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Case studies of conservation plans that incorporate geodiversity

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Abstract: *Geodiversity has been used as a surrogate for biodiversity when species locations are unknown, and this utility can be extended to situations where species locations are in flux. Recently, scientists have designed conservation networks that aim to explicitly represent the range of geophysical environments, identifying a network of physical stages that could sustain biodiversity while allowing for change in species composition in response to climate change. Because there is no standard approach to designing such networks, we compiled 8 case studies illustrating a variety of ways scientists have approached the challenge. These studies show how geodiversity has been partitioned and used to develop site portfolios and connectivity designs; how geodiversity-based portfolios compare with those derived from species and communities; and how the selection and combination of variables influences the results. Collectively, they suggest 4 key steps when using geodiversity to augment traditional biodiversity-based conservation planning: create land units from species-relevant variables combined in an ecologically meaningful way; represent land units in a logical spatial configuration and integrate with species locations when possible; apply selection criteria to individual sites to ensure they are appropriate for conservation; and develop connectivity among sites to maintain movements and processes. With these considerations, conservationists can design more effective site portfolios to ensure the lasting conservation of biodiversity under a changing climate.*

Keywords: abiotic surrogates, conservation planning, conserving nature's stage, geodiversity

Estudios de Caso de Planes de Conservación que Incorporan a la Geodiversidad

Resumen: *La geodiversidad se ha usado como un sustituto de la biodiversidad cuando la ubicación de las especies es desconocida y esta utilidad puede extenderse a situaciones en las que la ubicación de las especies está en cambio constante. Recientemente, los científicos han diseñado redes de conservación que buscan representar explícitamente la gama de ambientes geofísicos, al identificar una red de estados físicos que podrían mantener a la biodiversidad mientras permiten cambios en la composición de las especies en respuesta al cambio climático. Ya que no existe una estrategia estándar para diseñar dichas redes, compilamos ocho estudios de caso que ilustran la variedad de formas con las cuales los científicos han enfrentado el reto. Estos estudios muestran cómo se ha dividido la geodiversidad y cómo se ha usado para desarrollar portafolios de sitios y diseños de conectividad; cómo los portafolios basados en geodiversidad se comparan con aquéllos derivados de las especies y las comunidades: y cómo la selección y la combinación de variables influye sobre los resultados. Colectivamente, los estudios sugieren cuatro pasos clave al usar la geodiversidad para*

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aumentar la conservación basada tradicionalmente en la biodiversidad: crear unidades de suelo a partir de las variables relevantes para las especies combinadas de una forma significativa ecológicamente; representar las unidades de suelo en una configuración espacial lógica e integrarlas con la ubicación de las especies de ser posible; aplicar criterios de selección a los sitios individuales para asegurar que son adecuados para la conservación; y desarrollar la conectividad entre sitios para mantener los movimientos y los procesos. Con estas consideraciones, los conservacionistas pueden diseñar portafolios de sitio más efectivos para asegurar la conservación duradera de la biodiversidad bajo un clima cambiante.

Palabras Clave: conservación del estado de la naturaleza, geodiversidad, planeación de la conservación, sustituta abiótica

Introduction

Geodiversity has been incorporated into conservation plans as a coarse filter for capturing diverse species and communities, as a biodiversity surrogate when biotic information is not available (Hunter et al. 1988; Faith & Walker 1996), and as a direct target for representation (Spicer 1987). Recently, geodiversity has garnered renewed attention as conservationists recognize the transient nature of biotic patterns and search for a more enduring framework around which to organize land protection under a changing climate. Defined as the natural range of geological, geomorphological, and soil features (Gray 2013), *geodiversity* characterizes the available physical environments and shapes species distribution patterns both directly and through its influence on climate (Anderson & Ferree 2010). Using geodiversity, scientists can design conservation networks that represent the range of physical environments of a region, thus capturing the heterogeneity necessary to sustain a diversity of species and ecological processes, while allowing for change in species composition in response to climate change (Beier & Brost 2010). Here, we present 8 case studies that integrated geodiversity into conservation plans designed to support both current and future biodiversity.

To incorporate geodiversity into quantitative planning, it is often necessary to partition it into ecologically meaningful spatial units, map the distribution of those units, and assess their representation, abundance, and configuration. The availability of high-resolution (10–90 m) digital elevation models (DEMs), digitized maps of soils and geology, and interpolated surfaces of insolation or solar radiation, have made it practical to perform such assessments across large geographic regions. However, there are many ways to quantify the geophysical elements that influence species distributions and no single best approach has yet emerged to identify a meaningful geophysical template for conservation. The case studies presented here can help conservation biologists begin to understand the implications of variable choices, combination methods, and the effects of scale (Table 1).

The authors of this paper are all conservation scientists actively involved with testing and applying geodiversity to conservation planning, and each case study illustrates an important method, issue, or conclusion. Most of these studies focus on the delineation and representation of geophysical units, but some also address spatial processes such as the arrangement of topographically based microclimates or the degree of connectedness across units. The 8 studies are a mix of published and unpublished research (Supporting Information), and 6 of them summarize applied projects that were used to inform conservation decisions.

The case studies focus on terrestrial ecosystems and illustrate the key issues related to how geodiversity is measured and integrated into site prioritization. The first 2 studies describe 2 common and virtually synonymous methods used in the United States for mapping recurring geophysical land units: ecological land units (case study 1) and land facets (case study 2), and illustrate how they have been used to design conservation portfolios and identify corridors respectively. The next 3 studies (case studies 3–5) compare prioritization based on geodiversity to prioritization based on biodiversity, using conservation portfolios developed by The Nature Conservancy (TNC). Case studies 6 and 7 examine the sensitivity of site prioritizations to the choice of geophysical variables, the spatial resolution of the data, and the method used to define land units as multivariate entities. Finally, case study 8 illustrates a gradient approach to partitioning abiotic space to elucidate trade-offs in conservation planning.

Terminology for describing and labeling geodiversity spatial units has not been standardized. Here we use the following conventions: *abiotic diversity* to refer to geodiversity and climatic diversity; *geodiversity* to describe geologic, geomorphologic, and soil features; *geophysical setting* to describe large regions (thousands to millions of hectares) dominated by a single geology class; *land unit* to describe the synonyms *ecological land unit* (Anderson 1999) or *land facet* (Beier & Brost 2010), which are particular combinations of geodiversity features that characterize local landforms (e.g., high elevation, steep ridge).

Table 1. Comparison of attributes, data, and methods across 8 case studies of conservation plans that incorporate geodiversity.

	Case study							
	1	*2*	*4*	*5*	*6*	*3*	*7*	*8*
Region	western US	south-western US	north-western US	north-western US	north-western US	north-eastern US	south-western US	New South Wales AU
Analysis method	Marxan[a]	least-cost modeling	Marxan[a]	Marxan[a]	Marxan[a]	statistical scoring	statistical scoring	DIVERSITY[b]
Site prioritization criteria	optimization of 100s of land units	optimization of 5–15 land units	optimization of 41 land units	optimization of 121 land units	optimization of 7–3,884 land units	*Z* scores of hexagons relative to 29 settings	relative land-unit diversity value by ecoregion	maximum complementarity in environmental space
Selection of variables and thresholds	expert opinion and vegetation patterns	statistical clusters	expert opinion	correlation of variable with vegetation maps	expert opinion and sensitivity tests	rare species overlay and regression of species diversity on geodiversity	statistical thresholds using minimum variance or equal subsets	expert opinion
Method for combining variables	overlay	cluster	cluster	overlay	overlay, cluster, and hybrid	overlay	overlay (cluster also tested)	ordination
Grid cell size (m)	30 and 90-	30	240	270	270 and 1 km	30	90 and 270	1.0
Planning unit size	1,200–1,500 ha hexagons	30-m cell or aggregates	HUC[c] 12	270-m cell	HUC[c] 12	404 km hexagon	1–23 km^2 moving windows	0.1 × 0.1 degree grid cell
Elevation source[d]	30 and 90-m DEM	30-m DEM	30-m DEM	270-m DEM	30-m DEM	30- m DEM	90-m DEM	1-m DEM
Elevation partitioning	3–10 zones	continuous	continuous	6–10 zones	variable	3 zones	minimum variance and equal subsets	continuous

Continued

Table 1. Continued.

	Case study							
	1	*2*	*4*	*5*	*6*	*3*	*7*	*8*
Topography source[d]	30 and 90 DEM	30-m DEM	30-m DEM	270-m DEM	30-m DEM	30-m DEM	90-m DEM	1 m DEM
position	Y	Y			Y	Y		
slope	Y	Y	Y	Y	Y	Y		
aspect	Y	Y				Y	Y (THL)[e]	
Wetness	Y					Y	Y (CTI)[f]	
Geology Source	state maps[g]				state maps[g]	state maps[g]		
Surface Geology	6–10 classes				9 classes	9 classes		
Soil source	state surficial maps[g]		SURGO[h] 1:24,000	STATSGO[i] 1:250,000	STATSGO[i] 1:250,000	Soller 1998[j], SURGO[h] 1:24,000	SURGO[h] 1:24,000	
texture			Y			Y		
order				Y	Y		Y (suborder)	
depth			Y		Y			
Available water capacity			Y		Y			
Org spell out Content					Y			
Bulk Density					Y			
Climate source			CIG[j] 1/16th degree					ESOCLIM[k]
temp and precipi-tation			Y					Y

[a] *Ball and Possingham (2000).*
[b] *Software package for sampling phylogenetic and environmental diversity (Walker & Faith 1994).*
[c] *The USGS hydrologic cataloging unit. A cataloging unit is a geographic area representing part of all of a surface drainage basin, a combination of drainage basins, or a distinct hydrologic feature.*
[d] *Gesch et al. (2002), Oregon Geospatial Data Clearinghouse (1999), the Washington Department of Natural Resources (2002), and the Idaho Geospatial Data Clearinghouse (2004).*
[e] *Topographic heat load (McCune & Keon 2002).*
[f] *Compound topographic index (Moore et al. 1993).*
[g] *Bedrock and surficial geology maps compiled from individual state sources (various resolutions 1:100,000–1:1,000,000).*
[h] *Soil Survey Geographic (SSURGO) Database (NRCS 1995). SSURGO is incompletely mapped and most users supplemented this with STATSGO where needed (Soller 1998).*
[i] *State Soil Geographic (STATSGO) Database (NRCS 1994).*
[j] *Soller (1998), Quaternary sediments in the glaciated United States east of the Rocky Mountains (USGS Digital Data Series DDS-38).*
[k] *Climate Impacts Group (2011), ESOCLIM (Hutchinson 1984).*

Case Study 1: Incorporating Geodiversity into TNC Conservation Portfolios in the U.S. Intermountain West

In the 1990s, TNC developed ecoregional "portfolios" across much of the Americas, including all ecoregions of the United States. Each was intended to identify sites and strategies for conserving native biodiversity (Groves 2003), and each effort applied principles of systematic conservation planning (Margules & Pressey 2000) to identify a portfolio of conservation sites. In the western United States, the Marxan site selection software (Ball & Possingham 2000) was used to identify a portfolio of sites that met representation goals for each mapped vegetation type (Comer & Schulz 2007), and each of 100–300 vulnerable species. However, planners were concerned that the vegetation types (typically 30–40 per ecoregion) might not sufficiently represent within-type diversity, and that coarse filter portfolios (*sensu* Noss 1987) might be more robust to climate change if finer-grain environmental diversity was incorporated.

To address these concerns in four western ecoregions (Southern Rocky Mountains, Great Basin, Greater Yellowstone, Colorado Plateau [Supporting Information]), TNC modified each regional portfolio by adding targets for ecological land units (Anderson 1999). Each land unit was a combination of an elevation zone, a substrate class, and a landform type. Landforms were derived from a 30-m or 90-m DEM with slope, aspect, topographic wetness, and relative topographic position. Elevation zones were mapped using DEMs, and surficial geology maps were compiled from digitized state geology maps (Table 1). In each ecoregion, each variable was partitioned into discrete classes; breakpoints between classes were selected to reflect regional vegetation patterns or ecologically meaningful distinctions in elevation, soil chemistry, and drainage. Elevation zones followed long-established bioclimatic concepts, and surface geology classes emphasized soil chemistry and drainage. Landform classes reflected local vegetation responses to topographically driven temperature and moisture patterns. Commonly, 200–400 land units were mapped for each ecoregion with simple map overlay methods, and then these were further overlain with mapped vegetation types. For each vegetation type, knowledge of disturbance patch size and notions of minimum dynamic area (Pickett & Thompson 1978) were used to establish representation goals: a percentage of the current extent of each vegetation and land-unit combination and a minimum area threshold for each vegetation type.

The resulting portfolios are being used by TNC to guide conservation strategies. Land-unit methods ensured that the portfolios not only represented rare species and common vegetation types in sufficiently sized patches, but also fully captured the geodiversity within each vegetation type. Thus, the results incorporated existing ecological gradients that will become increasingly important with climate change. Interestingly, no net increase in portfolio area was required to incorporate this combined measure of geophysical and biotic diversity than to capture biodiversity alone.

Case Study 2: Integrating Geodiversity Corridors with Focal Species Corridors to Prioritize Desert Lands in the U.S. Southwest

Penrod et al. (2012) developed linkage designs that would conserve connections between 22 pairs of large protected areas (PAs). The designs were requested by the U.S. Bureau of Land Management (BLM) facing proposals for industrial solar energy projects in the Mohave and Sonoran deserts of southeastern California. The BLM wanted broad, multi-stranded linkages to serve the needs of focal species (e.g., bighorn sheep [*Ovis canadensis*], desert tortoise [*Gopherus agassizii*]) under today's climate and provide continuity and interspersion of geodiversity to conserve metapopulations of all or most species as climate changes.

To map each linkage, Penrod et al. (2012) compiled 30-m DEMs and characterized each pixel with respect to three topographic position classes (ridge, slope, canyon) and 3 continuous variables (insolation, slope, and elevation [Table 1]). Rivers and ephemeral streams were mapped as riverine features. In each planning area, multivariate clustering was used to define 5–15 dominant land units (land facets *sensu* Beier & Brost [2010], such as "high elevation, steep ridge") within the 2 PAs, and then each pixel in PAs and in the intervening matrix was assigned to 1 land-unit type. Each pixel was also given a diversity score based on the number and evenness of land units within a 200-m radius (Brost & Beier 2012*a*).

Within each PA, pixels of each land-unit type were aggregated into polygons (see Brost & Beier 2012*b*) and the larger polygons (over 2500 ha) served as termini for the corridor analysis between PAs. Least-cost modeling was used to identify 3 corridor types: a 2-km-wide corridor for each land-unit type (5–15 total), a corridor with high land-unit diversity, and a corridor for each of four focal species based on habitat suitability. To map the corridors connecting patches of similar land-unit types, individual pixel resistance scores were calculated as the multivariate dissimilarity from the characteristic values for that land-unit type. A corridor was discarded if it included a long segment of high resistance, such as when the termini for a rugged, high elevation land unit were separated by a large expanse of low desert flats. The 3 corridor types were combined with any riparian feature reaching both PAs, to form the linkage design. The final 22 linkage designs linked the 18 large PAs into a network that was intended to support biodiversity under current and future climates.

In this approach, species corridors (fine filter) were intended to provide connectivity under current climate, and land-unit corridors (coarse filter) were intended to provide connectivity under future climate. Corridors with high facet diversity were intended to support interactions between species, and across land units, during periods of rapid change (Beier 2012).

Case Study 3: Identifying Climate-Resilient Sites for Conservation across Geophysical Settings in the U.S. Northeast and Maritime Canada

Anderson et al. (2014) developed a method to identify a portfolio of climate-resilient sites representing geodiversity in the northeastern United States and Canada and compared it with a portfolio selected for biodiversity. The results were used by TNC to identify new conservation areas and apply a climate-change lens to land acquisitions. Site resilience was defined as the expected ability of a site to support a diversity of native species and ecological functions in the face of climate change. Land units based on the ecological land unit models described in case study 1 were defined at 2 scales. At the coarser scale, the region was stratified into 29 broad geophysical settings based on 4 elevation zones corresponding to changes in dominant vegetation, and 9 substrate classes (7 bedrock and 2 surficial) defined by overlays of rare species locations and regression tests on total species diversity. The classes recognized unique bedrocks such as limestone and serpentine and common types such as granite (Anderson & Ferree 2010) and were intended to represent distinct species environments.

Within each geophysical setting, a finer scale measure of site resilience was assessed for each 30-m pixel based on landscape diversity and local connectedness. To measure landscape diversity, a landform model was created from a 30-m DEM using slope, topographic position, aspect, and wetness to identify 11 topographic landforms that reflected distinct temperature and moisture combinations (e.g., northwestern sideslope, wet flat). Local landscape diversity was measured as the variety of landforms, the elevation range, and the density of wetlands within a 40-ha circular search area. Local connectedness was measured using a resistant kernel model (Compton et al. 2007) on a 90-m, expert-derived, resistance grid created from land cover and roads (Homer et al. 2007; Tele Atlas 2012). Sites were scored based on a sum of diversity and connectedness normalized within each geophysical setting.

High-scoring sites (>0.5 SD above the mean for each geophysical setting) were compared with the sites prioritized in TNC's ecoregional portfolios based on rare species and communities (Supplementary Information). The high-scoring sites captured 79% of the rare species taxa, 49% of their priority locations, and 53% of the priority locations for natural communities. When overlaid with a map of terrestrial vegetation types (Ferree & Anderson 2010), high-scoring sites captured all 98 of the vegetation types in amounts ranging from 1% to 91% of their respective area.

Anderson et al. (2014) concluded that this method offers a practical approach to conservation planning that captures a wide spectrum of rare and common targets while aiming to identify areas where species are most likely to persist given a changing climate. The method assumes that species persistence is more likely in connected areas with high micro-climate diversity (Weiss et al. 1988; Ackerly et al. 2010; Dobrowski 2011) and that the landscape between sites remains permeable.

Case Study 4: Comparing Conservation Priorities for Abiotic Units and for Biodiversity in the U.S. Columbia Plateau

Schloss et al. (2011) developed a potential reserve network selected to represent abiotic diversity and compared it with one selected to represent current biodiversity. From this, they identified regions where incorporating abiotic data could enhance a biodiversity-based network. To describe an abiotic reserve network, abiotic land units were created from nine topographic, edaphic, and climatic variables for the U.S. Columbia Plateau ecoregion. Elevation and slope were derived from 30-m DEMs. Data on three mapped soil properties were used as indicators of productivity: soil depth, available water storage, and particle size (Table 1). Maps of mean maximum temperature during the warmest month, mean minimum temperature during the coldest month, and mean total precipitation for both the wettest month and driest month were developed using 1/16th-degree resolution modeled climate surfaces averaged for 1915–2006 (Climate Impacts Group 2011). Data for all abiotic variables were aggregated to a 240-m grid.

The 9 variables were normalized and clustered into 41 abiotic land units across the Columbia Plateau using the *k*-means clustering algorithm. Conservation goals were to reserve 15% of the ecoregion, with an equal amount of PA in every unit. Reserve networks were created to efficiently represent the targeted area of every abiotic land unit using Marxan (Ball & Possingham 2000). The relative priority of each planning unit was calculated as the number of times (out of 1,000 Marxan runs) that each planning unit was included.

A separate Marxan parameterization was used to generate a biodiversity-based reserve network and to identify biodiversity-based conservation priorities based on

66 vegetation types and occurrences of 27 rare species mapped previously (Davis et al. 1999). Planning unit priority was compared between networks created to represent abiotic land units and networks created to represent biodiversity. Incidental representation of biodiversity targets was calculated as the percentage of biodiversity goals that were achieved in an abiotic-based network.

The 2 prioritizations resulted in different distributions of priority planning units. High priority planning units based on abiotic land units were mainly distributed at the margins of the Columbia Plateau ecoregion whereas high priority planning units based on biodiversity were largely in the interior. This may reflect Marxan's attention to complementarity, which prioritizes unusual combinations of land units, such as those at the transitional boundary of the region. Although few planning units were high priority for both abiotic facets and biodiversity, many planning units were of low priority in both networks. The abiotic-based network represented 76% of the vegetation types at target quantities but only 16% of the rare species.

Schloss et al. (2011) concluded that abiotic-based networks are effective at representing a large percentage of coarse-filter biodiversity targets, but the abiotic-based reserve network poorly represented current occurrences of rare species and did not provide a means for species to redistribute across the landscape. In regions where geodiversity-based priorities differ from biodiversity-based networks, high priority regions for abiotic units can be added to biodiversity-based conservation plans to make these networks more robust to the impacts of climate change.

Case Study 5: Ability of The Nature Conservancy's Biodiversity-Based Conservation Portfolio to Capture Geodiversity in the U.S. Northwest

Buttrick et al. (2014) assessed the ability of a portfolio of biodiversity-based conservation sites to capture diversity of land units derived from the intersection of soil, elevation, and slope in four ecoregions in the U.S. Pacific Northwest. The biodiversity sites were taken from TNC ecoregional portfolios developed between 1999 and 2007 (Columbia Plateau, Middle Rockies, East Cascades, Canadian Rockies [Supporting Information]) and aimed to capture rare species plus 10% to 30% of each mapped vegetation type within each ecoregion.

Before choosing variables to define land units, Buttrick et al. used measures of association to select ecologically meaningful variables and specify ecologically meaningful classes for continuous variables. For example, to select the most relevant soil-related variable, they cross-tabulated dominant mapped vegetation types (LANDFIRE 2009) with each potential soil variable (Table 1) and calculated an area-weighted measurement of association. Because soil order was most closely related to dominant vegetation, it was selected as the substrate variable. A similar procedure was used to choose the elevation and slope classes but they found no significant relationship between class limits and vegetation. They then generated two sets of land units each with a resolution of 270 m^2. Both sets had 9 soil orders, but one had 6 elevation classes and 3 slope-aspect classes, and one had 10 elevation classes and 5 slope-aspect classes. Within each ecoregion, both sets of land units were overlaid with and compared to the TNC portfolio sites.

The overlay indicated that TNC's portfolios encompassed a wide range of geodiversity; across the four ecoregions, 91% of all land units had 30% or more of their area included in portfolios. This is likely because the portfolio was designed to capture dominant vegetation types and the geophysical variables were also selected and divided based on how well they reflected the pattern of vegetation distribution. Representation was not influenced by the number of slope or elevation classes. The percentage of an ecoregion in the portfolio (tested at 10, 20, and 30%) had little effect on how well geodiversity was captured.

Buttrick et al. concluded that planning to conserve geodiversity of an ecoregion is compatible with efforts to conserve biodiversity. Networks of conservation areas designed to conserve all of the biodiversity within an ecoregion also contain much of the geodiversity. Expanding them to encompass the full suite of geodiversity features seemed to be an inexpensive, prudent step to potentially enhancing the conservation of species and changing communities in the future.

Case Study 6: Sensitivity of Conservation Priorities to Decision Rules in Designating Land Units in the U.S. Pacific Northwest

J.L and C.S. (unpublished, contact these authors for further information or data access) quantified how decisions about land-unit designation affected subsequent prioritization in three ecoregions in the U.S. Pacific Northwest. Land units were created in 3 ways: with topographic variables only, with topographic variables plus soil variables, and with topographic variables plus geologic type. Elevation and slope were used to identify areas of unique topography. Edaphic variables included soil order, organic matter, bulk soil density, soil depth, and available water capacity (Table 1). Geology compiled from state sources was classified into nine substrate classes as in case study 3. All data layers were converted to grids at both 270-m and 1-km resolution to explore the potential impact of resolution on land-unit definition.

Geophysical variables were combined into land units using one of three models: a simple overlay of variable classes, a statistical *k*-means clustering approach, which identifies the most homogenous groupings of variables through an iterative process, and a hybrid of the 2. Conservation networks were generated using Marxan (Ball & Possingham 2000) to represent 30% of the area of each land unit from a given land-unit model. Highest priority was assigned to planning units that were included in all of the 1,000 Marxan runs. Correlation coefficients were used to measure the similarity in the priority of planning units based on different land-unit models.

Between 7 and 3,884 land units were produced and tested, depending on the combination of variables and modeling approach used. Resulting priorities were most different between land units developed with a clustering (*k*-mean and hybrid) approach and those developed with the overlay approach (correlation coefficients 0.33–0.68). Within any single approach (*k*-means, hybrid, overlay), priority rankings were highly correlated between land-unit sets developed with different variables or at different resolutions (between 0.72 and 0.93). Although there were differences in the prioritization of planning units, a network of the highest priority planning units selected to represent 30% of each land-unit type from a given set of land units also represented the land units created from other variables, resolutions, and approaches relatively well.

J.L. and C.S. concluded that the inclusion of soil or geology in addition to topography and the choice of data resolution made less of a difference in the priority of planning units than did the modeling approach used to combine variables into land units. The spatial correlation among soil, geology, and topography appeared to make conservation prioritization fairly robust to the particular variable choice.

Case Study 7: GAP Status and Effects of Decision Rules on Characterization of Geodiversity in the U.S. Southwest

Albano (2015) characterized the geodiversity of the southwestern United States (Arizona, California, Colorado, Nevada, New Mexico, Utah) and assessed the sensitivity of this characterization to different classification methods and spatial scales. To assist land managers with prioritizing places for conservation, a Gap analysis (Scott et al. 1993) was performed to evaluate the degree to which the region's existing PAs network captured geophysically diverse places.

Land unit (at 90-m and 270-m resolution) were created based on unique combinations of elevation, topography, and dominant soil suborder (Table 1). Topography was quantified using two indexes derived from a DEM: compound topographic index (CTI) (Moore et al. 1993), an estimate of topographic wetness, and topographic heat load (THL) (McCune & Keon 2002), which integrates the effects of slope, aspect, and latitude. These variables captured abiotic conditions of importance to plant distributions.

Different land-unit characterizations were developed by varying the classification method used to subdivide each topographic variable (e.g., minimum variance vs. equal subsets, number of divisions in the classification), the spatial resolution at which the topographic variables were derived (90 m vs. 270 m), and the moving window size used to calculate land-unit diversity (window size: 1–23 km^2). Within the moving window, land-unit diversity was calculated using Shannon's diversity index averaged across all of the different land-unit classifications. Sensitivity was assessed using analysis of variance, and similarities among the different classifications were assessed using correlation analyses. Gap analysis was used to assess the proportion of protected lands with high land-unit diversity.

Land-unit diversity estimates were slightly more sensitive to moving-window size than to the classification method ($F = 2.49$, $p = 0.11$), but all were highly correlated ($r > 0.88$). Correlations between diversity estimates based on the 90-m versus 270-m resolution data decreased as search area decreased but were still significantly correlated, even at 1 km^2, the smallest sizes analyzed (average $r = 0.72$).

The protected status of areas with high land-unit diversity varied widely among ecoregions. Soils classified as "miscellaneous areas" and supporting little or no vegetation were the most highly protected soil type (USDA 1993). Areas at intermediate elevations with more productive soil types and high CTI values were relatively less protected, although these environments are more likely to have fine scale climatic diversity and provide refugia for species under a warming climate (Ackerly et al. 2010; Dobrowski 2011).

Albano (2015) concluded that although varying the variable classes, spatial resolution, and moving window size created observable differences among land-unit diversity estimates, results were still highly correlated and thus relatively robust to these decisions. Further, using these data sets to prioritize land for conservation could help identify and correct biases in the current set of protected lands to ensure that they represent all aspects of natural diversity.

Case Study 8: Environmental Diversity Used to Explore Trade-Offs between Conservation and Production in the Southeastern Forests of New South Wales, Australia

Faith et al. (1996) developed a general framework for evaluating trade-offs in systematic conservation planning using a continuous abiotic diversity metric consisting of geophysical and climatic data as surrogates for overall biodiversity. The results were used to address regional forestry planning issues in the Bateman's Bay region of New South Wales.

The approach used, called "environmental diversity" (ED) (Faith & Walker 1994, 1996), was based on recognizing environmental space as continuous and thus avoided the arbitrary splitting of what is really a continuum of variation among sites. The unimodal response model underlying ED links representation of the environmental space to representation at the species level. Graphically, the number of species represented by a set of sites is large to the extent that, on average, the distance from any point in the environmental space to its nearest PA is small (i.e., the PAs cover all the environmental space). The expected complementarity value of an area, estimated as the relative number of additional species it contributes, is indicated by the extent to which addition of the area to a partial set reduces the sum of these distances.

Twenty-five environmental variables were calculated for 5 primary factors (temperature, precipitation, radiation, nutrient index, and terrain roughness); there were 5 variables for each factor (Faith et al. 1996). Mean monthly temperature, precipitation, and solar radiation values were estimated from latitude, longitude, and elevation in the program ESOCLIM (Hutchinson 1984) at the center points of 0.01×0.01 degree grid cells. The resulting 3,439 cells were used as the sites for land-use allocations. Ordination was used to generate an environmental space based on all variables, and distance in ordination space was used as a measure of dissimilarity between grid cells. The 5 primary factors were given equal weight.

We used the DIVERSITY package (Walker & Faith 1994) to derive the allocation of sites to conservation that maximizes total net benefits. Net benefits were based on the estimated number of species captured through the complementarity value of each site in environmental space and the suitability of the site for forestry (Faith & Walker 1994, 1996). Forest suitability costs for each site were calculated based on 47 factors (e.g. distance to saw mill, site productivity). Each area selected for protection had to make a weighted complementarity contribution to biodiversity that exceeds its weighted forest suitability cost.

Faith et al. (1996) argue that the ED measure allowed for the systematic integration of estimated biodiversity consequences into planning efforts that include other preferences for different land uses. The approach avoids arbitrary percentage targets applied to environmental clusters and allows for a more nuanced view of potential trade-offs. This continuous view of biodiversity surrogate information side-steps the problem of first determining a number of types to be counted toward comprehensiveness and then deciding how much heterogeneity within types is to be captured. Weaknesses included the need for better justification of the choice of environmental variables. Subsequent work developed a combined approach based on biotic and environmental variables and revisited the study to include ecosystem services (Faith 2014).

Discussion

Geodiversity can add new dimensions to conservation planning that augment traditional biodiversity-based approaches and help ensure the lasting conservation of diversity. The case studies show that, in addition to its recognized role as a coarse-filter surrogate for species diversity, geodiversity has also been used to estimate within-ecosystem variation; as a measure of microclimate availability within topographic and elevational gradients; and as a template to assess how well site prioritizations, protected lands, or connectivity models encompass the range of physical and ecological gradients in a region. These functions seem particularly relevant when planning for a different future climate. Moreover, a geophysical approach uses data that are generally available worldwide and is grounded in fundamental concepts of ecology (Lawler et al. 2015 [this issue]). However, the choice of variables, assessment methods, and in particular, the approach to combining variables all have an effect on results and no agreed upon method has yet emerged for designing an effective geophysical template to support diversity into the future.

The degree to which geophysical patterns succeed as surrogates for biodiversity patterns depends in part on the careful selection of geophysical variables. All studies found that distribution patterns of some geodiversity elements, especially soils, elevation, and topography, had high correspondence with the distribution of dominant vegetation types. For instance, Schloss et al. (2011) (case study 4) found that planning units selected to include geodiversity also included most vegetation types (76%), and Buttrick et al. (2014) (case study 5) found that the TNC biodiversity portfolio also captured 91% of the land units that had been calibrated to dominant vegetation patterns. Because the distinctiveness of these geophysical factors is likely to persist under different climates, the utility of using them for developing a conservation plan seems well justified.

The effectiveness of geodiversity in capturing species distributions was generally better for common species than rare ones. Case study 3 suggests that in some regions, bedrock may be more highly correlated with rare species than soil order due to its correspondence with unique environments like serpentine and limestone. The study's high capture of both rare species taxa (75%) and mapped vegetation types (100%) may be because vegetation types are statistically easier to capture in a wide variety of configurations than are rare species, so calibrating geodiversity variables to rare elements should result in a more species comprehensive portfolio that also captures common vegetation types. However, the high species capture may also be due to additional criteria for local connectedness. Integrating geodiversity with other targets such as rare species locations, vegetation types, or intact landscapes may lead to a more comprehensive template, and the resulting site networks should be more robust to climate change because they incorporate finer-grain ED. Still, some fine-filter conservation targets, like wide-ranging mammals, are unlikely to be tightly linked to geodiversity and will need to be addressed with alternative planning approaches.

Across all studies there were marked similarities in the selection of primary variables, although the exact metric, thresholds, and mapping scale differed substantially. Elevation and slope were the most common topographic variables, and some authors are now experimenting with mapping isobioclimates (Metzger et al. 2013) to reflect orographic effects and better map elevation-related life zones. Case studies 5 and 6 found that strong correlations among many of the geophysical variables made the resulting site networks relatively robust to exact variable choice. The effect of scale was less clear. Case study 3 used explicitly different scales for measuring representation than for measuring micro-climate diversity arguing that these are scale-dependent. However, case study 6 and 7 found that site selection results were highly correlated across scales.

Besides variable choice, characterization of geodiversity requires other subjective decisions that can influence the number of land units and their distribution across a landscape. For example, the method of combining variables had greater effects on the resulting reserve networks than variable choice in 2 studies (6, 7). The overlay method has a strong appeal for conservation use because the resulting units are easy to understand and to locate on the ground. Ecological land units, for example, correspond directly to distinct and recognizable temperature and moisture combinations associated with familiar landforms. In contrast, the statistical *k*-means clustering approach and the ordination methods of Faith et al. (1996) (case study 8) are conceptually appealing because they avoid the artificiality of classification thresholds, are relatively unaffected by correlated variables, and provide a way to minimize within-unit variance in multidimensional space. However, the results are more difficult to interpret. Additionally, cluster methods can be less transparent than overlay methods because several decisions must be made in the cluster process (e.g., similarity metric, clustering algorithm) and the implications of these for site selection are not known. Further, most clustering approaches cannot accommodate a mix of continuous and categorical variables and many are sensitive to outliers.

A common goal of the case studies was to identify a network of representative geophysical stages upon which communities can transform and develop. To sustain biodiversity, this network must also capture most of the species that will evolve, and have enough spatial coherence and connectivity to maintain ecological processes. Each case study developed a version of such a network, but questions remain about overall spatial design. Case studies 1, 4, 5, and 6 treated the design as an optimization problem and used Marxan to identify the most efficient arrangement of sites that represented all land units. However, a prioritization based on the proportion of runs in which each land unit was in the near optimal solution is not the same as an actual network, which is one of the possible solutions and might look very different spatially. Case studies 3 and 7 prioritized individual sites based on key geodiversity characteristics. These sites are likely of high importance to future biodiversity, but a portfolio based only on high-scoring sites might not have the spatial configuration needed to function as a physical template that sustains all diversity across a region. Three case studies explicitly included connectivity as part of the network (2, 3) or used patch size criteria to get at the area needed for processes such as fire (1).

Research is needed to understand how a coherent geophysical network facilitates function, persistence, and movement under climate change. Collectively the studies suggest four key design steps: define land units based on species-relevant variables combined in an ecologically meaningful way; represent the land units in a logical spatial configuration that integrates species occurrences if possible and review results for ecological coherence; apply selection criteria to individual sites to ensure that they are appropriate for conservation and express desired characteristics (e.g., microclimates or intactness); and evaluate connectivity among sites to maintain movements and ecological processes. With these considerations, conservationists now have an array of tools to design more effective site portfolios incorporating geophysical elements to ensure the lasting conservation of natural diversity.

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Supporting Information

Additional references for case studies (Appendix S1) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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