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LETTER

Mapping environments at risk under different global climate change scenarios

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Abstract

All global circulation models based on Intergovernmental Panel on Climate Change (IPCC) scenarios project profound changes, but there is no consensus on how to map their environmental consequences. Our multivariate representation of environmental space combines stable topographic and edaphic attributes with dynamic climatic attributes. We divide that environmental space into 500 unique domains and map their current locations and their projected locations in 2100 under contrasting emissions scenarios. The environmental domains found across half the study area today disappear under the higher emissions scenario, but persist somewhere in it under the lower emissions scenario. Locations affected least and those affected most under each scenario are mapped. This provides an explicit framework for designing conservation networks to include both areas at least risk (potential refugia) and areas at greatest risk, where novel communities may form and where sentinel ecosystems can be monitored for signs of stress.

Keywords

Biodiversity conservation, climate change, domains, ecoregions, mapping, multivariate cluster analysis, scenarios.

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INTRODUCTION

Significant disruptions to natural ecosystems are widely expected as a result of global climate change. There is uncertainty about the pace of this change because that depends on future greenhouse gas emissions and complex feedbacks in the bio-geo-atmosphere system that are hard to predict (Pielke *et al.* 1998). Nonetheless, environmental changes will create additional stresses on those plant and animal populations whose adaptive responses are unable to keep pace.

There are several current approaches to assessing the magnitude of risk that climate change poses for biodiversity. Niche models project future distribution patterns from current or historical relationships between climate and biota (Peterson *et al.* 2002). Deterministic regression tree analysis models incorporate climatic and physical factors, such as soils, that constrain species' distributions but will be invariant under climate change (Iverson *et al.* 1999). Dynamic Global Vegetation Modeling (DGVM) projects the distribution of plant functional types based on environmental parameters (Sitch *et al.* 2003). These approaches are robust where relationships between the environment and taxa or growth form are well known and strong. They need to be complemented by generic tools to guide decision making for the majority of the biota whose historic, current or potential environmental ranges are unknown and for identifying future sets of environmental conditions with no current analogue, hence no readily predictable community structure or composition.

We introduce a novel approach to mapping global climate change in which environmental domains are identified based on climatic, edaphic and topographic attributes. Such factors are the foundation of widely used biogeographic ecoregions (Bailey 1996). We analyse current and modelled future climatic factors together with edaphic and topographic factors considered unlikely to change significantly over a century. Once every location in geographic space has been assigned to current and future domains in environmental space, we map the whereabouts of similar domains at different times and assess the magnitude of change between current and future domains at any location under each scenario.

Our approach is not limited to projecting the future whereabouts of current conditions. Constructing domains from data that include present and modelled future climatic factors allows us to recognize domains that occur in the future but have no current analogue as well as those that presently occur but cease to exist. All sufficiently unique combinations of topographic, edaphic and climatic factors are identified and tracked, regardless of where or when each combination occurs.

Hand-drawn ecoregions provide a framework for planning biodiversity conservation to represent physical environmental gradients at the ecoregion level (Olsen & Dinerstein 1998) and for sites within an ecoregion (Groves 2003). Our objective is to present climate-dynamic domains, enabling conservation practitioners to anticipate rapid climate change. We do this in three ways.

First, we map the magnitude of projected environmental change at every location. This identifies places where biotic communities will be under greater or lesser stress from rapid climate change and, hence, where loss of biodiversity and ecosystem services is at correspondingly greater or lesser risk.

Second, we compare the current and modelled future spatial distributions of today's environmental domains. This highlights places where species with good dispersal capabilities might move and places where those with poor dispersal capabilities might be stranded.

Third, we map all areas with similar environmental domains consistently, even if they are not contiguous. This highlights gaps where incompatible soils, terrain or land use change are most likely to interrupt corridors for poleward or up slope dispersal by plants and animals attempting to track climate change (Malcolm & Markham 2000).

METHODS

The study area comprised 695 768 5 × 5 km grid cells covering the continental USA and a portion of north-western Canada. There were four steps in our analysis. First, we associated each 5-km × 5-km grid cell with topographic data, edaphic data and three sets of climatic data – those under current conditions and those under two different emissions scenarios. Second, treating every grid cell/climate combination as independent data points in a multi-dimensional data space, we used a multivariate clustering algorithm to allocate every point to one of 500 non-overlapping domains within the same data space. Third, we mapped these domains back into geographic space to see where they are located currently and under each climate change scenario. Lastly, we calculated the distance in data space between the current and future domains assigned to every location.

To represent current climate, we used 4-km data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) for the period 1961–1990 (Daly *et al.* 2002), resampled to 5-km resolution. To represent future climate, the changes projected by the Hadley Centre's general circulation model HadCM3 for the year 2100 under two emission scenarios were downscaled to half-degree resolution (Mitchell *et al.* 2003) and added to the current climate values for each grid cell. This method assumes that current local climate patterns persist. We selected the HadCM3 model for our experiment because it is one that incorporates positive feedback between climate change and vegetation change and it shows little drift in surface climate due to a higher ocean resolution (Gordon *et al.* 2000; Pope *et al.* 2000). An inter-model comparison is planned.

Like previous IPCC assessments, our intent was not to make forecasts, but rather to explore the magnitude of environmental change and geographic shifts in the distribution of environmental domains under different greenhouse gas emissions scenarios. We examined two scenarios: A2 (reaching concentrations of 735–1080 p.p.m. CO_2 in 2100) and B2 (reaching concentrations of 545–770 p.p.m. CO_2 in 2100) (Nakicenovic & Swart 2000). These span a range from approximately twice to approximately four times the pre-industrial levels of 275 p.p.m. CO_2. Scenario A2 assumes modest reductions in the growth of global population, the energy intensity of developed economies and the disparities between the developed and developing world. Scenario B2 assumes more substantial reductions.

We selected environmental variables by first conducting a literature search on physical predictors of vegetation and primary productivity and then discarding those factors we could not replicate with the available data sets. We found data for three topographic variables (US Geological Survey 1996) four edaphic variables (Global Soil Data Task Group 2000) and 19 climate variables in both the HadCM3 and PRISM data sets. In order to give equal weight to stable and dynamic variables and to minimize their cross-correlation, we used Principal Component Analysis (PCA) to select the seven most distinct climate variables (Table 1). These include both process-limiting variables such as moisture stress (annual precipitation/potential evapotranspiration) and distribution-limiting variables such as seasonal extremes of moisture and temperature. All 14 variables received equal weighting in the analyses and were normalized to a consistent range.

We used a non-hierarchical iterative *k*-means algorithm based on Euclidean distance in data space to allocate all cells to domains. The choice of the number of domains was based on previous runs with two to 5000 domains using climate data for the 48 contiguous US states. We found that 500 domains are enough to separate large uniform areas, such as the south-eastern Atlantic seaboard, without creating excessive numbers of units in small heterogeneous areas, such as the Rocky Mountains.

Initially, the most dissimilar cells served as domain seeds. Each observation was assigned to the closest seed. Then

Table 1 A Principal Components Analysis of the 14 standardized input values at the centroid of all 500 domains shows that temperature, edaphic factors and precipitation load respectively on the first three principal components and account for 77.4% of the variance

PCA	1	2	3
Eigenvalue	6.460	2.673	1.706
Per cent of variance accounted for	46.1	19.1	12.2
Cumulative per cent	46.1	65.2	77.4
Topographic variables (stable)			
Elevation (m)	−0.5627	−0.2507	0.5072
Compound Topographic Index	0.4529	0.1322	−0.6377
Potential solar radiation	0.7737	−0.0382	−0.0559
Edaphic variables (slow)			
Profile available water capacity (mm)	0.1064	0.8965	−0.1369
Soil bulk density (g/cm)	0.1293	0.8058	−0.0709
Soil carbon density (kg/m^2)	0.0893	0.8304	−0.2602
Total soil nitrogen (g/m^2)	0.0693	0.8573	−0.2659
Climate variables (fast)			
Potential evapotranspiration (mm)	0.6933	0.2141	−0.2507
Precipitation/potential evapotranspiration	−0.1248	−0.1682	0.8937
Precipitation coldest quarter (mm)	−0.0709	−0.1993	0.9186
Precipitation warmest quarter (mm)	−0.1956	−0.2395	0.8817
Mean temperature coldest quarter (°C)	0.9233	0.0278	−0.0016
Mean temperature warmest quarter (°C)	0.9126	0.1768	−0.2374
Average monthly temperature (excluding months < 0 °C) (°C)	0.9244	0.1278	−0.2254

Loading of the individual variables is calculated after varimax rotation of the PCA space.

domain centroids were recalculated and observations were re-assigned to the new centroids. The iterative process continued until acceptable convergence on an equilibrium classification (> 0.5% of cells changing) was obtained. We obtained 500 unique domains, each having mutually exclusive combinations of the 14 variables and a consistent level of environmental heterogeneity. The coordinates of each centroid represent the domain's position in environmental space (its *P*-median index). Additional methodological details, examples of maps derived from climate factors alone and examples of maps with random colour assignments to emphasize domain boundaries are reported by Hargrove & Hoffman (2004).

We used PCA to assess the relationships among the 14 variables. Temperature, edaphic variables and precipitation load respectively on the first three principal components, which together explain 77.4% of the total variation (Table 1). By assigning the first three principal components to primary colours in the Red–Green–Blue (RGB) colour scheme, it is easy to visualize the relationships among the domains in environmental space as colours and their geographic relationships as patches on a map.

The distance in environmental (PCA) space between the centroids of two domains is an index of their environmental diversity (Faith & Walker 1996). Thus we use the same metric when comparing the current domain with a future domain at the same location and when comparing two concurrent domains at different locations.

RESULTS

The primary results of our analysis are three maps (Fig. 1) in which the same RGB colour scheme was used to depict every environmental domain whenever and wherever it occurs. By comparing the maps of current domains with those for modelled future domains, one can see how different emissions scenarios would drive different future biogeographic patterns. The most obvious feature of Fig. 1 is the influence of higher temperatures in the American Midwest and the Appalachian Mountains, clearly more pronounced under Scenario A2 than under Scenario B2.

We scaled change over time between the domains at each grid cell against the difference between the current domains at Miami FL and Barrow AK, set arbitrarily as 10 (Fig. 2). On this index, the magnitude of change from current conditions to conditions under Scenario B2 is less than 3.75 over most of the study area. Under Scenario A2, changes in some cases exceed 5.0 – a displacement in environmental space more than half as great as the current difference between Miami FL and Barrow AK. In order to evaluate the significance of such change for particular ecosystems or species, the specific variables for current and modelled future scenario domains may be compared. As an example, average climatic variables for current and future scenario domains in the US Corn Belt (US Geological Survey 1997) are given in Table 2.

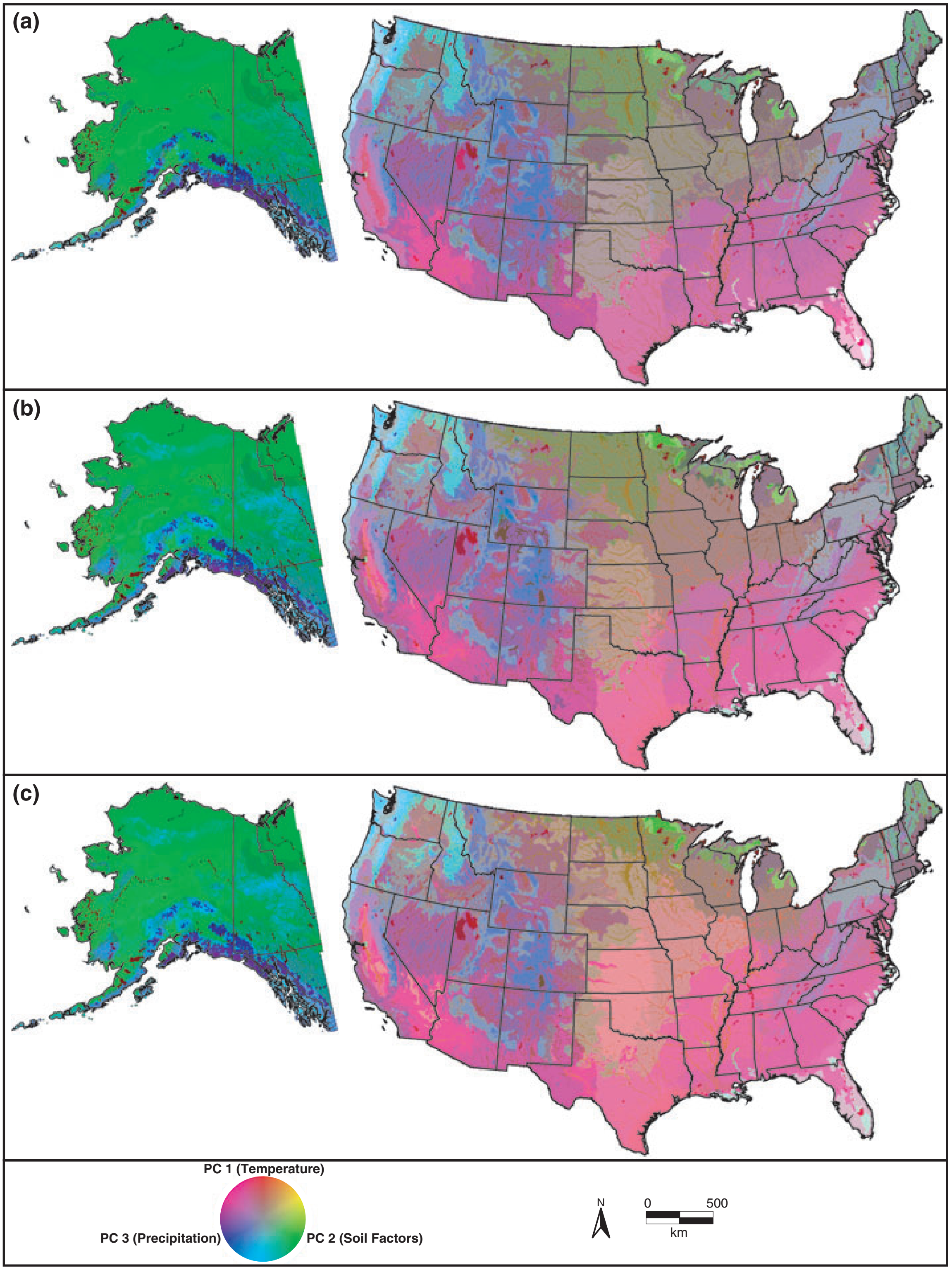

Figure 1 Five hundred domains in the continental USA and north-western Canada are depicted in colours reflecting the relative dominance of temperature factors (red), edaphic factors (green) and precipitation (blue). Colour assignments are consistent regardless of when or where each domain occurs. (a) Current conditions. (b) Scenario B2, moderate greenhouse gas increases. (c) Scenario A2, rapid greenhouse gas increases.

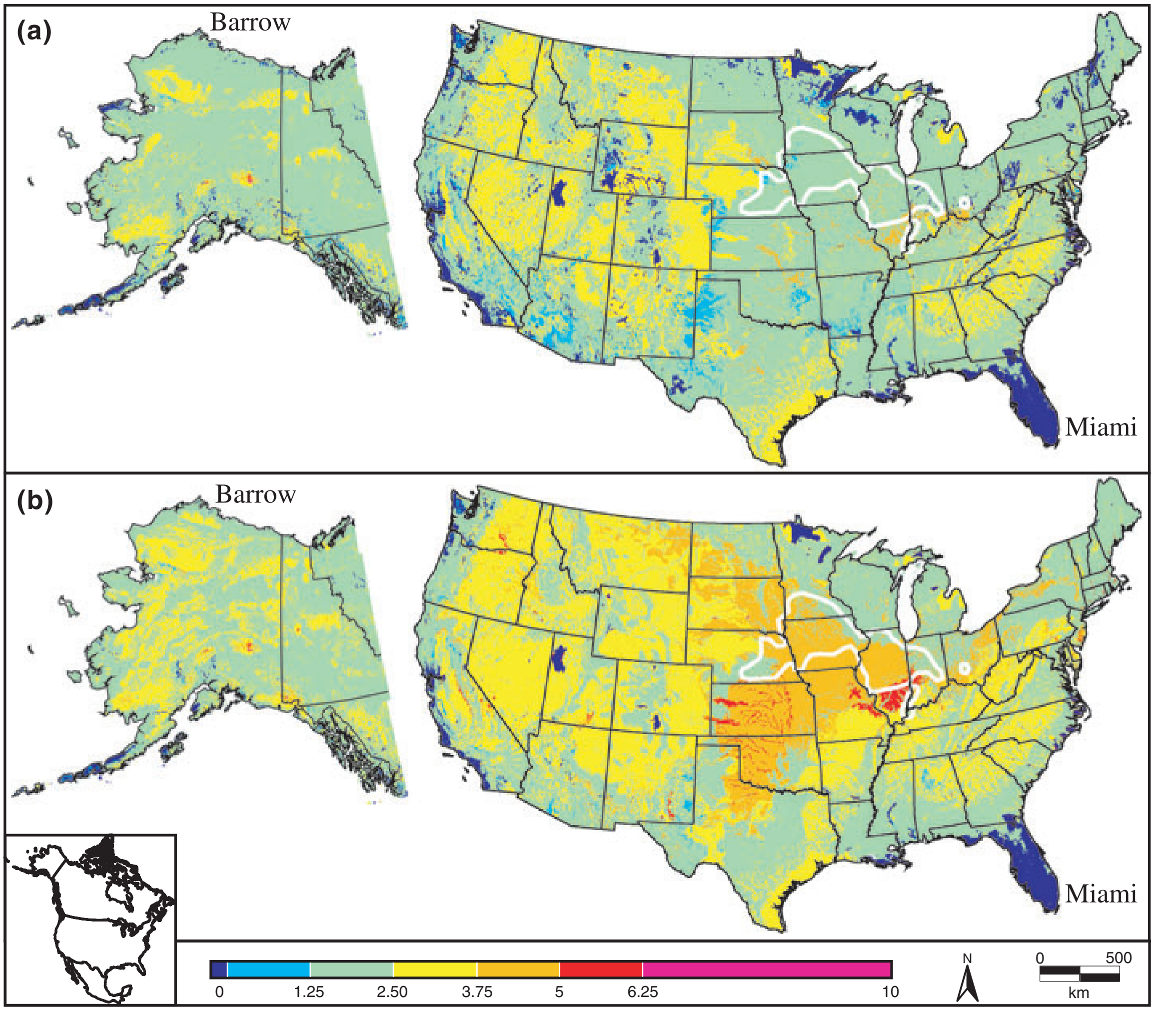

Figure 2 Magnitude of difference in environmental data space between current conditions and those for 2100 scenarios as measured on an arbitrary scale in which the current difference in environmental space between Miami FL and Barrow AK is set at 10. (a) Difference between current conditions and Scenario B2, moderate greenhouse gas increases. (b) Difference between current conditions and Scenario A2, rapid greenhouse gas increases. The white line surrounds counties with more than one-third of their land under corn crops.

Current domains often shrink or disappear altogether from the study area under a future scenario (Fig. 3) and the appearance of new, non-analogue domains is common (Fig. 4). Future non-analogue domains will have one or more variables entirely outside the range of otherwise similar current domains (Overpeck *et al.* 1992). Even under the scenario with significant emissions reductions (B2), combinations of abiotic environmental factors that currently characterize 13.3% of the study area disappear from it, while 53.6% of the study area will have non-analogue domains by 2100.

These metrics of change increase greatly if only modest emissions reductions are made. Under Scenario A2, domains that currently characterize 63.2% of the study area disappear, while 63.1% of the study area will have non-analogue domains. Mid-range values for atmospheric concentrations of greenhouse gasses in terms of CO_2 abundance under Scenario A2 and Scenario B2 are 856 and 621 p.p.m., respectively. Thus a 28% reduction in future atmospheric concentration is associated with a disproportionate 50% reduction in future domains entirely lost.

DISCUSSION

The United Nations Framework Convention on Climate Change has a goal of limiting the rate of change so as not to exceed the ability of ecosystems to adapt naturally [United Nations Framework Convention on Climate Change (UN-FCCC) 1992, Article 2]. Our method translates emissions scenarios into environmental domains and quantifies the

Table 2 Average climate variables for domains currently associated with the US Corn Belt and in 2100 under each scenario

	Scenario		
Climate variables	Current	Moderate increase (B2)	Rapid increase (A2)
Precipitation coldest quarter (mm)	123.7	157.9	139.9
Precipitation warmest quarter (mm)	302.4	266.1	216.0
Potential evapo-transpiration (mm)	210.1	262.8	324.5
Precipitation/potential evapo-transpiration	4.3	3.8	3.0
Average monthly temperature (excluding months < 0 °C) (°C)	11.3	18.2	24.0
Mean temperature coldest quarter (°C)	−8.9	−3.3	1.7
Mean temperature warmest quarter (°C)	29.3	41.4	48.4

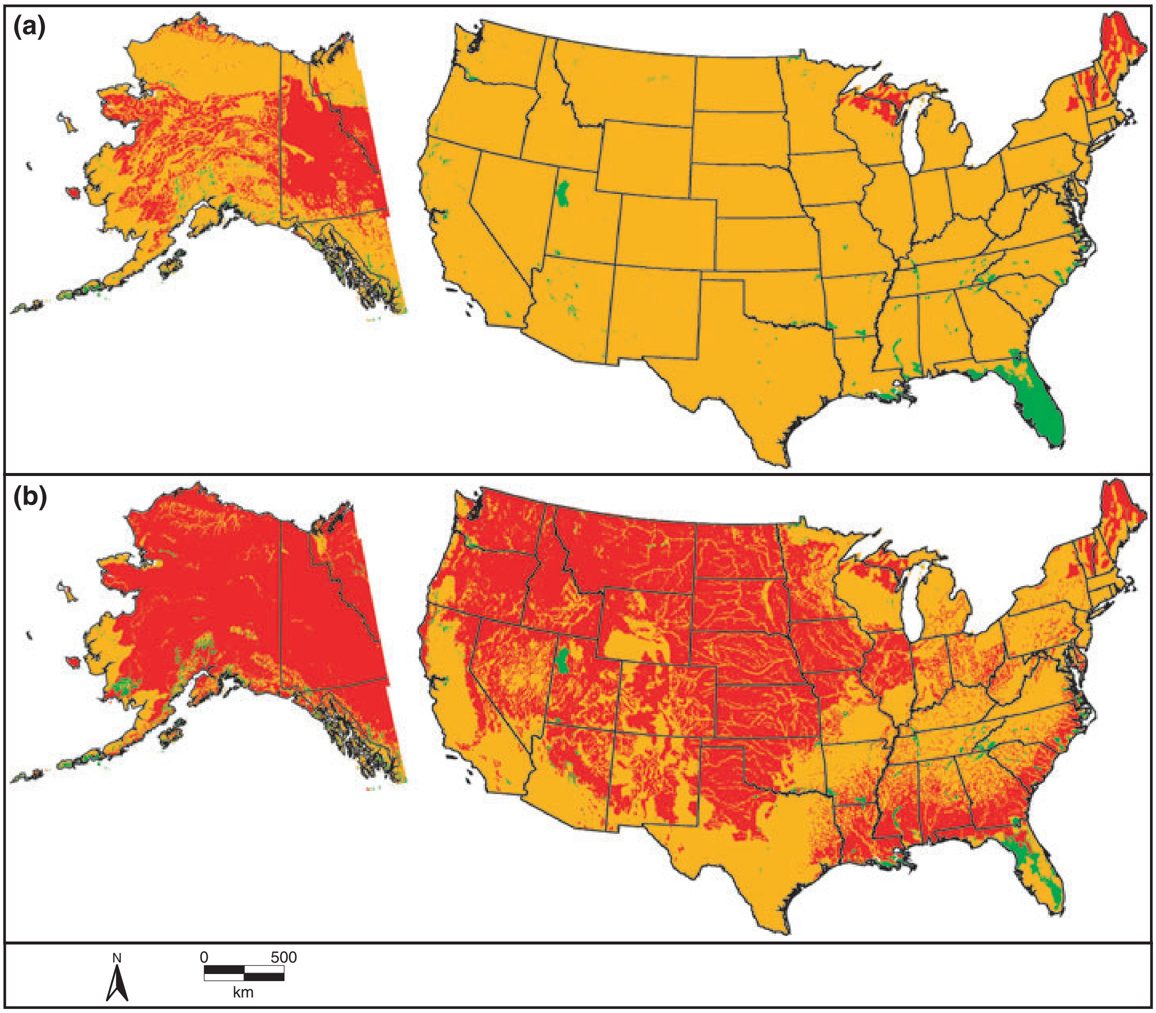

Figure 3 Current locations of domains that disappear from the study area are shown red, those that decrease are shown orange and those that increase are shown green. (a) Scenario B2, moderate greenhouse gas increases. (b) Scenario A2, rapid greenhouse gas increases.

uneven spatial distribution of environmental change among them. This can guide interventions to assist ecosystems to adapt without loss of their component species or ecosystem services.

Climate-dynamic domains provide an objective basis for designing conservation networks in conjunction with models of other biodiversity surrogates, models of land use change and other threats to biodiversity and species-

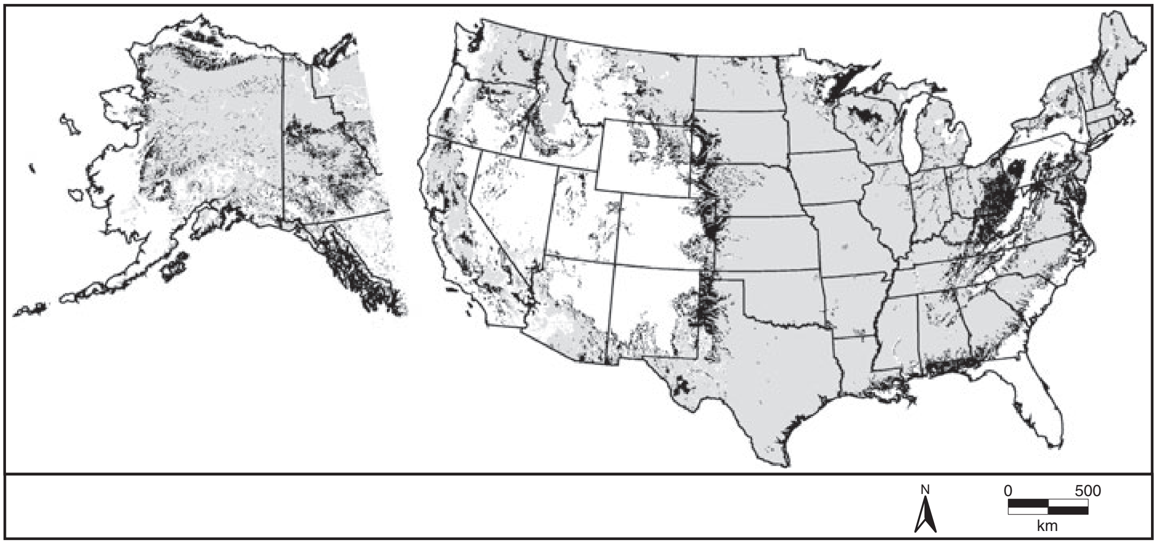

Figure 4 Future locations of domains that have no current analogue in the study area. (White) Future locations of domains that currently exist, although not necessarily at these locations (Grey) Non-analogue domains that appear under both Scenario A2 and Scenario B2. (Black) Addition non-analogue domains that appear under Scenario A2 only.

specific assessments where available (Saxon 2003). All else being equal, ecosystems will be least at risk from climate change in domains that maintain their location and extent. These are also potential refugia for species.

A domain's future locations may overlap little, if at all, with its current ones. For example, one domain in northern Alaska increases dramatically in extent, but changes its location from the south side of the Brooks Range to the arctic coast on the north side of the Range. Ancient boreal forests occur at its present location, but the responses of tundra communities at its future location will generate novel and unstable biotic communities (Rupp *et al.* 2001). The process of structural change without change in species composition has already started there (Sturm *et al.* 2001). Domains that shrink and/or move will require deliberate conservation strategies to enhance the adaptive capacity of their ecosystems, reducing the loss of biodiversity that would otherwise occur.

Biodiversity will be at greatest risk where domains disappear and non-analogue ones take their place. There, sentinel ecosystems can be monitored for early signs of stress and disturbance regimes may have to be manipulated to maintain complex ecosystems as novel communities form. Dispersal to a familiar environment is certainly not an option for the plants and animals presently confined to these locations.

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