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Is U.S. climatic diversity well represented within the existing federal protection network?

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Abstract. Establishing protection networks to ensure that biodiversity and associated ecosystem services persist under changing environments is a major challenge for conservation planning. The potential consequences of altered climates for the structure and function of ecosystems necessitates new and complementary approaches be incorporated into traditional conservation plans. The conterminous United States of America (CONUS) has an extensive system of protected areas managed by federal agencies, but a comprehensive assessment of how this network represents CONUS climate is lacking. We present a quantitative classification of the climate space that is independent from the geographic locations to evaluate the climatic representation of the existing protected area network. We use this classification to evaluate the coverage of each agency's jurisdiction and to identify current conservation deficits. Our findings reveal that the existing network poorly represents CONUS climatic diversity. Although rare climates are generally well represented by the network, the most common climates are particularly underrepresented. Overall, 83% of the area of the CONUS corresponds to climates underrepresented by the network. The addition of some currently unprotected federal lands to the network would enhance the coverage of CONUS climates. However, to fully palliate current conservation deficits, large-scale private-land conservation initiatives will be critical.

Key words: climate classification; climate rarity; conservation; gap analysis; principal components analysis; protection network.

Introduction

Protected areas represent important core units for in situ conservation, and they serve as key ecological benchmarks in the context of global land-use and climate change. Effective networks of protected areas are thus the best hope for conserving biodiversity and associated ecosystem services in the face of changing environments and increasing human pressure on the planet's resources (Folke et al. 2004, Chape et al. 2005). Maximizing the effectiveness of protection networks depends on effectively identifying and locating conservation areas to promote the persistence of species, habitats, and ecosystem processes (Rodrigues et al. 2004, Sarkar et al. 2006). A crucial first step requires identifying currently preserved landscapes and additional conservation areas capable of further protecting biodiversity and ecosystem function (often called gap analysis; Scott et al. 1993).

An extended system of protected areas (e.g., national parks, national wildlife refuges, wilderness areas) is managed by four federal agencies in the United States of America (U.S; Fig. 1). Research efforts such as the National Gap Analysis Program (Jennings 2000) are devoted to identifying individual species, species-rich areas, or vegetation types that are underrepresented in such a network. For instance, it has been suggested that over 50% of the land-cover types (Scott et al. 2001) and ecosystem types of the conterminous United States (CONUS) (Dietz and Czech 2005) are underrepresented within natural U.S. protected areas. Although many assessments of the effectiveness of current protected areas may not apply under changing climates (e.g., McKelvey et al. 2011), protecting the diversity of current abiotic conditions may be important both now and into the future (Schloss et al. 2011).

Climatic factors strongly influence distribution patterns of plants and animals (e.g., Thuiller et al. 2005, Rehfeldt et al. 2012, Levinsky et al. 2013), disturbance regimes (e.g., Allen et al. 2010, Parisien et al. 2012), and hydrologic dynamics of ecosystems (e.g., Rodriguez-Iturbe 2000). Despite the importance of climate to ecosystem structure, pattern, and process, the degree to which U.S. climates are represented within the existing federal network of protected areas is unknown. Without

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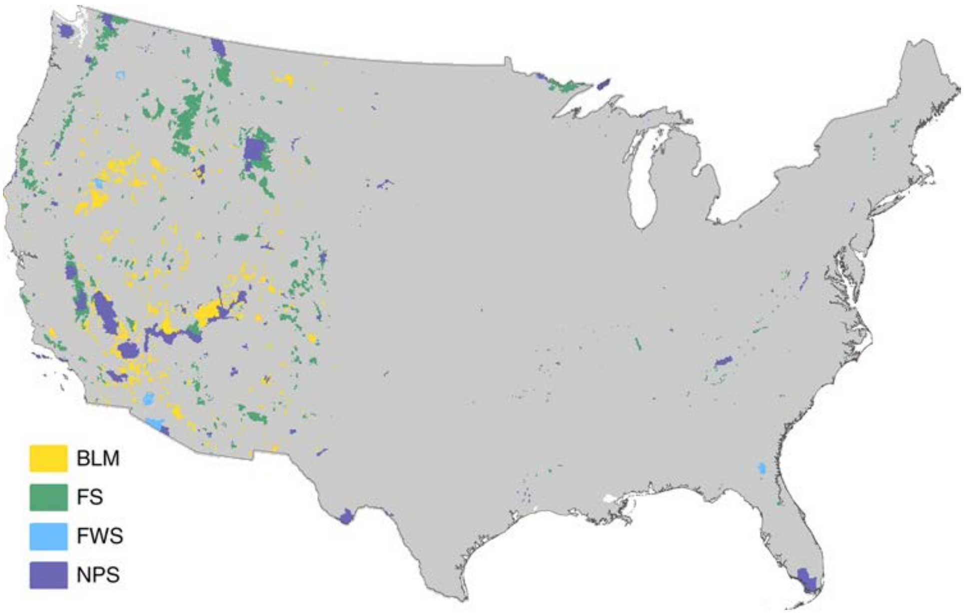

FIG. 1. Conterminous U.S. (CONUS) federal protection network by management agency; BLM, Bureau of Land Management; FS, Forest Service; FWS, Fish and Wildlife Service; NPS, National Park Service.

this understanding, it is impossible to know whether and how the current network can preserve environments and natural features into the future (Stephenson and Millar 2012). Objective assessment methods are needed to evaluate current climatic coverage of the network and to improve the chances that conservation plans will remain effective in the face of environmental change (Groves et al. 2012, Moritz et al. 2013, Hansen et al. 2014).

We developed a quantitative classification that stratified the CONUS climate to (1) evaluate the characteristics and rarity of the climate in federally protected areas, (2) determine cases where climate is not well represented by the network of protected federal lands (i.e., a climate gap analysis), and (3) assess the potential to fill existing gaps in the protected area network with federal lands and undeveloped land-cover types. Our goal is not to generate yet another classification of the U.S. ecosystems and environments (e.g., Bailey 1983, Omernik 1987, Hargrove and Hoffman 2005), but rather to complement existing and proposed approaches to climate change adaptation (e.g., Groves et al. 2012).

METHODS

We defined the current climate space of the CONUS independent from its geographic space (Wiens et al. 2011, Metzger et al. 2013). We restricted our analysis of the environment to climate, as climate modulates multiple stresses to species and ecosystem function and can encompass more ecologically important variation than other variables (e.g., Weigelt et al. 2013). First, we used ordination techniques to obtain a reduced set of three axes of variation encompassing the spatial variability of multiple climate variables. We divided the resulting climate space into homogeneous units or climate domains (CDs). We then evaluated the representation of protected federal areas in each CD, and assessed conservation opportunities for extending the current network to fill existing gaps in the coverage.

Climate variables

We selected a set of 15 climate variables (Appendix: Table A1 and Fig. A1) depicting annual and seasonal trends that have been linked to species richness (Kreft et al. 2008), the physiological requirements of plants (Stephenson 1990, Prentice et al. 1992), and to ecosystem processes at large spatial scales (e.g., productivity [Beer et al. 2010], biogeochemical cycles [Arneth et al. 2010]). Monthly climate data at 800-m resolution (precipitation, minimum temperature, maximum temperature, and dew-point temperature) were obtained from the PRISM Group (Daly et al. 2008). Monthly potential evapotranspiration was obtained from the Consortium for Spatial Information (CGIAR-CSI; Zomer et al. 2007, 2008), and growing season length and growing degree days above 5°C were obtained from Natural Resources Canada (McKenney et al. 2011). Additional variables such as moisture index and relative humidity were computed following Engler et al. (2011) and the U.S. National Oceanic and Atmospheric Administration, respectively. Monthly data for each variable covering the period 1981–2010 were aggregated into long-term averages (climate normals; Daly et al. 2008) to summarize current climate conditions for the CONUS. All analyses were conducted using a pixel size of 800 m in the USGS Albers Conic Equal Area projection.

Protected areas boundaries

Maps of biological reserves and stewardship designations from several sources (Wilderness.net, National Park Service, USDA Forest Service, and the Bureau of Land Management) were combined into a spatial database providing boundaries and management status for 1481 protected areas managed by the U.S. federal government (Fig. 1). Some nonfederal public and private lands may have protected status, but the purposes and levels of that protection can vary considerably; as such, we focused exclusively on federal lands. We included protected areas larger than 500 ha managed by four U.S. federal agencies: Bureau of Land Management (BLM), Fish and Wildlife Service (FWS), Forest Service (FS), and National Park Service (NPS). Although small protected areas (<500 ha) potentially have important conservation value, we excluded such areas because they are often designated to protect cultural or historical values (e.g., lighthouses and civil war battlefields) and are not likely to functionally contribute to current or future climate representativeness. We included federal areas in conservation classifications corresponding to The World Conservation Union categories I–IV (IUCN 1994). These categories include designated, candidate, and officially recommended wilderness areas; forest reserves; natural areas and landmarks; wildlife refuges; cooperative management and protection areas; and national parks, preserves, monuments, and conservation areas. Such lands are managed mainly for ecosystem protection and conservation of specific natural features, with limited or no resource exploitation and human interaction.

Analyses and mapping

We used principal component analysis (PCA) to reduce the dimensionality of the climate space of the CONUS as defined by the 15 climate variables (Appendix: Table A1 and Fig. A1). Because this technique is not scale invariant, variables were standardized prior to PCA so that each one has mean zero and unit variance independent of its scale. This ensures that all variables have the same weight in the analysis. The first three PCA axes (PC1, PC2, and PC3; Fig. 2a) were used to define the climate space independent from the geographic location of the initial climate data. Subsequently, this multivariate climate space (Fig. 2b) was stratified into climate domains (CDs). The number of CDs was determined through a systematic approach in which we evaluated within- and among-domain variance (Fig. A2). Ultimately, the PCA-derived climate space was partitioned into $12 \times 12 \times 12$ homogeneous and equally spaced CDs; the CONUS climate space encompasses 116 of the 1728 ($12 \times 12 \times 12$) possible CDs (Fig. 2c). Each 800-m pixel was assigned to one of the 116 CDs and its location was then mapped back in geographic space (Fig. 2d).

We used the geographic extent of each CD to describe its rarity, which was defined as 1/(number of pixels in each CD). To evaluate the proportion of CONUS climate space managed by the four main U.S. land management agencies (BLM, FWS, FS, and NPS), we collapsed the climate space as defined by PC1, PC2, and PC3 into a two-dimensional space (ternary plot). The representativeness, extent, and position of each of the 1481 protected areas within the overall climate space was then evaluated by computing its mean ($\pm$SD) conditions along each PCA axis and located within the two-dimensional space.

We assessed the coverage of the protected area network by quantifying the protected fraction of each CD. CDs with less than 10% of their geographic extent protected were identified as gaps in the network's coverage (Scott et al. 1993). We adopted a fixed 10% target for all CDs, which has been used in other gap analyses and conservation approaches (e.g., Scott et al. 2001, SCBD 2004, Dietz and Czech 2005; but see Rodrigues et al. 2004).

Finally, we evaluated the potential to fill the gaps identified in the federal protection network. Federal lands from the four natural resource management agencies (BLM, FS, FWS, and NPS) but currently unprotected (i.e., those not in IUCN protected areas categories I through IV) were considered feasible conservation opportunities for extending the current coverage of the climate space. We evaluated whether such federal lands would enable the 10% target to be reached in currently underrepresented CDs. We also assessed how other lands could contribute to address current conservation deficits in those CDs where gaps cannot be filled with lands from the four natural resource management agencies alone. Specifically, we assessed how non-federal lands and federally owned lands that are not managed for their natural resources (e.g., Department of Defense, DOD) could fill gaps. To this end, we used the National Land Cover Database 2006 (NCLD2006; Fry et al. 2011) to evaluate the land characteristics of areas outside the existing federal protection network; NLCD2006 was reclassified into two categories reflecting the level of human-induced modifications: altered (developed areas, pastures and cultivated crops) and natural (water, ice/snow, barren, forest, shrublands, grasslands, and wetlands).

Results

The set of three axes delineating the climate space of the CONUS (PC1, PC2, and PC3; Fig. 2a) accounts for 90% of the variance of the 15 original climate variables (Fig. A1). Factor loadings for each variable (Appendix: Table A1) indicate that PC1 reflects a gradient from drier to wetter areas (negative and positive loadings, respectively); PC2 captures a temperature gradient, from warmer (negative) to cooler areas (positive); and PC3

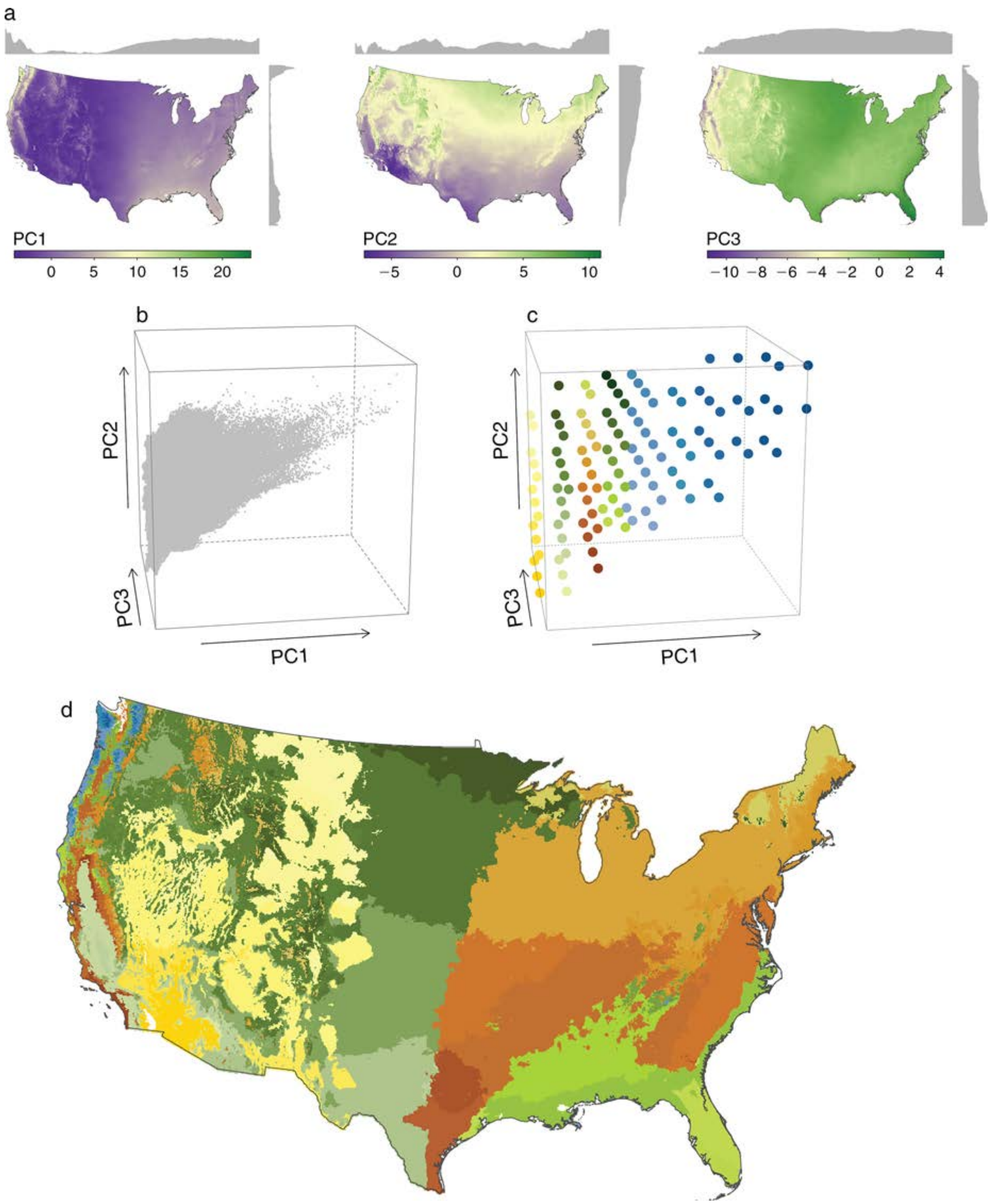

FIG. 2. Characterization of the climate space of the conterminous United States (CONUS). (a) Maps of the loadings of the first three axes of the principal component analysis (PCA) used to characterize the CONUS climate (Appendix: Table A1). The gray plots at the top and right-hand side of each map represent the latitudinal and longitudinal variation in mean pixel values of the PCA scores. (b) Distribution of all pixels within the CONUS data space as defined by PCA axes. (c) Stratification of the climate space using a $12 \times 12 \times 12$ regular grid; each point corresponds to one of the 116 occupied climate domains and is represented with a unique color. (d) Geographic location of the climate domains using the same color scale as in panel (c). See *Methods: Analyses and mapping* for methodological details.

mostly differentiates between winter-moist (negative) and summer-moist (positive) areas (Fig. 2a). Although the extent of each CD is homogeneous within climate space and thus encompasses the same degree of climate variability, its size in geographic space can vary substantially (Fig. 2d and Table A2); 20% of the CDs occupy ~91% of the CONUS area. The largest CD (i.e., the most common climate) occupies ~13% of the CONUS area (1 008 777 km^2) and covers the middle-latitude portion of the Midwest and Northeast regions. The smallest CDs (rare climates) occupy less than 0.0001%, and ~29% of them correspond to less than 100 km^2. The geographic extent of the CDs is inversely related to elevation (Fig. A3). Rare CDs mostly represent wetter mid- to high-elevation areas and are geographically located over the Cascade Range, Sierra Nevada Mountains, and the highest elevations of the Rocky Mountains and Appalachian Mountains (Fig. 3a and b). Rare CDs also occupy the Florida peninsula. Conversely, the Great Plains and the central parts of the CONUS contain the most common CDs.

The protected area network (Fig. 1) covers approximately 391 493 km^2, or ~4.9% of the CONUS. Protected areas are located mostly at mid to high altitude (Fig. A3), and the vast majority (~91% in terms of area) are found in the 11 westernmost U.S. states. Overall, ~11.2% of the geographic area of these westernmost states is protected, whereas only ~0.72% is protected in the remainder of the CONUS. The portion of the climate space managed by each federal agency (BLM, FS, FWS, and NPS) is somewhat complementary across the CONUS (Fig. 3c–e). In general, BLM manages protected areas occupying relatively common, mid-elevation, semiarid climates and deserts, whereas FS manages a set of protected areas in rather uncommon high-elevation climates that include some of the rarest CDs. Protected areas managed by FWS are generally restricted to coastal and low-elevation lands. Protected areas managed by NPS but occur in both common and rare climates, many of them in mountain areas. Some protected areas represent specific climates, covering very small parts of the entire climate space, whereas others contain more heterogeneity and span across substantial portions of the climate space (Fig. 3c–e).

Overall, we found that ~36% of CONUS climates (42 of the 116 CDs) do not meet the conservation target of having at least 10% of their area in the protected area network. We identified these climates as conservation gaps (Fig. 4a and b). Some of the most prominent conservation gaps occur within the most common climates of the CONUS (Fig. 4b and Table A2), and such underrepresented climates collectively correspond to 83% of the geographic extent of the CONUS. Conservation gaps mostly cover the Great Plains, the central CONUS, and the eastern states (Fig. 4a). Conversely, the highest proportional coverage of CDs by the protection network is found in western mountain ranges such as the Olympic, southern Sierra Nevada, or Rocky Mountains. For 24 of the 42 gaps we identified, 114 143 km^2 of federally owned lands in the BLM, FS, FWS, and NPS have the potential to complement the current protection network to meet the 10% conservation target, including both common and rare CDs (Figs. 4b and A4). Two of the remaining 18 gaps represent land-cover types that are already human-altered and therefore unsuitable for conservation (Fig. 5), whereas for the other 16 gaps, the conservation target of 10% cannot be met with federal lands alone. The protection network would require substantial additions (207 379 km^2) from the state and private sectors and other federal agencies (e.g., DOD) to address the current conservation deficit.

Discussion

Our analysis shows that rare climates of the CONUS are, in general, well represented within the current network of protected areas managed by federal agencies. These rare climates are largely associated with the environmental diversity of mountain areas. In contrast, the network is acutely deficient among the most common climates and is far from providing a representative sample of CONUS climatic diversity. We found that most of the CONUS (83%) does not meet the 10% preservation target with the current federally owned protected area network. Although uniform conservation targets may not be adequate for large and diverse areas such as the CONUS (e.g., Soulé and Sanjayan 1998, Rodrigues et al. 2004), the 10% area target was deemed as an adequate reference for the purpose of this study. According to this threshold, the network should increase by ~140% from its current geographic extent to represent the climatic diversity of the CONUS. This would require the incorporation of ~542 524 km^2 of currently unprotected lands mostly concentrated at low and moderate elevations (Fig. A3), including densely populated areas near the coast and the most productive lands within the United States (Scott et al. 2001).

Federally owned lands in the BLM, FS, FWS, and NPS that are currently unprotected may offer the most realistic and feasible opportunities for expanding the protected area network. The distribution of these lands in climate space provides the four federal agencies with dissimilar opportunities to meet overarching conservation targets. In fact, filling certain climate gaps may be in the control of a single agency (Fig. A4). Therefore, any effective national level conservation strategy would thus require institutional and policy changes promoting coordination among the four agencies (White et al. 2010). However, because federally owned lands are mostly located at mid to high altitudes, even if all of them were considered effective conservation opportunities to extend the current protection network, ~16% of the CONUS climates would still remain underrepresented. This highlights the importance of state- and private-land conservation and restoration initiatives (Knight et al. 2010) for locating conservation

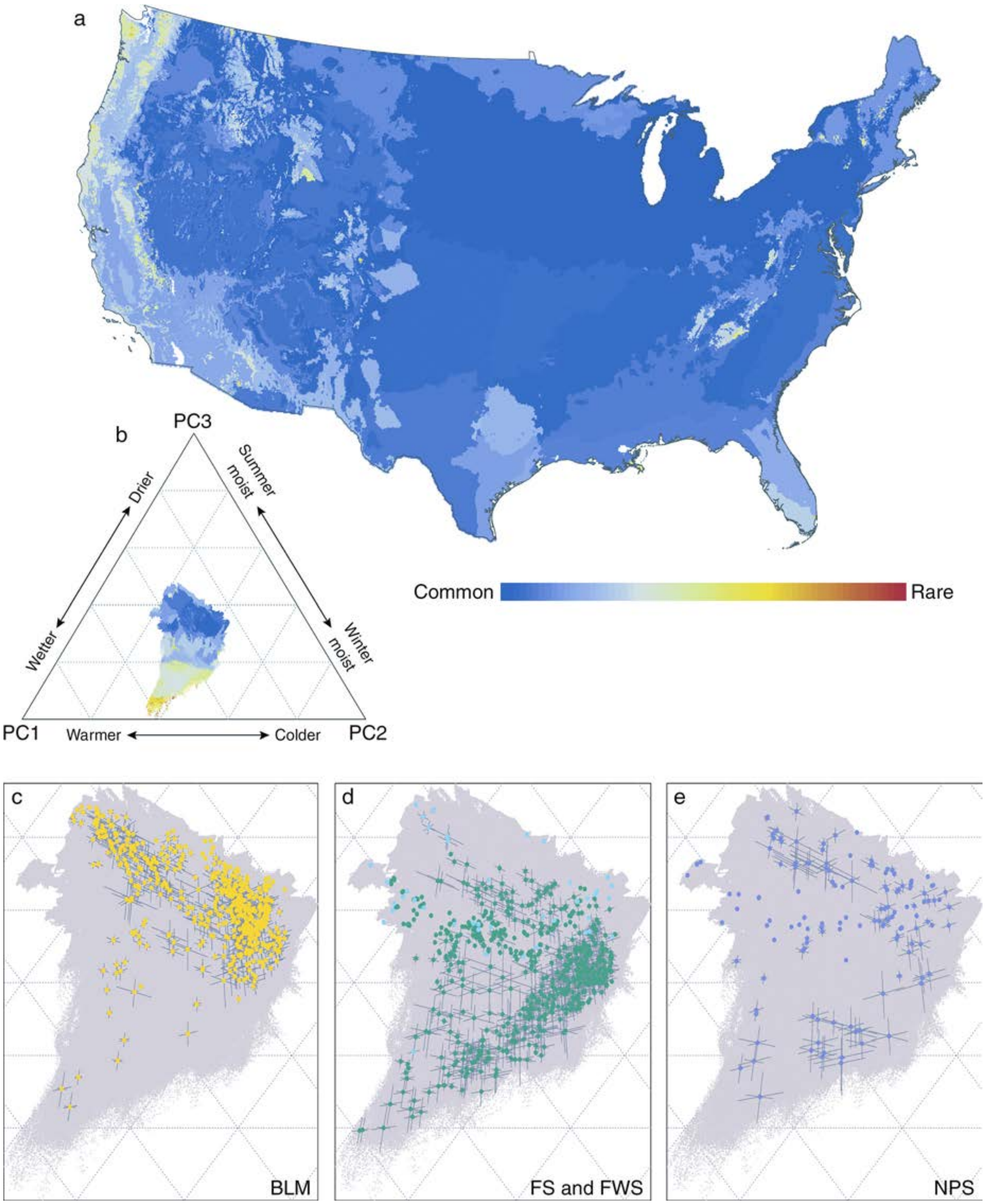

FIG. 3. Rarity (1/[number of pixels in each domain]) of the climate domains (CDs) and management responsibilities of the climate space of the CONUS. (a) Rarity in geographic space, where each CD has assigned a unique color that reflects its rarity within the context of CONUS. (b) Bi-dimensional representation (ternary plot) of the climate space of the CONUS where each pixel is depicted on the basis of the rarity of the CD where it is located. This bi-dimensional space was used to display which sections of the CONUS climate space are managed by each agency (c–e). In panels (c–e), notation and color scheme follows Fig. 2, and each dot represents the mean climatic conditions in a given protected area and the gray solid lines depict ±SD in each direction of the data space.

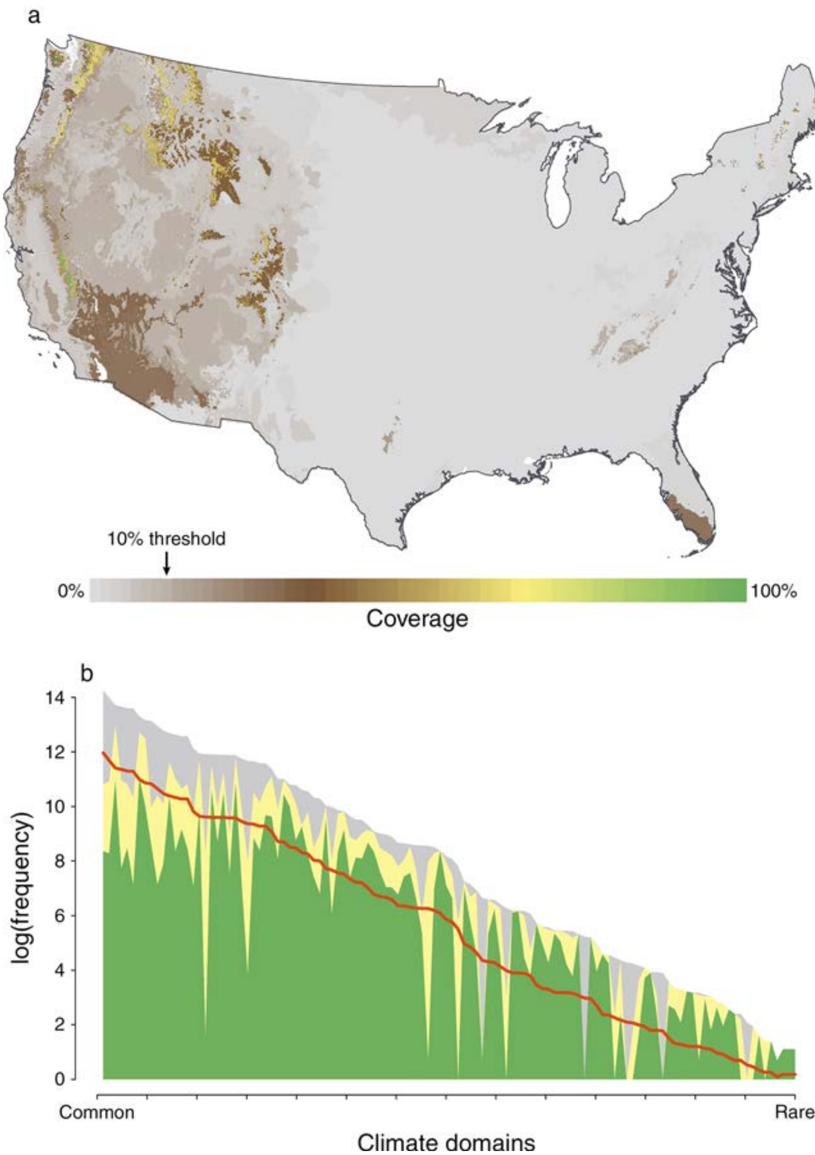

FIG. 4. Coverage of the climate domains (CDs) by the protection network. (a) Coverage of each CD in geographic space represented as the percentage of its geographic extent occupied by protected areas, and (b) presence of underrepresented CDs ("gap" analysis). In panel (b), green indicates representation of the CDs by protected areas managed by federal agencies (BLM, FS, FWS, and NPS), yellow indicates federal lands outside the existing protection network (see *Methods: Analyses and mapping* for details), and gray indicates state-held and privately owned lands. Underrepresented CDs are those where the green shading falls completely under the orange line, which indicates a 10% conservation target (see *Results* for details). Note that, in panel (b), CDs are sorted from common to rare (*x*-axis) and the *y*-axis is on a logarithmic scale.

areas to promote the persistence of species and habitats. Timely protection of such non-federal lands and lands managed by other federal agencies for other than their natural resources (e.g., DOD) may be especially important as they may be more heavily impacted by human-induced land-use changes, which are among the biggest threats to biodiversity (e.g., Parks and Harcourt 2002, Foley et al. 2005). Fortunately, substantial conservation potential exists as the vast majority of conservation gaps we identified within the CONUS can be found over natural land-cover types; only 1.7% of these gaps (166 km^2) are located in landscapes that are already ~100% human altered. Common climates, which cover ~91% of the CONUS area and are underrepresented in the network, are at least partly found over natural land-cover types (Table A2). Despite the potential threats posed by land-use change, a scarcity of natural habitats as a result of human-induced alterations is not yet the limiting factor to effectively protect the diversity of climates within CONUS.

Although conservation based on climatic diversity alone will not function as a perfect surrogate strategy for biodiversity (e.g., Araújo et al. 2001, Bonn and Gaston

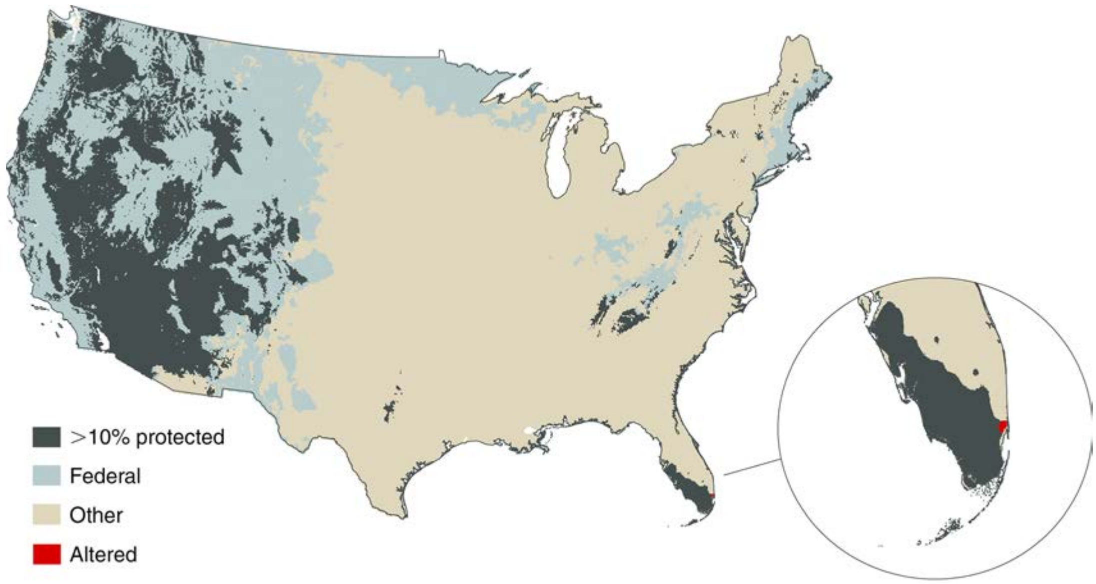

FIG. 5. Potential to improve the coverage of the existing network of federal protected areas. Climate domains (CDs) with >10% of their area protected are depicted in dark gray, light blue depicts those CDs where federal lands outside the existing network would allow reaching the 10% conservation target, and khaki depicts CDs where reaching such target would require the incorporation of state managed and private lands. Red shows CDs unsuitable for conservation as a result of human alterations of the land-cover types.

2005; but see, e.g., Faith 2003, Schloss et al. 2011), it can be a powerful conservation planning approach. The classification of the natural world into discrete units helps integrate ecological complexity into successful management and conservation strategies (Olstad 2012, Andrew et al. 2013). Ecoregion classifications (e.g., Bailey 1983, Omernik 1987) may have, however, limited utility in the future due to the difficulty and uncertainty in predicting vegetation responses to projected climates (e.g., Hobbs et al. 2013). Climate-based stratifications have therefore been promoted for conservation assessments (Metzger et al. 2013). The framework presented here meets the requirements of effective conservation tools: it is computationally efficient, flexible, transparent, generic and modular (Sarkar et al. 2006), making it imminently useful for climate change vulnerability and adaptation analyses.

Potential applications and future directions

Facing an uncertain future, it is crucial that we prioritize conservation efforts to fill gaps and maximize the effectiveness of protection networks. Because rapid climate-driven changes in ecosystems can outpace the capacity for adaptation in many species (Jump and Peñuelas 2005), focusing conservation efforts on those areas least likely to undergo sudden climatic changes or representing broad ecological gradients are among the strategies proposed to adapt national conservation plans to changing climates (Smith et al. 2001, Game et al. 2011, Groves et al. 2012). With increasing availability of gridded high-resolution projections of climate change, the approach presented here represents a powerful tool for evaluating future representativeness of the existing network, and for identifying areas where climatic changes are attenuated (climate refugia) or areas that may provide potential corridors for species adapting to ongoing environmental changes. Similarly, this framework could be used to assess the magnitude and expected trajectories of climate change within the protection network: overlaying the protected area network with future climate projections would reveal how protected areas are expected to "migrate" in climate space. Multi-model ensembles and individual climate models depicting alternative climate scenarios (e.g., warmer-wetter vs. warmer-drier) could be used to quantify the agreement among different climate projections (Littell et al. 2011), as well as the uncertainty in the magnitude and trajectory of change within the network. This will hopefully guide the definition of common or complementary management strategies among land management agencies promoting the spatial and temporal connectivity between environments required for climate change adaptation (Rose and Burton 2009, Game et al. 2011, McKelvey et al. 2011).

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Supplemental Material

Ecological Archives

The Appendix is available online: http://dx.doi.org/10.1890/14-0227.1.sm

Data Availability

Data associated with this paper have been deposited in the USDA Forest Service Research Data Archive: http://dx.doi.org/10.2737/RDS-2014-0016.