Conservation Biology

Contributed Paper

Use of Land Facets to Plan for Climate Change: Conserving the Arenas, Not the Actors

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Abstract: *Even under the most optimistic scenarios, during the next century human-caused climate change will threaten many wild populations and species. The most useful conservation response is to enlarge and link protected areas to support range shifts by plants and animals. To prioritize land for reserves and linkages, some scientists attempt to chain together four highly uncertain models (emission scenarios, global air–ocean circulation, regional circulation, and biotic response). This approach has high risk of error propagation and compounding and produces outputs at a coarser scale than conservation decisions. Instead, we advocate identifying land facets—recurring landscape units with uniform topographic and soil attributes—and designing reserves and linkages for diversity and interspersion of these units. This coarse-filter approach would conserve the arenas of biological activity, rather than the temporary occupants of those arenas. Integrative, context-sensitive variables, such as insolation and topographic wetness, are useful for defining land facets. Classification procedures such as k-means or fuzzy clustering are a good way to define land facets because they can analyze millions of pixels and are insensitive to case order. In regions lacking useful soil maps, river systems or riparian plants can indicate important facets. Conservation planners should set higher representation targets for rare and distinctive facets. High interspersion of land facets can promote ecological processes, evolutionary interaction, and range shift. Relevant studies suggest land-facet diversity is a good surrogate for today's biodiversity, but fails to conserve some species. To minimize such failures, a reserve design based on land facets should complement, rather than replace, other approaches. Designs based on land facets are not biased toward data-rich areas and can be applied where no maps of land cover exist.*

Keywords: adaptation, climate change, coarse-filter approach, conservation planning, ecological process, land facets, soil, topography

Uso de Elementos Territoriales para Planificar para el Cambio Climático: Conservando las Arenas, No los Actores

Resumen: *Aun bajo los escenarios más optimistas, el cambio climático provocado por humanos será una amenaza para muchas poblaciones y especies silvestres durante el próximo siglo. La respuesta de conservación más útil es ampliar y conectar áreas protegidas para soportar cambios en la distribución de plantas y animales. Para priorizar tierras para reservas y corredores, algunos científicos intentan enlazar cuatro modelos sumamente inciertos (escenarios de emisión, circulación global de aire y océanos, circulación regional y respuesta biótica). Este método tiene el alto riesgo de propagación e intensificación de errores y produce resultados a una escala más gruesa que las decisiones de conservación. En su lugar, proponemos que se identifiquen los* elementos territoriales *– unidades paisajísticas recurrentes con atributos topográficos y edáficos uniformes. Este método de filtro grueso podría conservar las arenas de actividad biológica en vez de los ocupantes temporales de esas arenas. Variables integradoras, sensibles al contexto, como la insolación y la humedad topográfica, son útiles para definir los elementos territoriales. Los procedimientos de clasificación como el algoritmo de las k medias o el agrupamiento difuso son adecuados para definir elementos territoriales porque pueden analizar millones de pixeles y son insensibles al orden de casos. En regiones que*

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Paper submitted June 25, 2009; revised manuscript accepted September 9, 2009.

Conservation Biology, Volume **, No. **, ***–***

DOI: 10.1111/j.1523-1739.2009.01422.x

carecen de mapas de suelo útiles, los sistemas hidrológicos o las plantas ribereñas pueden indicar elementos importantes. Los planificadores de la conservación deberían fijar objetivos de representación más altos para elementos raros y distintivos. La gran diseminación de los elementos territoriales puede promover procesos ecológicos, interacción evolutiva y cambios en la distribución. Estudios relevantes sugieren que la diversidad de elementos territoriales es un buen sustituto para la biodiversidad actual, pero deja de conservar algunas especies. Para minimizar esas fallas, un diseño de reservas basado en elementos territoriales podría complementar, no reemplazar, otros métodos. Los diseños basados en elementos territoriales no están sesgados hacia áreas ricas en datos y pueden ser aplicados donde no existen mapas de cobertura de suelos.

Palabras Clave: adaptación, cambio climático, elementos territoriales, método de filtro grueso, planificación de la conservación, proceso ecológico, suelo, topografía

Introduction

Human-caused climate change will have profound impacts on biodiversity. Reversing human-caused emissions of carbon dioxide and other greenhouse gasses is critically necessary to halt and reverse climate change and its consequences. Nevertheless, even under the most optimistic scenarios of emissions and carbon sequestration programs, past emissions will drive temperature and precipitation changes for at least 50 years (IPCC 2001). These changes, interacting with habitat loss, habitat fragmentation, and invasive species, will cause range shifts by plants and animals and reassembly of biotic communities and threaten many wild populations and species with extinction (Lovejoy & Hannah 2005).

Given the inevitability of human-caused climate change, conservation biologists are beginning to develop strategies to help ecosystems cope with environmental change. Efforts to increase ecosystem resistance and resilience to climate change may be futile attempts to "paddle upstream" (Millar et al. 2007), so most strategies try to improve the ability of organisms to respond to change in three ways. First, conserving or increasing genetic diversity can help species adapt evolutionarily to new temperature and precipitation regimes (Millar et al. 2007; Skelly et al. 2007). Second, managers can translocate species to areas expected to have suitable future climate (Hunter 2007; McLachlan et al. 2007). Third, managers can support range shifts by enlarging protected areas or linking them with corridors (Hannah et al. 2002). The last-mentioned strategy avoids over-reliance on evolutionary response or the artificiality of assisted colonization. It is also consistent with paleoecological evidence that extensive shifts in "species' geographical ranges have been the most important response of biota to past large, rapid climatic changes" (Huntley 2005:121).

Some efforts to design reserves and linkages for climate change involve complex analyses in which emission scenarios drive linked global and regional circulation models to predict future climate. Climate envelope models are then used to produce dynamic maps of the expected future distribution of biomes or species to develop coarse-filter or fine-filter plans, respectively (Cramer et al. 2001; Hannah & Hansen 2005; Hannah et al. 2007). Unfortunately, each step has an enormous uncertainty. For example, emission scenarios over the next 100 years vary by a factor of six (Fig. 1). For a single emission scenario, the seven air–ocean global circulation models (AOGCMs) produce markedly different climate projections (Raper & Giorgi 2005; IPCC 2001), and climate-envelope models may perform no better than chance (Beale et al. 2008). Because these sophisticated models have not been able to simulate the large shifts that paleoecologists have documented during the last 100,000 years of glacial oscillations, Overpeck et al. (2005:99) conclude the "lesson for conservationists is not to put too much faith in simulations of future regional climate change" in designing robust conservation strategies. In addition, the resolution

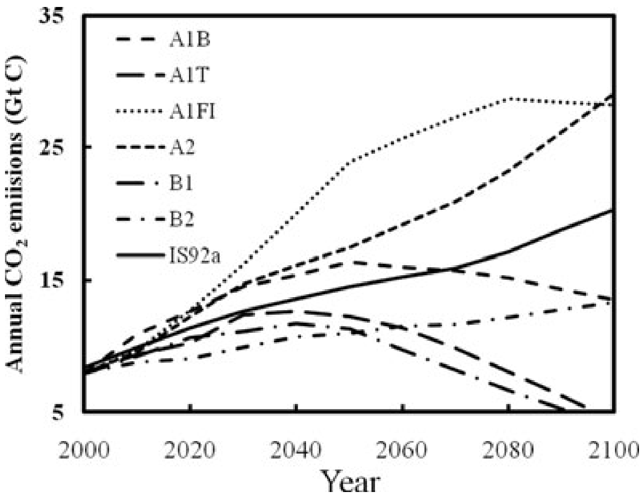

Figure 1. Seven emission scenarios developed by the Intergovernmental Panel on Climate Change (2001) for 2000–2100. The IS92a scenario (solid line) is "business as usual"; world population grows to 11.3 billion by 2100, economic growth continues at 2.3–2.9% per year, and no active steps are taken to reduce emissions. Most emissions are from fossil fuel and industrial sources. Depending on scenario and year, up to 24% of emissions are due to deforestation and land use. Actual emissions during 2000–2004 were higher than any of these scenarios (Raupach et al. 2007).

Table 1. Studies and conservation plans that used landscape units based on topography and soils as a surrogate for vegetation communities, species, or other elements of biodiversity.

Citation	*Number of landscape units*	*Name of landscape unit*	*Abiotic factors used to define landscape units*[a]	*Feature landscape units are intended to represent*	*Procedure used to define landscape units*	*Size of study area (km²)*	*Pixel size or map scale*[b]
Mackey et al. 1988	12–23	bioenvironment	E, G_S, I, P, T	geomorphic region	numerical classification	2750	~0.13 km²
Belbin 1993	3	environmental partition	G_S, I, P, R, T	environmental region	numerical classification	3599	~1 km²
Kirkpatrick & Brown 1994	68	environmental domain	E, G_S, I, P, T	variation in the physical environment	numerical classification	7140	10 km²
Wessels et al. 1999	8	land facet	G_P, G_S, S, H	unit of uniform slope, parent material, soil, and hydrological conditions	air photo interpretation and geological survey	350	1:10000–1:50000
Fairbanks & Benn 2000	97	landscape	E, L, P, T	landscape	ordination	92100	1 km²
Burrough et al. 2001	6	topo-climatic class	C, E, H, I, S	land-cover class	numerical classification	10000	100 m²
Reyers et al. 2002	676	land type	G_S, L, P, T	unit of uniform terrain, soil, and climate	spatial intersection of factor levels	122305	1:250000
Carlson et al. 2004	126	landscape diversity unit	E, G_P, L	natural community type	spatial intersection of factor levels	84	30 m²

[a] *Abbreviations: E, elevation; L, landform or topographic position; C, landscape curvature; F, suitability for farming; G_P, geology of parent material or bedrock; G_S, geology at land surface or soil type; H, hydrologic conditions; I, insolation; P, precipitation; R, ruggedness; S, slope; T, temperature.*

[b] *Minimum detectable size of a unit on a map is approximated by dividing the denominator in the map scale by 1000 (Tobler 1988) (e.g., the minimum detectable unit on a map with scale 1:250000 is 250 m²).*

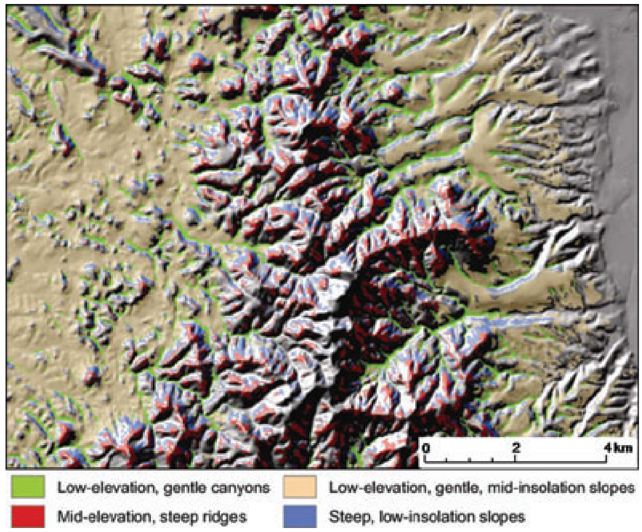

Figure 2. Illustration of the geographic distribution of land facets, defined on the basis of elevation, slope, insolation, and topographic position, draped over a hillshade map. For clarity, not all land facets in the landscape are shown.

of the final maps (square kilometers) is coarser than the typical scale at which lands are targeted for conservation.

Hunter et al. (1988) suggest an alternative coarse-filter conservation strategy to address climate change, namely to protect areas with a high diversity of physical landscape units defined by topography and soils. Several other researchers subsequently used some combination of topographic and soil variables to define landscape units for use as surrogates in conservation planning (Table 1). Following Wessels et al. (1999), we call these units *land facets*, defined as recurring areas of relatively uniform topographic and soil attributes (e.g., Fig. 2). Somewhat surprisingly, these authors (Table 1) used physical landscape units as surrogates only for current diversity of communities and species. None of them adopted the strategy of Hunter et al. (1988) and explicitly focused on the utility of physical landscape units as surrogates for ecological and evolutionary processes during the impending period of rapid climate change.

Cowling et al. (1999, 2003), Rouget et al. (2006), Pressey et al. (2007), and Klein et al. (2009) used physical features (e.g., upland–lowland gradients) as surrogates to conserve ecological and evolutionary processes, including biotic response to climate change, in a reserve design for the Cape Floristic Region. Nevertheless, their procedures did not include a formal, quantitative landscape classification based on physical attributes.

The purpose of this paper is to promote the utility of land facets for coarse-filter conservation planning in the face of climate change. We argue that this strategy is less subject to uncertainty than other modeling approaches, can enhance planning of both reserves and corridors, and

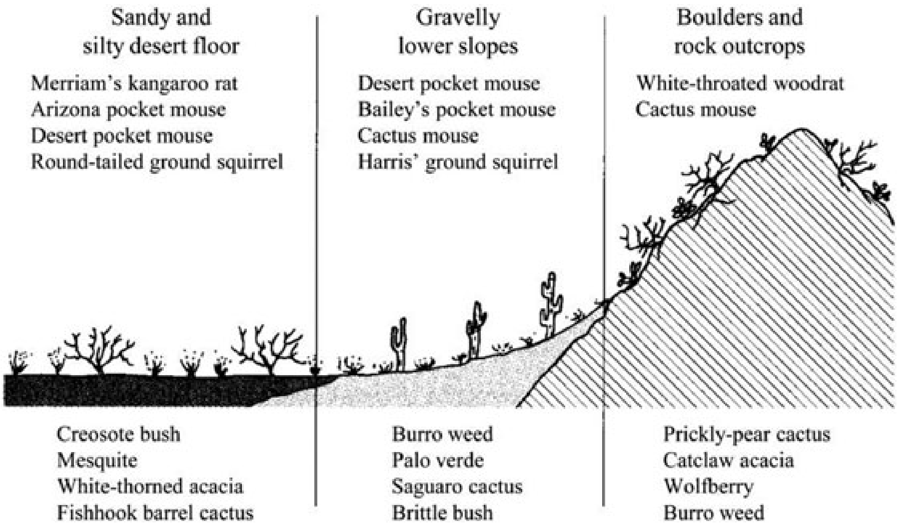

Figure 3. Influence of topography and soils on distribution of plants and animals in North American deserts (from Hugget 2004).

can be readily applied even in parts of the world where no maps of land cover exist. We discuss variables and procedures that can be used to define land facets and suggest strategies for using land facets in concert with other coarse-filter and fine-filter approaches to design reserves and linkages.

Land Facets as Surrogates for Future Biodiversity and Ecological Processes

Since the life zone concept was introduced by Merriam (1890), ecologists have recognized the influence of topography and geology on plant and animal communities (Fig. 3). These influences are obvious on aerial photographs (Fig. 4). More recent research shows that most modern plant communities are <8000 years old and are not highly organized units, but rather are transitory co-occurrences of plant taxa (Hunter et al. 1988; Huntley 2005). Because they are ephemeral, communities are not appropriate units for coarse-filter conservation planning. Accordingly, Hunter et al. (1988:380) "advocate basing the coarse-filter approach on physical environments as ''arenas'' of biological activity, rather than on communities, the temporary occupants of those arenas."

The species present at any given site are a function of climate, other organisms present in or adjacent to the site, disturbance regime, topography, the underlying geological material, and time (Jenny 1941; Amundson & Jenny 1997). Land facets reflect the more stable factors, namely topography, geology, and time (geology and time represented by a single soil-related variable). Topography also governs local (i.e., within the geographic extent of a typical conservation plan) variation in precipitation and temperature. Thus, reserves and linkages that capture diverse land facets should also support biodiversity under any future climate regime (Hunter et al. 1988).

Conserving diverse physical environments may also ensure persistence of the ecological and evolutionary processes that maintain and generate biodiversity. For example, protecting environmental gradients helps conserve intraspecific genetic diversity necessary for adaptive evolution and speciation (Noss 2001; Moritz 2002; Rouget et al. 2003). Protecting upland–lowland interfaces and soil interfaces can conserve ecological processes such as nutrient cycling and disturbance regimes (Rouget et al. 2003, 2006; Pressey et al. 2003).

Figure 4. Aerial photograph of eastern Tehama County, California (U.S.A.), shows bands of vegetation corresponding to geological strata and elevation contours intersected by heavily vegetated drainages.

Hunter et al. (1988), and most of the papers listed in Table 1, note another advantage of land facets, namely that topography and soils are relatively easy to inventory and map. In contrast, species diversity can be assessed only by long-term inventories (Cowling et al. 2009).

Several studies describe the correspondence between land facets and the current distribution of land-cover types or species. For instance, six of eight land facets identified by Wessels et al. (1999) supported distinctive communities of birds and dung beetles. Similarly, Burrough et al. (2001), Kintsch and Urban (2002), and Carlson et al. (2004) found that land facets were correlated with vegetation types in a statistically significant way, but the strengths of the associations varied among vegetation types and were low for some types. Modest correlations may be a consequence of a nonequilibrium between modern vegetation and land facets due to recent and ongoing climate change, biotic interactions (e.g., competition, seed rain, mutualists), past disturbance, and other historical legacies. Thus, land facets may not correspond well to modern land cover despite being a major driver. The moderate level of correspondence is of limited relevance, though, because the land-facet approach does not depend on a 1:1 mapping of land cover or species on land facets. Rather, the central idea is that a reserve or linkage designed to encompass the full diversity of dominant land facets at multiple spatial scales will encompass the full diversity of land-cover types and species, today and in the future, and will conserve ecological and evolutionary processes.

Several studies address whether the full diversity of land facets is a good surrogate for today's biodiversity. Kirkpatrick and Brown (1994) found a statistically significant correspondence between grid squares selected on the basis of land facets and those selected on the basis of forest types, endemic species, rare or vulnerable species, and poorly reserved plant communities. Nevertheless, the proposed reserve network based on land facets failed to capture known occurrences of some of the rarest species and communities. Similarly, Cowling et al. (1999) report that a hypothetical reserve network designed to conserve ecological processes (including biotic response to climate change) conserved 37% fewer rare species than a similar-sized hypothetical reserve designed to maximize representation of those species. The unrepresented species tended to be those that were rare, required specialized habitat, or had distributions determined by historical factors (Lombard et al. 2003). Reyers et al. (2002) found that an extensive reserve design (60% of the landscape) based on land facets (676 land types) represented most species, including rare and endemic species. The results of these studies suggest that although a land-facet approach should help conserve ecological processes, including range shifts of many species in the face of climate change, it remains a coarse-filter approach that will not conserve all species.

Selecting Useful Topographic and Soil Variables

Conservation strategies based on land facets can be applied worldwide because digital elevation models (DEM) are available for all continents at 30-m resolution (http://www.gdem.aster.ersdac.or.jp/), and 10-m resolution is available for some areas. Topographic attributes derived from a DEM include elevation, slope, aspect, topographic position, solar insolation, profile curvature (down-slope curvature), planiform curvature (horizontal, or cross-slope curvature), ruggedness, and topographic wetness index (Moore et al. 1991; Franklin 1995). Topographic position is usually characterized into several classes such as ridgetop, steep slope, gentle slope, or canyon bottom on the basis of elevation of the focal pixel relative to neighboring pixels (Jenness Enterprises 2006). Topographic wetness index is a proxy for soil water content; it is a function of slope and the area of the catchment that drains into a focal pixel (Moore et al. 1991).

Many researchers report a strong correlation between the distribution of plant and animal species and topographic variables such as elevation, insolation, slope, aspect, landform, curvature, and ruggedness (DeVelice et al. 1988; Davis & Goetz 1990; Forman 1995; Parker 1995; Pinder et al. 1997; Bolstad et al. 1998; Gottfried et al. 1998; Guissan et al. 1999; Franklin et al. 2000; Pfeffer et al. 2003; Dickson & Beier 2006). Nevertheless, the relative importance of a variable depends on spatial scale, species, and location of the study (Pfeffer et al. 2003; Deng et al. 2007).

The European Digital Archive of Soil Maps (EuDASM 2009) offers soil maps for every inhabited continent, typically at a scale of 1:200,000 (minimum mapping unit approximately 600 ha) to 1:2,000,000. Attributes of each soil map polygon may include soil order (e.g., mollisol, aridisol), the two dominant particle size classes, mineral composition class for the dominant particle size classes, cation exchange activity class (typically four classes), and soil-depth class (typically shallow or not shallow). Unfortunately, soil maps have many limitations (Sanchez et al. 2009). For instance, accuracy and sampling methods are rarely described. Furthermore, some polygons may lack values for a certain attribute or contain several states of that attribute, indicating the presence of unmapped heterogeneity. All soil maps are of low resolution and often fail to depict local conditions. In nonagricultural parts of the western United States, we found that soil maps consist of large, heterogeneous polygons from which inferences about relevant traits, such as moisture, texture, depth, or soil nutrients, cannot be made. Maps of bedrock type are especially problematic because soil properties may differ greatly within a bedrock type due to weathering, age, and alluvium or till that formed from a source different than the local bedrock (Carlson et al. 2004).

Where available soil maps are not helpful, conservation planners can use presence of streams, standing water, or riparian plants to map important soils. In the arid southwestern United States, for example, typically only one or two of several watersheds in a potential reserve or linkage area support perennial stream flows. Thus, even without a good soil map, conservation planners can prioritize the impervious soils associated with these watersheds. Similarly, vernal pools and karst lakes are features related to soil and geology that are relevant to biodiversity and identifiable without a soil map. In the long term better soil maps are needed to ensure rigorous mapping of land facets across the entire planning region.

Defining Land Facets in a Landscape

We recommend using explicit and repeatable procedures to derive a land-facet taxonomy from topographic and soil variables. Nevertheless, explicit and repeatable procedures are not entirely "objective" because the analyst subjectively chooses the topographic and soil attributes that will define facets and decides how many land facets to recognize (Mackey et al. 1988).

We suggest limiting the number of topographic and soil factors used to define land facets because a large number of explanatory factors can yield hundreds of land facets, many of which defy interpretation (Mackey et al. 1988; Pressey et al. 2000). If the resulting classification scheme and conservation maps cannot be explained to stakeholders and implementers, their value is diminished. Also, if an analysis includes three highly correlated variables (e.g., general curvature, planiform curvature, and profile curvature), these variables can "gang up" in many statistical procedures to swamp the importance of a single variable related to, say, soil depth (Mackey et al. 1988; B.B. & P.B., unpublished data).

The number of variables can be reduced by choosing those that are highly interpretable or ecologically most influential (DeVelice et al. 1988; Fairbanks et al. 2001) or by choosing a variable that integrates several other variables in a biologically meaningful way. For instance, solar insolation integrates many important influences of latitude, aspect, and slope on plants and animals.

Once topographic and soil variables have been selected, several rule-based or statistical procedures can identify land facets (Table 1). Various numerical classification procedures such as principle components analysis, k-means cluster analysis, and fuzzy-clustering algorithms can define land facets in a repeatable, transparent way. Procedures that require a pairwise distance matrix between all pixels (e.g., hierarchical cluster analysis and nonmetric multidimensional scaling) are limited to data sets smaller than typical DEM data sets. Procedures sensitive to case order (i.e., the order in which pixels are listed in the input file), such as two-step cluster analysis (SPSS, Chicago, Illinois) should also be avoided.

Various metrics—many of them specific to a particular clustering procedure—can help identify the number of classes that corresponds to the natural multivariate "lumpiness" in the topographic and soil attributes. In our experience, these metrics often disagree on the best number of classes, and they differ trivially among the two or three best options. Selecting the largest number of classes among the best options reduces the risk of failing to recognize and conserve a distinctive facet (Ferrier 2002). Mackey et al. (1988) provide a good example of evaluating different alternative classification schemes. They used interpretability of classes, color maps to reflect multivariate similarity of facets, maps of facet polygons draped over a topographic hillshade, plots of facet centroids in multivariate space, and hierarchic dendrograms to evaluate alternative schemes. Ground-truthing and inspection of the map by someone familiar with the landscape will reveal whether the scheme corresponds to natural units or imposes artificially discrete categories on a continuous landscape.

Land Facets in Reserve Design for a Changing Climate

Once land facets have been defined, planners can apply the same tools and criteria used in other coarse-filter approaches to reserve design. Selection algorithms such as simulated annealing (Margules & Pressey 2000) can ensure that targets for each land facet are achieved in an efficient area. Targets are typically expressed as minimum area or percent of each land facet to be captured in a reserve.

Deciding how much is enough will be subjective, just as it is for conservation plans based on today's communities or species. Setting targets is useful nonetheless because it makes goals explicit and encourages thoughtful discussion (Margules & Pressey 2000). Following Pressey et al. (2003), we advocate setting higher targets for distinctive and rare land facets, such as those likely to concentrate soil moisture (rivers, karst lakes, vernal pools) or support unique plant communities (e.g., serpentine soils, other resource-limited soils). Conserving a higher proportion of a rare class is important because a small fraction of a small area is less likely to support its associated populations and ecological processes. The proposed reserve should include at least one large polygon of each facet type to support disturbance regimes, seral stages of future communities, and species that will not survive on the same total area distributed among several small polygons of that land facet.

Setting targets for juxtaposition of land facets will be even more difficult than setting goals for minimum areas. Highly interspersed land facets can allow relatively immobile plants and invertebrates to quickly move to a land facet with more favorable conditions (e.g., to a higher-elevation site or a site with a more poleward aspect). High interspersion also promotes various alternative combinations of species and future communities and thus is more likely to sustain ecological processes and evolutionary opportunities (McKenzie et al. 1989; Cowling et al. 1999; Fairbanks et al. 2001). To increase interspersion and conserve processes, Pressey et al. (2003) advocates setting targets for edaphic interfaces and upland–lowland interfaces. A map of land facets could provide a more rigorous basis for identifying and prioritizing these interfaces. Fairbanks et al. (2001) provide procedures to prioritize areas with high beta diversity (negative spatial autocorrelation) in species assemblages; the same procedures readily apply to land facets. Ferrier (2002) and Ferrier et al. (2007) describe how to model species dissimilarity between locations (i.e., beta and gamma diversity) as a function of environmental dissimilarity. They advocate using this relationship to prioritize locations on the basis of their contribution to the beta and gamma diversity of a proposed reserve system.

The need for minimum areas and interspersion should be considered at more than one spatial scale. For instance, when the planning area includes several major geophysical regions (e.g., coastal lowlands, foothills, major mountains, and interior basin and range), we suggest conducting separate analyses for each major geophysical region and assembling these into an overall reserve design. This would reduce the risk that a mechanical procedure might achieve the targets by selecting land facets only within a single geophysical region and would maximize conservation of evolutionary potential (Rouget et al. 2006).

Rivers and ephemeral drainages span elevational gradients in a way that increases interspersion (e.g., Fig. 4) and promotes ecological processes and flows, such as movement of animals, sediment, water, and nutrients. Because mechanical geospatial algorithms may fail to identify important riverine connections that are obvious to a human expert, we recommend manual inclusion of riverine elements if necessary (e.g., Cowling et al. 1999, 2003).

Land Facets in Linkage Design for a Changing Climate

During the impending period of climate change, species will have to shift their ranges in ways that are more complex than simply moving to higher elevation and toward the poles (Halpin 1997; Peterson et al. 2005). We found only three studies that designed corridors specifically to support range shifts in a changing climate. Rouget et al. (2006) used an approach that maximized continuity along elevation gradients, and Williams et al. (2005) and Phillips et al. (2008) used models of emissions, global and regional atmospheric circulation, and bioclimatic envelopes to design movement corridors.

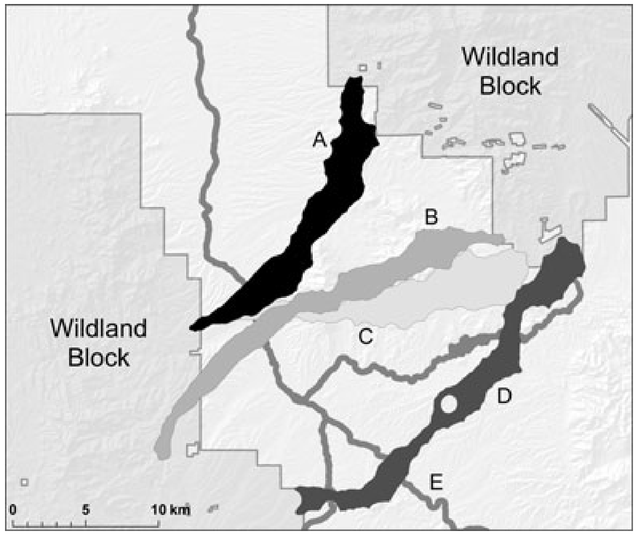

Figure 5. A multistranded linkage of land facets designed to allow species to shift their range in response to climate change and to support movement during periods of quasi equilibrium. Area A optimizes continuity for high local diversity of land facets. Other areas provide the best continuity of high-insolation, steep slopes (area B), low-elevation, gentle canyons (area C), and low-elevation, gentle ridges (area D). Area E encompasses the region's main river and its only perennial tributaries from each wildland block.

When designing corridors on the basis of land facets, we recommend giving top priority to the land facets that are dominant in the natural landscape blocks to be connected. Some facets that occur only in the matrix may also be considered, but the linkage should focus most fundamentally on the larger areas to be linked.

Like linkages designed for multiple focal species (Beier et al. 2008), linkages for diversity of land facets should contain multiple strands. The linkage design should include at least one strand intended to maximize continuity of each land facet (Fig. 5). Each such strand is intended to support occupancy and between-block movement by species associated with that land facet in periods of climate quasi equilibrium. The linkage design should also contain at least one strand with high beta diversity (i.e., high local interspersion of facets; Fig. 5) to support range shift, species turnover, and other underlying processes (Cowling et al. 1999; Fairbanks et al. 2001; Rouget et al. 2006).

Least-cost modeling (Beier et al. 2008) or circuit theory (McRae et al. 2008) can be used to identify optimal strands for individual land facets. Both these tools rely on an underlying map of resistance, wherein each pixel's resistance represents its dissimilarity to the focal facet type. We recommend multivariate measures of dissimilarity such as Mahalanobis distance or Bray-Curtis percentage dissimilarity. Useful variables include elevation, insolation, slope, and density of the focal land facet within the pixel's neighborhood.

The linkage design should always include the major riverine or riparian connections between landscape blocks. As with land facets in reserve design, rivers can efficiently be included by having a local expert draw by hand the riverine system (Fig. 5).

Prior to corridor design, we recommend masking highly degraded, unrestorable areas, such as urban areas that are unlikely to support species movements (Knight et al. 2006; Rouget et al. 2006). We caution against wholesale exclusion of agricultural areas, especially if they can be restored to natural vegetation or occupy a large portion of the most productive land facets (those with gentle slopes and high soil moisture).

Conclusions

We advocate the use of land facets as a tool to prioritize land for conservation in the face of climate change. Compared with climate-modeling approaches, an approach based on land facets does not depend on emission scenarios or climate predictions. Compared with approaches based on mapped species occurrences, land-facet maps are not biased toward data-rich areas. Indeed, because digital elevation models are available everywhere, an approach based on land facets can be used even in areas lacking maps of current land cover and species distributions. We believe designs based on land facets should conserve ecological and evolutionary processes.

Relevant studies (see "Land Facets as Surrogates") suggest that a reserve or network based on land facets may include half or more of the landscape. Although this is an ambitious goal, any credible reserve design, including designs based on distributions of current species, will require a large fraction of the landscape (Soulé & Sanjayan 1998).

Although this approach will not conserve every species, conserving the stage for ecological and evolutionary processes should be an overarching goal for conservation biologists. Climate change and other human impacts will drive some species to extinction, but new biodiversity can be generated in large, diverse, well-connected systems of land facets. It does little good to conserve each species in a small patch of land if the stage on which those species evolve is not conserved. To minimize loss of individual species, we advocate using land facets to complement, rather than replace, fine-filter approaches (e.g., critical habitat for endangered species, maps of rare species occurrences) and coarse-filter approaches based on modern distribution of plant communities, biodiversity hotspots, and focal species. Conservation is too complicated and too important for any single approach.

There are several ways to combine land facets with other approaches. The most obvious is to create a thoughtful union of reserve designs produced by land facets, other coarse-filter approaches, and fine-filter approaches (e.g., Noss 1987). One complementary coarse-filter strategy is to identify and conserve refugia that remained stable during previous periods of rapid climate change (e.g., Eeley et al. 1999; Hewitt 2000; Noss 2001). Similarly, Klein et al. (2009) propose high conservation priority for drought refugia, defined as areas of high gross primary productivity in a time series of satellite images.

Another fruitful step would be to learn from the mismatch between locations prioritized by different approaches. An area with high species diversity, or large genetic and phenotypic variability within a species, apparently has ecological conditions that generate or maintain diversity. Conservation biologists should investigate areas of high diversity outside a land facet reserve to identify important physical factors missing from the current land facet classification. This will improve the way land facets are defined and used.

Systematic conservation planning has been slow to develop tools to address dynamic threats, such as the threat posed by ongoing climate change (Pressey et al. 2007). We acknowledge a mismatch between static maps of land facets and the dynamic nature of climate change, and the dynamic ecological and evolutionary processes we seek to conserve. Nonetheless, we believe that using land facets to help design reserves and linkages can be a simple and effective conservation strategy. A more dynamic strategy might be temporary or moveable conservation areas (Hannah & Hansen 2005; Pressey et al. 2007). Another dynamic strategy would be to reduce the uncertainty in the complex chained models we disparage in our Introduction.

Regardless of the types of strategies used, landholders and other interest groups should be involved throughout the design process (Cowling et al. 1999; Knight et al. 2006; Beier 2008). Analysts should engage stakeholders and generate several scenarios (alternative maps with accompanying recommendations) for achieving targets and collectively decide which of several similarly effective options should be implemented.

Finally, we caution against using this approach, or any other adaptation strategy, as an excuse to avoid addressing the root causes of climate change, namely human burning of fossil fuels and release of carbon from destruction of natural landscapes. Conservation biologists must persuade governments, corporations, and individuals to reduce energy use, halt conversion of natural land cover, transition from energy sources that produce greenhouse gasses to nonpolluting alternatives, and sequester CO_2 in naturally evolving ecosystems.

Acknowledgments

We acknowledge M.L. Hunter as senior author of the 1988 paper that is seminal to the approach we promote here, other cited authors for their thoughtful work on these issues, and R.M. Cowling and two anonymous reviewers for helpful comments. Our work was supported by the Arizona Board of Forestry and the U.S. Forest Service Rocky Mountain Research Station.

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