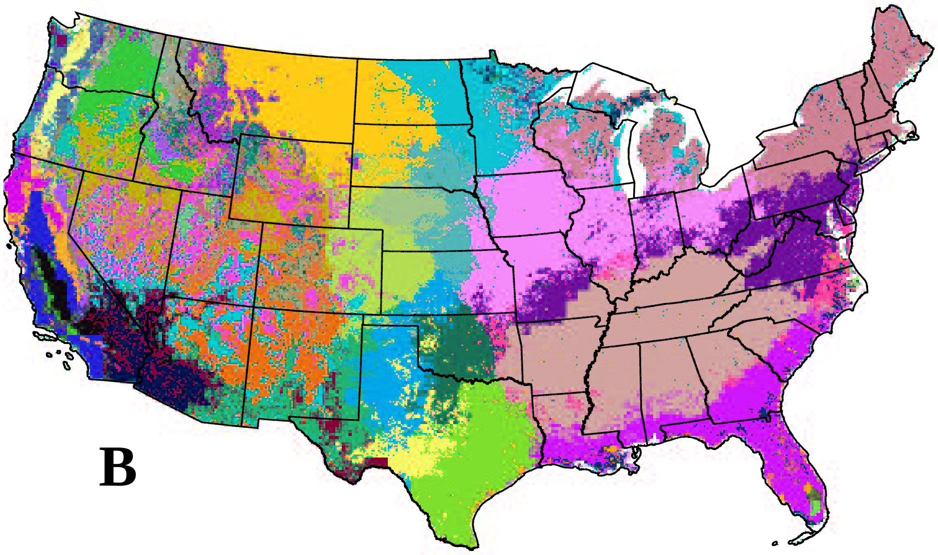

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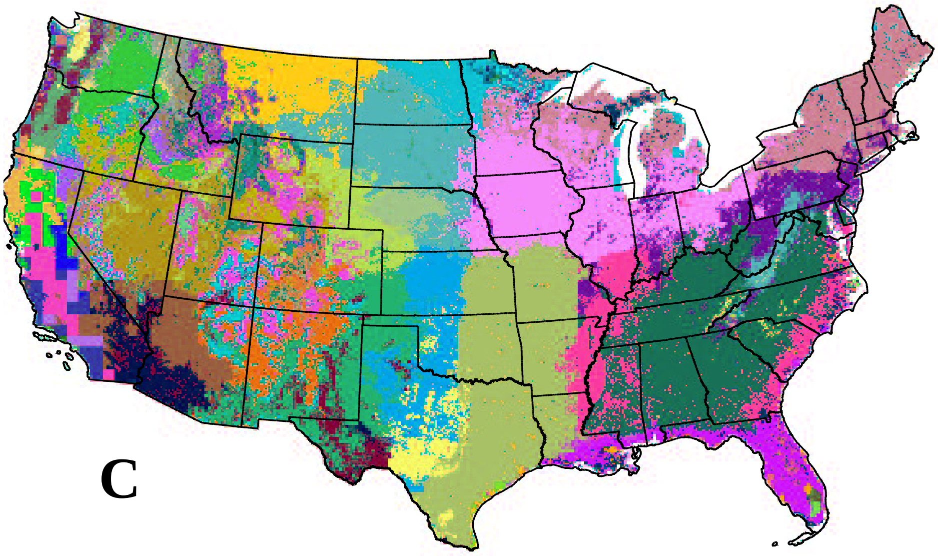

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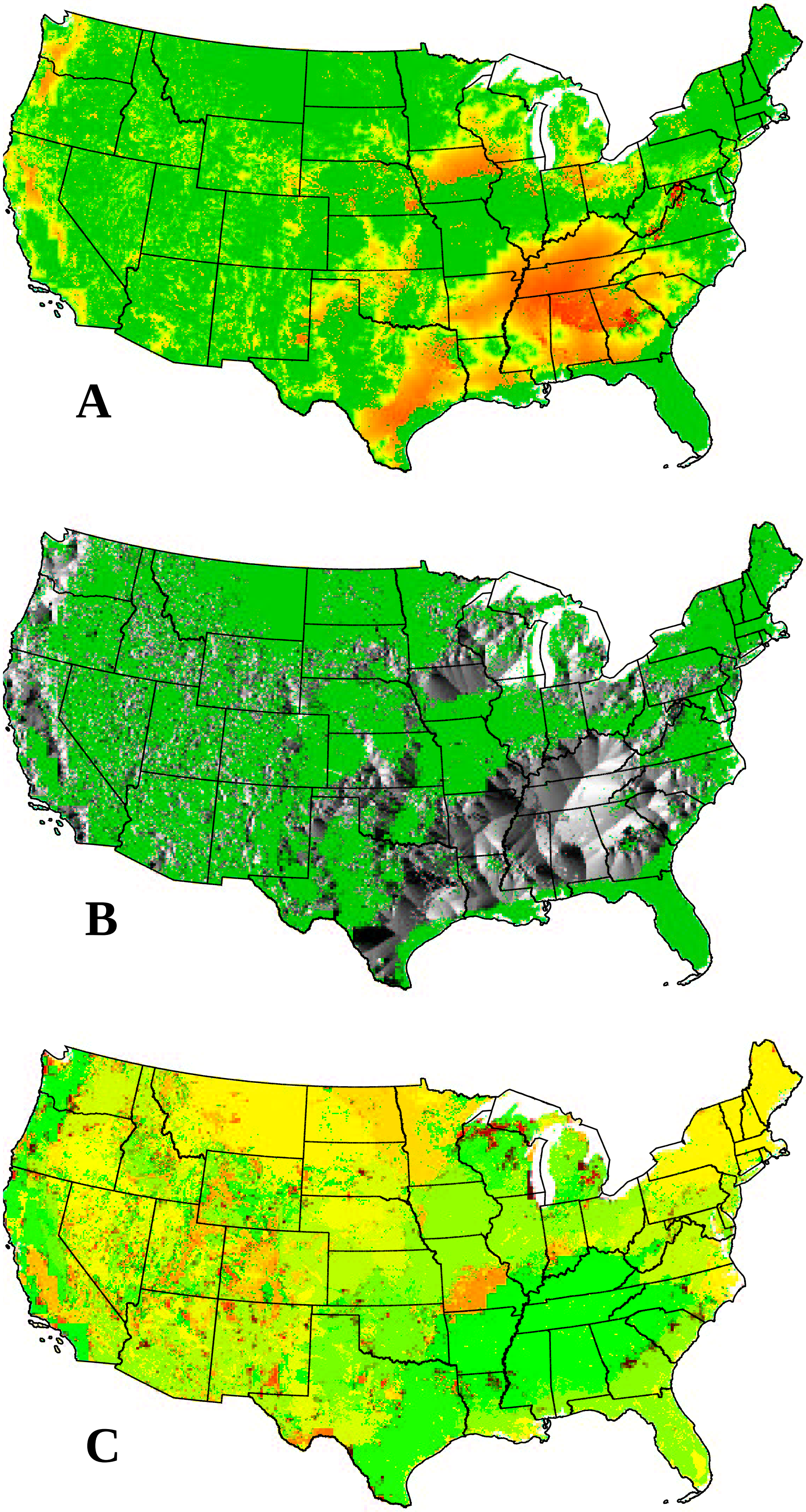
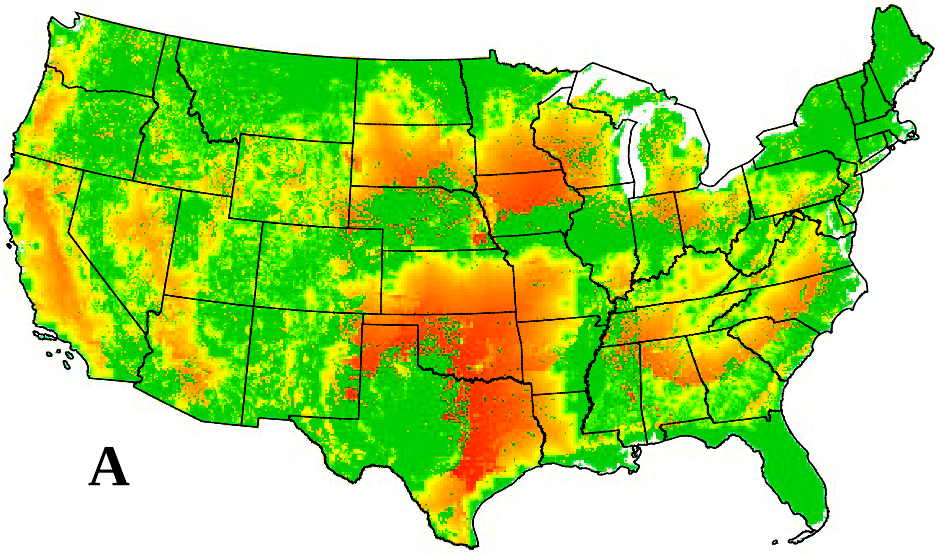

A
B
C



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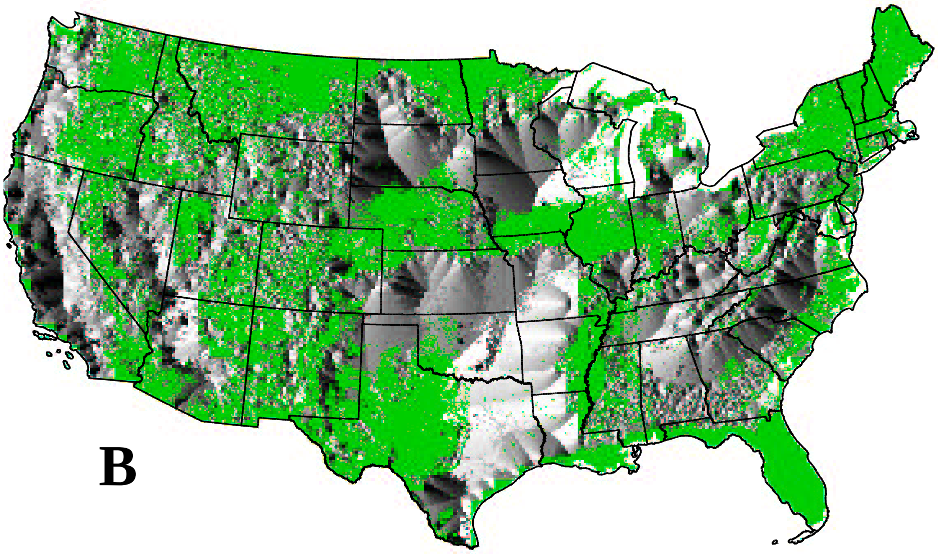
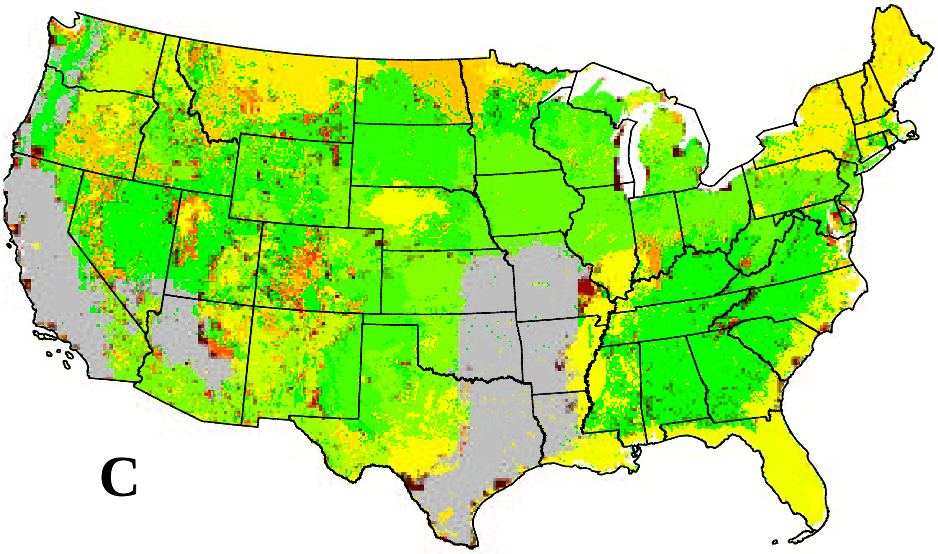


B



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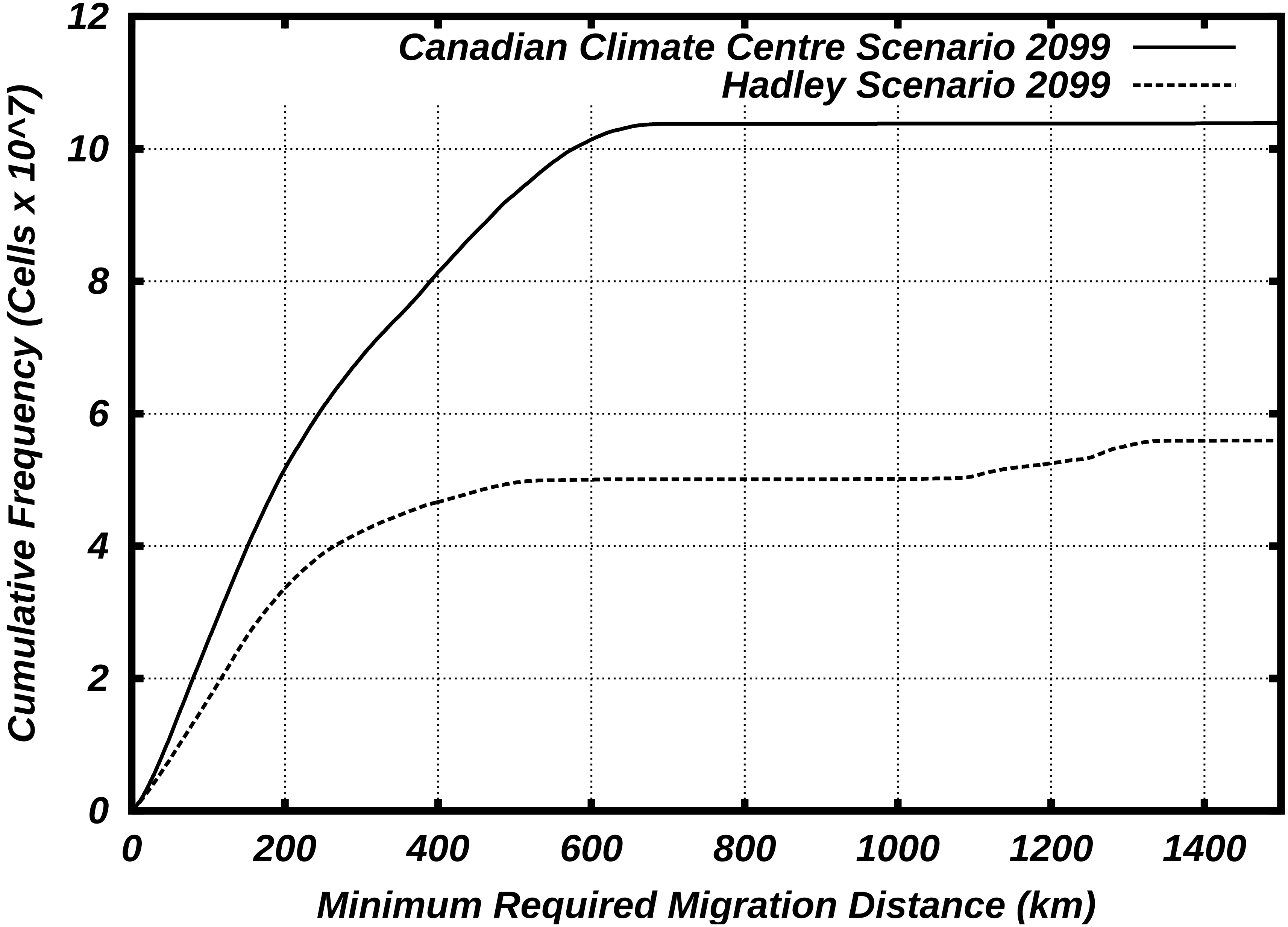
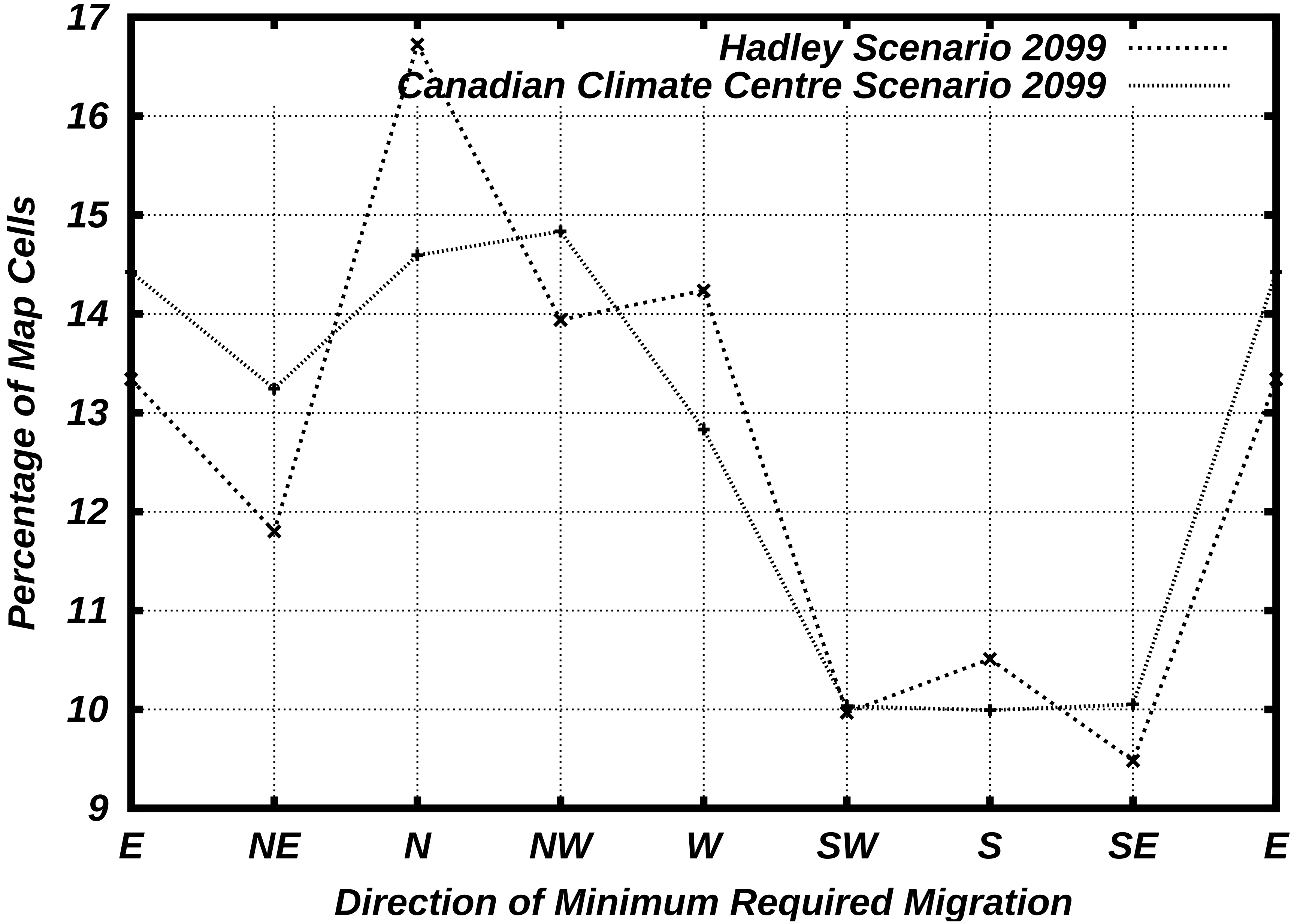

Canadian Climate Centre Scenario 2099
Hadley Scenario 2099
Cumulative Frequency (Cells x 10^7)
0
2
4
6
8
10
12
0
200
400
600
800
1000
1200
1400
Minimum Required Migration Distance (km)


Hadley Scenario 2099
Canadian Climate Centre Scenario 2099
Percentage of Map Cells
17
16
15
14
13
12
11
10
9
E
NE
N
NW
W
SW
S
SE
E
Direction of Minimum Required Migration