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Protected area, easement, and rental contract data reveal five communities of land protection in the United States

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Abstract. Land protection efforts represent large societal investments and are critical to biodiversity conservation. Land protection involves a complex mosaic of areas managed by multiple organizations, using a variety of mechanisms to achieve different levels of protection. We develop an approach to synthesize, describe, and map this land protection diversity over large spatial scales. We use cluster analysis to find distinct "communities" of land protection based on the organizations involved, the strictness of land protection, and the protection mechanisms used. We also associate identified land protection communities with socioenvironmental variables. Applying these methods to describe land protection communities in counties across the coterminous United States, we recognize five different land protection communities. Two land protection communities occur in areas with low human population size at higher elevations and include a large amount of protected land primarily under federal management. These two community types are differentiated from one another by the particular federal agencies involved, the relative contributions of smaller actors, and the amount of protection by designations vs. conservation easements or covenants. Three remaining land protection communities have less overall protection. Land in one community is primarily protected by federally managed rental contracts and government managed easements; another is managed by a diversity of non-federal actors through fee-ownership and easements; and the third stands out for having the lowest amount of formally recorded protection overall. High elevation and poor quality soils are over-represented in U.S. protected lands. Rental contracts help fill in gaps in counties with high productivity soil while the U.S. Fish and Wildlife Service fills in gaps in low-elevation counties. Counties with large numbers of threatened species have more and stricter protection, particularly by regional entities like water management districts. The ability to synthesize and map land protection communities can help conservation planners tailor interventions to local contexts, position local agencies to approach collaborations more strategically, and suggest new hypotheses for researchers regarding interactions among different protection mechanisms.

Key words: agri-environment schemes; collaborative conservation; Conservation Reserve Program; incentive payments; national parks; natural resource management; nature reserves; private land; Protected Areas Database of the United States; state agency; typology.

Introduction

Land protection efforts are key to biodiversity conservation and represent large societal investments, totaling billions of dollars per year worldwide (Mansourian and Dudley 2008, Hickey and Pimm 2011, Organisation for Economic Cooperation and Development 2020). A complex mosaic of protected lands is involved, consisting of land managed by different public and private agencies and individuals to achieve different levels of protection (Groves et al. 2000, Aycrigg et al. 2013). These organizations vary in the scales over which they work (Keeley et al. 2019, Crain et al. 2020) and the objectives

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motivating their land protection actions (Redford et al. 2003, Kroetz et al. 2014, Baldwin and Leonard 2015). Mechanisms of protection also vary (Cortes Capano et al. 2019). Some organizations favor long term protection, perhaps by securing ownership of land outright or by relying on easements or covenants (Kabii and Horwitz 2006, Fishburn et al. 2009). Others rely on short-term agreements, such as rental contracts (Lerner et al. 2007, Hanley et al. 2012, Batáry et al. 2015, Zhu et al. 2018) or habitat recovery credits (Kreuter et al. 2017). To better evaluate and expand land protection programs, we need a means to synthesize this complexity and reveal communities of land protection.

There are several reasons why land protection is better viewed as a community enterprise than as the act of individual agencies (Imperial 2005, Guerrero et al. 2020). Natural values in a protected area are affected by land use and practices occurring outside the protected area (hence the call for environmental education of nearby communities, Martin et al. 2011, and protection of buffer zones, Palomo et al. 2012). Ecological processes occur over different scales than those defined by human administrative boundaries (Armitage et al. 2012). Agencies are limited not only by geography, but also mandate (e.g., protection of air, land, water, or species) and expertise (Imperial 2005, Bodin 2017). Finally, compliance, cooperation, and/or collaboration of stakeholders is necessary for effective protection (Arias 2015). For these reasons, the social context of conservation is a major factor predicting conservation success (Ostrom 1990).

An improved understanding of geographic variation in the human community of land protection activities could help inform many aspects of conservation. National-scale policymakers could better find local partners, tailor policies and programs to a particular regional conservation context, and complement ongoing local land protection efforts more effectively (Palomo et al. 2012, Kroetz et al. 2014). Mapping communities of land protection would also enable local conservation organizations to take a strategic approach to collaborations and partnerships (Simmons et al. 2020). For example, they might benefit from sharing experiences with other organizations operating in similar land protection communities about what kind of partnering arrangements with large-scale conservation actors proved most effective (Yonavjak and Gartner 2011, Ruseva et al. 2016). Meanwhile from a research perspective, better understanding of geographic variation in different types of land protection activities is a necessary first step to understanding interactions among land protection measures including whether they crowd one another out (Albers et al. 2008, Parker and Thurman 2011), and to understanding how innovations in conservation spread (Mills et al. 2019).

Any holistic picture of land protection must consider the diversity of ways in which land is protected including through changes in fee ownership, easements, designations, rental contracts, and other mechanisms. Changes in fee ownership involve a land protection organization taking full ownership of a property (Fishburn et al. 2013). Alternatively, easements, or covenants, involve a land protection organization acquiring partial property rights, such as the right to subdivide the property, to clear-cut timber, or to develop land, but the fee title is retained by the original owner (Merenlender et al. 2004, Fishburn et al. 2009, Stroman and Kreuter 2015, Stroman et al. 2017). Government agencies sometimes use policy designations to permanently alter management of public and, in some cases, private property (Dudley et al. 2013, Comay et al. 2018). Fixed-term conservation contracts typically involve rental contracts made to private landowners in return for them undertaking particular management actions for a finite time period. For example, the Conservation Reserve Program, the largest rental contract program in the United States (Lerner et al. 2007), pays food producers to retire land from production and to maintain perennial cover under 10–15 yr contracts (Claassen et al. 2008). In many locations, landscapes are protected through a combination of these instruments acting in concert.

Past studies of land protection have tended to collapse the richness of land protection activity down to a single dimension, describing whether land is protected or not (Scott et al. 2001, Rodrigues et al. 2004, Chape et al. 2005, Goettsch et al. 2019), the degree of protection (Chape et al. 2005, Aycrigg et al. 2013, Jenkins et al. 2015, Land Trust Alliance 2016), the mechanism used (Merenlender et al. 2004, Yonavjak and Gartner 2011, Villamagna et al. 2017), or the conservation agency responsible (Groves et al. 2000, Land Trust Alliance 2016). While a handful of studies consider two dimensions of protection at one time (Rissman and Merenlender 2008, Aycrigg et al. 2013), none appear to consider fuller patterns of spatial correlation and overlap among the many types of protection involved.

Understanding the distributions of multiple types of protection simultaneously is fundamentally a multivariate question. Community ecologists have a long tradition of studying simultaneously the distributions of multiple types (usually species) across landscapes as well as the relationship of those multivariate distributions with environmental factors (e.g., Legendre and Legendre 2012). We exploit multivariate approaches common to community ecology to study the distribution of types of land protection, where "types" are described by unique combinations of strictness, protection mechanisms, and managing agency.

We limit our definition of "land protection" to geographically bound fee-ownership, designations, and easements reported by the Protected Area Database of the United States 2.0 (PAD-US; U.S. Geological Survey Gap Analysis Project 2018) and rental contracts reported by the Conservation Reserve Program (CRP; U.S. Department of Agriculture Farm Services Agency 2018). This is a broad definition of protection that includes strict protection for biodiversity objectives as well as protection that is either temporary and/or for which conservation is not a stated objective. Even so, we recognize that some forms of protection on private lands, such as certified conservation programs and voluntary non-binding conservation activity (Kamal et al. 2015), will be missed by this approach. Furthermore, although federal- and state-managed lands are well reported and cover the greatest area, areas protected by municipalities, smaller non-government organizations, and other private stewards, especially those protected by mechanisms other than fee-ownership, may be missed due to incomplete reporting (see information *available online*).[8,9] Even so, we are confident that our analysis captures broad patterns of protection in the United States.

In this paper, we examine spatial covariation in the abundance of land protection types in the coterminous United States to identify what we call "land protection communities," or groups of land protection types that cluster together. We associate those covariation patterns with underlying socioenvironmental gradients that could suggest why different protection approaches are being relied upon and that delineate what different protection strategies can help to protect. When doing so, we pay particular attention to whether land protection instruments ignored in past studies, like rental contracts, help fill widely reported gaps in the protection of low-elevation, high-soil-productivity locations within the U.S. land protection system (Scott et al. 2001, Aycrigg et al. 2013).

Methods

We considered the spatial configuration of land protection in the coterminous United States. Specifically, we used all 3,108 U.S. counties as our units of analysis (median county area in coterminous United States = 1,670 km^2). While other choices of spatial unit would have been possible, counties provide meaningful spatial units for many smaller conservation actors, a convenient reporting unit for relevant socioenvironmental data, and a large enough area to encompass a range of conservation actors.

Data

Protected area data.—Protected area data were obtained from the PAD-US 2.0 (U.S. Geological Survey Gap Analysis Project 2018). Data for lands managed by the Bureau of Indian Affairs were collected from PAD-US 1.4 (U.S. Geological Survey Gap Analysis Project 2016) because those data are absent from PAD-US 2.0. Data for rental contract lands managed by the USDA Farm Service Agency (FSA) under the Conservation Reserve Program in 2016 were collected from the USDA Conservation Reserve Program Statistics (U.S. Department of Agriculture Farm Services Agency 2018). All easement data were contained in PAD-US 2.0, which gathered its data from the National Conservation Easement Database in February 2018. We note that this database has been updated since February 2018 to include data missing from our analysis. Just between April 2019 and September 2020, the hectares listed under easement in the National Conservation Easement Database grew by 32%, or 3.2 million hectares.

We consider protected areas along a continuum, from those managed strictly for biodiversity outcomes (GAP 1 and 2) on one end to those for which conservation is not a primary objective (GAP 4) or for which protection is temporary on the other (not given GAP status). GAP 3 lands are multi-use lands with mixed conservation and social objectives. Only lands under GAP 1, 2, and 3 status would be considered "protected areas" under the IUCN definition (Dudley et al. 2013). GAP 4 protection and protection under temporary rental contracts, however, often also support conservation objectives and might be classified as "other effective area-based conservation measures" (IUCN-WCPA 2019).

With a few adjustments, we used the categories defined by PAD-US 2.0 to describe land protection by strictness of protection, managing agency, and protection mechanism (Table 1). Land protection agencies were placed in groups according to PAD-US "Agency Type" categories: federal (FED), state, regional districts, city and county governments (hereafter local governments), non-governmental organizations (NGO), Native American tribes (hereafter tribes), private entities, and unknown agencies. When an agency was the fee-owner, easement holder, and/or designating agency for more than 10 million hectares of land, we specified the individual agency by name, including the U.S. Fish and Wildlife Service (FWS), the Bureau of Land Management (BLM), the U.S. Forest Service (USFS), the Bureau of Indian Affairs (BIA), the U.S. Department of Agriculture Farm Services Agency (FSA), and the National Park Service (NPS). These were all federal agencies. We combined the PAD-US "joint" agency category (<0.5% of protected lands) with the unknown agency category (0.13% of protected lands). We added a "no reported protection" category to describe the area of a county not covered by any recorded protection (i.e., not recorded by PAD-US or FSA). These lands are likely to be managed by nonfederal actors, especially private entities, local governments, and small NGOs, for whom records are less complete.

We retained spatial overlaps in protected area data. For example, a portion of the Beaverbrook Watershed in Clear Creek County, Colorado is fee-owned by the U.S. Forest Service (GAP 3), is designated as a watershed protection area by the county (GAP 3) and is protected by an easement held by an NGO (GAP 2). Tiering of conservation activity, with multiple actors involved in protection on the same land, is common in other countries as well (Eigenbrod et al. 2010, Scullion et al. 2014)

[8] http://www.protectedlands.net/data-stewards/
[9] https://www.conservationeasement.us/completeness/

TABLE 1. Total coterminous U.S. hectares of protection by (A) GAP status, (B) managing agency, and (C) protection mechanism.

Code	Total area (10^6 ha)	Description
(A) Strictness of protection (gap status)		
1	31.4	managed for biodiversity; disturbance events proceed or are mimicked
2	43.8	managed for biodiversity; disturbance events suppressed
3	294.6	managed for multiple uses; subject to extractive (e.g., mining or logging) or OHV use
4	54.2	no known mandate for biodiversity protection
No GAP	540.8	no protection documented in PAD-US 1.4 or 2.0
(B) Managing agency		
No recorded protection	516.9	no recorded protection by either PAD-US 1.4 or 2.0 or by FSA
BLM	200.1	Bureau of Land Management (federal); agency with a multiple-use and sustained yield mandates, historically focused on mineral rights and grazing leases
USFS	105.6	U.S. Forest Service (federal); agency with multiple-use and sustained yield mandates, historically focused on forest reserves and, more recently, grasslands
State	42.6	state-level agencies (includes departments of natural resources, state land boards, fish and wildlife departments, departments of land, parks and recreation departments, departments of conservation, other unknown state agencies)
BIA	28.4	Bureau of Indian Affairs (federal); agency that manages land held in trust for Native American tribes
FSA	23.9	USDA Farm Service Agency (federal); agency provides programs and services to farmers and ranchers; not documented in PAD-US
NPS	17.8	National Park Service (federal); agency preserves natural and cultural resources
FWS	8	U.S. Fish and Wildlife Service (federal); agency conserves and protects fish, wildlife, and plants
Other federal	7.3	miscellaneous federal agencies (includes U.S. Department of Defense, U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, Department of Energy, Agricultural Research Service, and Tennessee Valley Authority)
NGO	5.8	non-governmental organizations; 33% The Nature Conservancy, plus many other land trusts and conservancies
Local government	4.4	county and city governments
Regional district	1.3	regional districts; 67% water districts, but also other regional districts such as school, open space, sanitation, and cemetery
Unknown agencies	1.3	unknown; includes joint management category from PAD-US 2.0
Private entities	1.2	private managers
Tribes	0.1	Native American tribes; fee-ownership only. See BIA for land held in trust for Native American tribes by federal government.
(C) Protection mechanism		
Designated	180.1	permanent legal designation requiring management for natural values, including (in order of area covered): national monuments, resource management areas, wilderness areas, roadless areas, wilderness study areas, areas of critical environmental concern, federal conservation areas, recreation management areas, state conservation areas, wild and scenic rivers, national recreation areas, and several others that collectively cover $<1 \times 10^6$ ha
Easement	9.5	a voluntary, legally binding agreement between landowner and either land trust or government to restrict the rights of a landowner for the sake of conservation objectives
Fee-owned	751.1	landowner manages for natural values
Rental contract	23.9	Conservation Reserve Program rental contracts to rural landowners in exchange for management for natural values as part of temporary agreements (~15 yr)

Notes: Some hectares of land are counted more than once because designations and easements can overlap with fee-ownership. For cluster analysis, a single protected area type is a unique combination of these three attributes. For example, GAP 3 BLM designated is GAP 3 land managed by the Bureau of Land Management and protected by designation. FSA CRP is land not documented in PAD-US 1.4 or 2.0 managed by the USDA Farm Services Agency and protected by CRP rental contracts. See Appendix S1: Table S1 for a listing of each unique protected area type along with the total hectares covered and the percentage of counties with that protected area type.

and provides additional information about the conservation community in an area. Retaining overlapping protection types means that the sum of the area covered by different protected area types in a county can add up to more than the total area of the county in our data set.

We identified 116 protected area types for our analysis, where a protected area type is a unique combination of strictness, managing agency, and protection mechanism (see Appendix S1: Table S1). There are only 116 types because several potential combinations of these aspects do not occur in the data. Several other combinations exist but are so uncommon (present in <0.13% of counties) that they were also excluded and removed from county totals. Similarly rich complexes of land protection activities have been documented elsewhere (Shwartz et al. 2017, Donald et al. 2019). Although some protected areas in our data set could have been "slivers," or artifacts of geoprocessing errors, most are likely to represent real protected areas (Baldwin and Fouch 2018). One benefit of the update from PAD-US 1.4 to 2.0 is a reduction in the number of slivers[10] (https://www.sciencebase.gov/). To control for variations in county area, we focus on the relative abundance of each protected area type. In community ecology, relative abundance is a measure of how common or rare a species (or, in our case, protection type) is relative to other types in a given location (Hubbell 2001).

Socioenvironmental variables.—Socioenvironmental variables were also summarized by county and included average elevation, average soil productivity, state population density in 1900, county population density in 2010, number of IUCN-listed threatened species whose range overlaps with a county, median household income in 2018, and the percentage of the adult population over age 25 with a bachelor's degree (five year average from 2013–2017). Spatial variables included county size, longitude, and latitude. Details about how we put together our data set are in Appendix S1: Table S2. A description of correlations among socioenvironmental predictors can be found in Appendix S1: Fig. S1.

This set of socioenvironmental variables was chosen because we had a priori hypotheses about the relationship between protected area types and socioenvironmental values that we sought to test. We examined the relationship of socioenvironmental variables to both land protection communities and individual protected area types. We developed seven hypotheses, five based on literature and two based on our own intuition.

(1). The higher the elevation the greater the strictness of protection (GAP status) (as was found in Aycrigg et al. 2013).
(2). The higher the soil productivity, the lower the strictness of protection (as was found in Aycrigg et al. 2013); CRP rental contracts will be associated with high soil-productivity because CRP rental contracts target agricultural land. (We say this even though FSA often targets marginally productive land, because counties with marginally productive agricultural land are still likely to have higher average soil productivity than land in non-agricultural counties).
(3). NGO, USFS, and federally managed land is associated with more threatened species per county (as was found in Groves et al. 2000).
(4). The number of threatened species does not predict GAP status (similar to Jenkins et al. 2015).
(5). More non-federal protection is positively predicted by education and, to a lesser extent, household income (as in Fovargue et al. 2019).
(6). State population size in 1900 is a stronger predictor of lack of protection than longitude or current population size (see next hypothesis).
(7). State population in 1900 is a negative predictor of federal protection, especially USFS, FWS, NPS, and BLM. Protection by USFS, FWS, and NPS greatly expanded in the late 19th and early 20th century, likely into land not yet distributed out of the public domain. We do not have data on the amount of land held in the public domain in 1900. However, we use state population density at that time as a negative indicator of the amount of public land in a state. We return to this issue in *Discussion*.

Analysis

Defining communities of land protection.—Our approach examined multiple dimensions of protection to synthesize the richness of 116 distinct land protection types. We adapted techniques community ecologists use to identify distinct assemblages of land protection activity, our "land protection communities" (i.e., clusters). Specifically, we transformed the relative abundances of protected area types, submitted the transformed data to cluster analyses, and used the cluster analysis to categorize each county according to a land protection community.

The relative abundances were transformed using the Hellinger transformation (Rao 1995), which makes double zeroes (i.e., absences in multiple counties) amenable to common linear community analyses such as PCA and RDA (Legendre and Gallagher 2001). Euclidean distances among Hellinger-transformed data were used in our cluster analyses.

We used a fuzzy clustering method to identify land protection communities. Fuzzy c-means clustering (ppclust package in R; Cebeci et al. 2019) is like the more well-known k-means clustering method, but has the additional benefit of providing an estimate of how well a county fits within a given cluster. Instead of being assigned to a single cluster, a county is "spread out" among clusters with membership scores indicating the degree to which a county belongs to each cluster, with the membership scores for a county adding up to one. The closer a county's maximum membership score is to 1, the more centrally located within the cluster is the county. At the other extreme, if a county's cluster membership is perfectly fuzzy, it will have equal membership scores for all clusters. In developing our typology of land

[10] https://www.sciencebase.gov/catalog/item/5b043619e4b0da30c1c367e3

protection communities, we needed to decide how many communities to describe. We considered multiple possible partitions (or numbers of land protection community types) and cluster performance metrics (partition entropy [Bezdek 1981], average silhouette width [Rousseeuw 1987], modified partition coefficient [Dave 1996], Dunn index [Halkidi et al. 2001], fuzzy silhouette index [Campello and Hruschka 2006]). For reasons described in the results, we focus many of our analyses on a classification of five distinct land protection communities (i.e., clusters). We compare this five land protection community classification with more finely and coarsely resolved classifications. More details about our clustering approach are reported in the Appendix, including a discussion of other clustering methods we considered, a summary of cluster validity metrics, and outcomes from more finely and coarsely resolved partitions (see Appendix S1: Figs. S3–S7).

Characterizing land protection communities.—We conducted four permutation tests to determine the expected relative abundances of protection types in each county. For all permutation tests, cluster membership was described by a county (n = 3,108) by cluster (n = 5) matrix with cluster membership scores identifying the extent to which each county belonged to each cluster. The four permutation tests compared cluster membership to a matrix with values indicating the relative abundance under different forms of protection but differed in how protection was described. Protection was described by (1) a county by strictness (n = 5) matrix, (2) a county by protection mechanism (n = 5) matrix, (3) a county by managing agency (n = 15) matrix, and (4) a county by protected area type (defined by combined strictness, agency, and mechanism; n = 116) matrix. For each test, we calculated the cluster centroid (a weighted average) of coverage of each form of protection within each cluster by weighting protection coverage by cluster membership score. In other words, counties that are more core to a cluster have a greater influence on the estimated cluster centroid. With the permutation test, we randomly reordered the counties and their protection coverage while holding the cluster membership score matrix constant. We then recalculated the centroid for each cluster. We repeated this procedure 10,000 times for each test and used the distribution of randomly generated centroids to evaluate whether observed centroids were different than expected by chance. We checked the robustness of our clustering methods by comparing results with those of a principal components analysis (Appendix S1: Fig. S8).

Socioenvironmental characteristics of protection communities and protection types.—We tested our hypotheses concerning the relationships between socioenvironmental characteristics and land protection in two ways: (1) by using a permutation test to identify which socioenvironmental characteristics were associated with different land protection communities and (2) by using multivariate regression to measure the relationship between socioenvironmental characteristics and different individual land protection types.

We used a permutation test similar to those described above to describe how socioenvironmental values varied across clusters, except that instead of calculating centroids using a county (n = 3,108) by land protection (n = 116) matrix we used a county (n = 3,108) by socioenvironmental matrix (n = 10).

To test our hypotheses about associations between protected area types and socioenvironmental variables, we conducted three separate multivariate regressions for which the response matrix consisted of the relative abundance of land protected by (1) GAP statuses (n = 5), (2) mechanisms (n = 5), and (3) agencies (n = 15). Elevation, both population density metrics, % of adults with a bachelor’s degree, median household income, county area, and latitude were $\log_{10}(n + 1)$ transformed to better meet the assumptions of linear regression. We used the magnitude and direction of the standardized partial regression coefficients to compare the relative importance of socioenvironmental variables (Smith et al. 2009). These coefficients indicate by how many standard deviations coverage of a county by a particular land protection type would increase for each standard deviation increase in a particular socioenvironmental variable.

For each model, the predictor was a matrix of seven socioenvironmental variables, three spatial descriptors (latitude, longitude, and county area), and one variable describing spatial autocorrelation. Unlike the cluster analysis, which was purely descriptive, the socioenvironmental analysis relies on tests whose inferential power depends on the number of independent samples. To account for likely non-independence among nearby counties, a different autocorrelation variable was calculated for each model by creating a Moran’s Eigenvector Map (Dray et al. 2006) from the residuals of the corresponding non-spatial-autocorrelation model using the adespatial package in R (Dray et al. 2019). By accounting for spatial autocorrelation, the effects of proximity (Tobler 1970) are less likely to be confused with the effects of socioenvironmental variables. An assumption of tests for spatial autocorrelation is a lack of systematic spatial trend (such as with latitude or longitude; Dray et al. 2012), which is why those spatial characteristics were accounted for before estimating spatial autocorrelation. We took county area into account because it is another spatial characteristic that can be confounded with socioenvironmental traits.

Results

Univariate distributions of protection types

Individual protected area types vary widely in the area they cover and in how they are distributed across the United States (Appendix S1: Table S1). The protected area type covering the largest area is GAP 3 Bureau of

Land Management (BLM) designations, which covers over 113 million of the 808 million hectares in the coterminous United States. But its distribution is highly skewed; only 13% of counties contain this protection type, mostly in the intermountain west. The next four protected area types covering the most area are, in order, GAP 3 BLM fee-owned (70 million hectares), GAP 3 United State Forest Service (USFS) fee-owned (66 million hectares), GAP 4 Bureau of Indian Affairs (BIA) fee-owned (28 million hectares), and Conservation Reserve Program (CRP) rental contracts (24 million hectares). The most extensive protected area type is CRP rental contracts; 81% of counties have some CRP rental contract land. The next four most extensive protected area types are, in order, GAP 2 state fee-owned (65% of counties), GAP 3 state fee-owned (53%), GAP 2 other federal easement (52%), and GAP 4 state fee-owned (51%). All 3,108 counties have areas with no recorded protection (median proportion of a county = 89%, IQR = 77%–95%). See Table 1 and Appendix S1: Table S1 for a reminder of protected area type abbreviations.

Defining communities of protection

A classification into five major land protection communities describes U.S. counties well. Before arriving at a five-community classification, we considered both finer and coarser classifications. For example, cluster validity metrics consistently supported a two-cluster classification that divided heavily protected counties, mostly including counties to the west of and including the Rocky Mountains, from less protected counties, including most of the Great Plains and eastward (Fig. 1A, Appendix S1: Figs. S2–S4). Depending on the metric, secondary peaks in cluster validity are found with classifications of four, eight, and nine clusters (Fig. 1B, Appendix S1: Fig. S2). With up to five clusters in a classification, all clusters contain core counties, defined here as counties with membership scores greater than 0.5. However, when land protection communities are more finely resolved, two or more clusters display similar membership score profiles and the maximum membership scores of counties decrease (Fig. 1C, Appendix S1: Fig. S5). In subsequent analyses, we focus on the five-cluster classification, the classification giving the largest number of clusters that have unique membership score profiles; more details of finer and coarser classifications are given in Appendix S1: Figs. S5–S7.

We named each land protection community (cluster) after the dominant protected area type(s) and socioenvironmental characteristics in that community, giving us the multi-use open space, public forest, agricultural heartland, low formal protection, and diversified lowlands clusters. Fig. 1D maps counties according to land protection community with which they have the strongest membership. Some counties are very clearly identified with a particular land protection community while the membership of others is more evenly distributed among communities (i.e., their maximum membership score is low, Fig. 1C, Appendix S1: Figs. S5, S6). When we resolve land protection community types beyond our five-way classification, membership of the multi-use open space, agricultural heartland, and low formal protection land protection communities remains stable. However, the diversified lowlands land protection community becomes fuzzier, and there is some crossover of counties from the diversified lowlands cluster to the public forest cluster (Appendix S1: Fig. S7).

Our five land protection community types group together in principal components analysis. Consistent with the concept of fuzzy clusters, the boundaries of different communities do not have discrete spaces between them (Appendix S1: Fig. S8).

Characterizing land protection communities

The five land protection communities are characterized by differences in the strictness of land protection measures, mechanisms used to achieve this protection, and managing agencies. We used four permutation tests to estimate the expected relative abundance of protection types in a county. The typical county in the multi-use open space cluster has greater overall protection than those in any other cluster, much of it provided by BLM (Bureau of Land Management) and managed for multiple uses (GAP 3) using designations and fee-ownership. Here we report the amount relative to the median expected relative abundance with $P < 0.0001$ unless otherwise noted. The multi-use open space cluster has more than the median expected abundance of protection by BLM (15.1×), designation (9.0×), GAP 3 status (7.1×; managed for multiple uses), BIA (4.9×; Bureau of Indian Affairs), fee-ownership (3.5×), USFS (3.5×; U.S. Forest Service), GAP 1 (3.1×; strict protection for biodiversity), GAP 4 (2.2×; protection with no biodiversity objectives), NPS (2.8×; $P < 0.05$; National Park Service), and GAP 2 (1.6×; $P < 0.05$; strict protection but disturbances suppressed; Fig. 2). The top five protection types with the most unexpectedly high relative abundances per county within the multi-use open space cluster are GAP 3 BLM designated, GAP 3 BLM fee-owned, GAP 2 BLM designated, GAP 1 BLM designated, and GAP 3 USFS designated (Fig. 3).

The typical county in the Public Forest land protection community has over twice as much land with no formal protection as the multi-use open space community. Even so, over 50% its area is protected. While most of its protection is also provided by federal actors, mostly USFS (U.S. Forest Service), the Public Forest cluster has significant protection from smaller actors and relies more on easements, similar to the diversified lowlands community discussed below. Specifically, it has significantly more than the median expected amount protected by USFS (7.1×), GAP 1 (5.4×), GAP 3 (4.0×), designation (3.5×), NPS (3.5×), fee-ownership

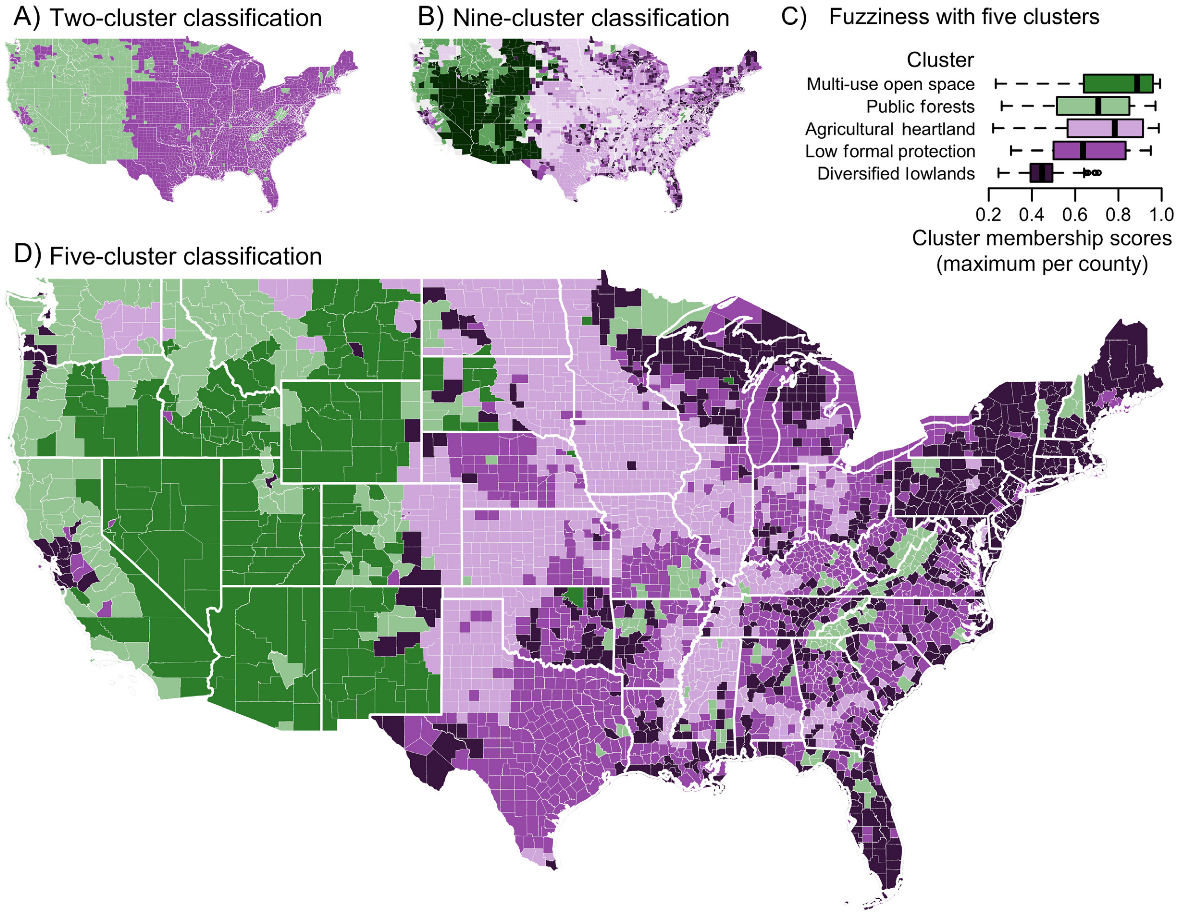

FIG. 1. Land protection communities (clusters) by county under different cluster classifications. States are outlined in heavy white. (A) Land protection communities with two clusters. Counties are colored according to the cluster with which they have the highest membership score. (B) Land protection communities with nine clusters. Counties are colored according to the cluster with which they have the highest membership score. (C) Fuzziness with five clusters. Each county had five membership scores, one for each cluster. We take the highest of the five membership scores for each county and plot them here according to the associated cluster. Box edges show the interquartile range (IQR); center heavy line is the median; whiskers are 95% confidence intervals (1.58 × IQR); dots are values more extreme than 95% CI. (D) Land protection communities with five clusters. Counties are colored according to the cluster with which they have the highest membership score.

(3.1×), BIA (2.6×), GAP 4 (1.7×), GAP 2 (1.6×), NGO (1.6×; non-government organizations), state (1.6×), unknown agency (2.6×; $P < 0.05$), and easement (1.3×; $P < 0.05$; Fig. 2). The five protection types with the most extreme relative abundances within the Public Forest cluster are GAP 3 USFS fee-owned, GAP 1 USFS designated, GAP 3 USFS designated, GAP 2 USFS designated, and GAP 1 NPS designated lands (Fig. 3).

Like other land protection communities that are predominantly east of the Rocky Mountains, the agricultural heartland cluster has more land with no recorded protection than expected by chance (1.1× the median expected amount; Fig. 2). Even so, the typical county in the agricultural heartland cluster has 2.5× the median expected amount of CRP rental contract land. Although when all easement lands are combined there is not an exceptional amount of them (Fig. 2), easement-protected lands make up four of the five individual protection types with the most unexpectedly high relative abundance: CRP rental contracts, GAP 2 state easements, GAP 2 other federal easements, no recorded protection, GAP 3 FWS fee-owned (Fig. 3).

The single most notable attribute of the typical county in the low formal protection land protection community is the amount of land with no recorded protection (1.2× the median expected amount; Fig. 2). No recorded protection is the only individual protection type in this cluster with a high relative abundance at $p < 0.05$ significance (Fig. 3).

The typical county in the diversified lowlands land protection community has more protection than those from the other two east-of-the-Rockies clusters, with protection coverage managed by a variety of agencies, mostly nonfederal (Fig. 2). Significantly more

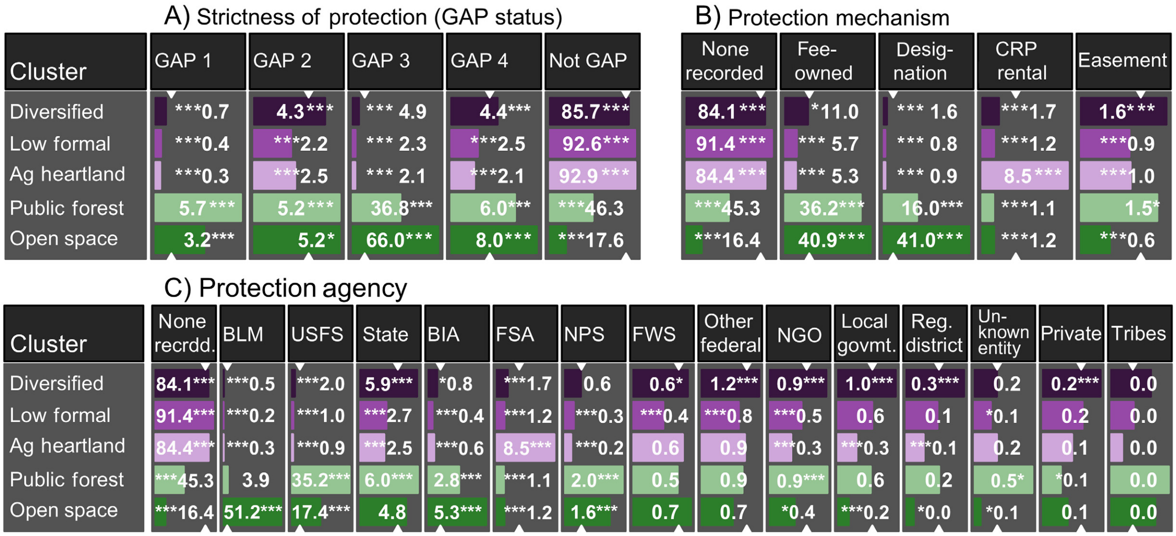

Fig. 2. Percentage land area of the typical county in a cluster protected by different (A) strictness levels, (B) protection mechanisms, and (C) managing agencies, given a partition of five clusters. "Not GAP" includes CRP rental payments (because they are not included in GAP classification by PAD-US), but "no recorded protection" does not. Bars and values indicate the weighted average relative abundance of protection in a cluster. Notches at the tops and bottoms of plots indicate the median expected value based on 10,000 random permutations. Abbreviations "govmt.", government; reg., regional. Asterisks indicate how much more or less extreme than expected the observed centroid is, with symbols on the left indicating that the value is lower than expected and those on the right indicate the value is greater than expected: * $P < 0.05$, *** $P < 0.0001$.

protection than expected is provided by local government (1.7× relative to median random cluster), regional district (1.7×), state (1.5×), NGO (1.5×), private entities (1.5×), easement (1.4×), GAP 2 (1.3×), other federal (1.3×), GAP 4 (1.2×), no recorded protection (1.1×), and FWS (1.2×; $P < 0.05$; U.S. Fish and Wildlife Service). The five individual protection types with the most unexpectedly high relative abundance in the diversified lowlands cluster are GAP 2 state fee-owned, GAP 3 NGO fee-owned, GAP 3 local government fee-owned, GAP 3 state fee-owned, and GAP 4 local easement (Fig. 3).

Socioenvironmental characteristics of protection communities

Permutation analysis relating cluster membership scores to socioenvironmental characteristics of clusters shows that land protection communities are not randomly distributed across the socioenvironmental spectrum but are instead associated with distinct socioenvironmental profiles (Fig. 4). Multi-use open space is the most extreme cluster, with 7 of 10 centroid values for socioenvironmental variables falling completely outside of their expected range (from most to least extreme: low historic state population size, low current county population size, large county size, high elevation, low numbers of threatened species, western longitude, northerly latitude, and low soil productivity). Though less extreme than multi-use open space, the public forest cluster is also characterized by high elevation, low historic population size, low current population size, large county size, western longitude, low soil productivity, and northerly latitude. In contrast to multi-use open space, its education levels are higher than expected. Low current population size is the most extreme feature of the agricultural heartland, followed by small county area, high soil productivity, low elevation, large numbers of threatened species, low education levels, western longitude, and northern latitude. The Low formal protection community's most extreme attribute is low elevation followed by small county area, high current population density, low soil productivity, eastern longitude, large numbers of threatened species, southern latitude, and high historic population size. Most similar to the low formal protection cluster, the diversified lowlands cluster is also characterized by low elevation, high historic population size, small county area, high current population size, eastern longitude, large numbers of threatened species, and southern latitude. Unlike the low formal protection cluster, it is extreme in terms of high education levels and high household income.

The results of a multivariate model relating the matrix of individual protected area types to socioenvironmental characteristics add nuance to, and in some cases refutes, our hypotheses (Fig. 5). While discussing our hypotheses here, we use the words "very strong," "strong," "moderate," and "weak" to describe standardized regression coefficients with absolute values of greater than 0.3, between 0.2 and 0.3, between 0.1 and 0.2, and less than 0.1, respectively.

(A) Multi-use open space

Cluster	GAP 3 BLM designated	GAP 3 BLM fee-owned	GAP 2 BLM designated	GAP 1 BLM designated	GAP 3 USFS designated
Diversified	***0.29	***0.14	***0.03	***0.01	***0.18
Low formal	***0.14	***0.07	***0.01	***0.00	***0.08
Ag heartland	***0.20	***0.09	***0.02	***0.00	***0.09
Public forest	2.13	1.44	0.30	0.06	6.07***
Open space	30.24***	17.43***	3.05***	0.48***	4.26***

(B) Public forest

Cluster	GAP 3 USFS fee-owned	GAP 1 USFS designated	GAP 3 USFS designated	GAP 2 USFS designated	GAP 1 NPS designated
Diversified	***1.17	***0.10	***0.18	***0.06	0.08
Low formal	***0.62	***0.05	***0.08	***0.03	***0.04
Ag heartland	***0.50	***0.05	***0.09	***0.03	***0.04
Public forest	24.23***	3.71***	6.07***	0.73***	0.68***
Open space	11.15***	1.59***	4.26***	0.26*	0.43*

(C) Agricultural heartland

Cluster	CRP rental	GAP 2 state easement	GAP 2 federal easement	No recorded protection	GAP 3 FWS fee-owned
Diversified	***1.66	0.01	0.20	84.05***	0.01
Low formal	***1.17	***0.01	***0.14	91.40***	0.01
Ag heartland	8.47***	0.04***	0.33***	84.44***	0.03*
Public forest	***1.09	0.01	***0.06	***45.26	0.00
Open space	***1.18	0.01	***0.04	***16.40	0.00

(D) Low formal protection

Cluster	No recorded protection
Diversified	84.05***
Low formal	91.40***
Ag heartland	84.44***
Public forest	***45.26
Open space	***16.40

(E) Diversified Lowlands

Cluster	GAP 2 state fee-owned	GAP 3 NGO fee-owned	GAP 3 local fee-owned	GAP 3 state fee-owned	GAP 4 local easement
Diversified	2.13***	0.03***	0.37***	2.13***	0.15***
Low formal	***1.00	0.01	0.19	***0.85	0.07
Ag heartland	***0.90	***0.01	***0.10	***0.85	***0.04
Public forest	1.28	0.02	0.14	2.22***	0.08
Open space	***0.44	0.01	0.04	2.45***	***0.01

FIG. 3. The five protected area types with the most extremely high relative abundances (%) in the (A) multi-use open space cluster, (B) public forest cluster, (C) agricultural heartland cluster, (D) low formal protection cluster, and (E) diversified lowlands cluster. The low formal protection cluster only had four protected area types with extremely high relative abundances ($P < 0.05$). These are based on the same data as Fig. 2, but instead of aggregating information along three separate axes (strictness, agency, and mechanism of protection), individual protected area types are retained. See Appendix S1: Table S1 for explanation and description of each protected area type. Bars and values indicate the weighted average relative abundance in a cluster. Notches at the tops and bottoms of plots indicate the median expected value based on 10,000 random permutations. Asterisks indicate how much more or less extreme than expected the real centroid is, with symbols on the left indicating that the value is lower than expected and those on the right indicate the value is greater than expected: * $P < 0.05$, *** $P < 0.0001$.

(1). Low elevation is a very strong predictor of no recorded protection, but even more strongly predicts FWS protection. It is also a moderate predictor of GAP 2 protection (a strict protection). High-elevation counties are very strongly associated with USFS and designated protection.

(2). Soil productivity is very strongly associated with no recorded protection, and yet the strongest association with soil productivity is the abundance of CRP rental contract land. Protection by fee-ownership and USFS are very strongly negatively correlated with soil productivity.

(3). Regional districts are the only agency group strongly positively associated with threatened species, and that association is very strong.

(4). The number of threatened species in a county is associated with more and stricter protection. In fact, the best predictor of the strictest protection (GAP 1) is the number of threatened species, followed by high elevation.

(5). Except for a strong positive relationship between education and easements, education and income are only moderate or weak predictors of protection.

(6). Along with low elevation and high soil productivity, state population size in 1900 is a strong predictor of no recorded protection, much stronger than longitude or current population size. Eastern longitude is a very strong predictor of easement and state protection, while western longitude is a very strong predictor of USFS protection.

(7). BLM and FWS are the only federal agencies that have the expected very strong (BLM) or strong (FWS) negative association with historic population size. Bureau of Indian Affairs and regional district land are also very strongly negatively associated with historic population size.

Discussion

Land protection comprises a complex mosaic of conservation organizations pursuing different goals and using different land protection mechanisms. However, research into protected areas often simplifies this richness down to a single dimension (protected or not) (Scott et al. 2001, Rodrigues et al. 2004, Chape et al. 2005, Goettsch et al. 2019). An important step in

Cluster	Elevation (m)	Soil productivity score	Population density in 1900 (per ha)	Current population density (per ha)	No. threatened species	Adults with Bachelor's degree (%)	Household income (thousands of US$)	County area (x 10^4 ha)	Longitude (°W)	Latitude (°N)
Diversified	***294	***7.8	0.20***	1.49***	14.2***	22.1***	52.0***	***20.8	87.3***	***38.0
Low formal	***274	***8.2	0.16*	1.43***	13.9***	21.0	50.9	***18.3	88.4***	***36.9
Ag heartland	***384	11.0***	0.14	***0.48	***12.2	***19.8	*50.2	***19.7	***92.8	39.2***
Public forest	970***	***8.0	***0.08	***0.40	13.4	23.7***	51.1	41.3***	***100.6	40.0***
Open space	1589***	*8.4	***0.02	***0.11	***9.6	21.7	51.6	102.2***	***110.8	40.6***

FIG. 4. Average socioenvironmental conditions in each cluster. Bars and written numbers indicate the weighted average of the socioenvironmental variable in a cluster. Notches at the tops and bottoms of plots indicate the median expected value based on 10,000 random permutations. Asterisks indicate how much more or less extreme than expected the real centroid is, with symbols on the left indicating that the value is lower than expected and those on the right indicate the value is greater than expected: * $P < 0.05$, *** $P < 0.0001$.

bridging gaps between conservation science and practice involves paying greater attention to the role of institutions in conservation and how overlaps and differences among institutions enable or inhibit effective management (Keppel et al. 2012, Guerrero et al. 2014, Meretsky and Fischman 2014). Here, we focused on institutions active in land protection. We sought to map these in ways that could inform conservation programs and priority setting over large spatial scales. To do so, we adapted techniques usually used to study ecological communities, and applied them to delineate, map and begin to describe communities of land protection in the coterminous United States.

Our approach of describing land protection communities as if they were ecological communities provided a way to synthesize rich, high dimensional data on land protection. Previous studies document geographic patterns in land protection but ignore covariation among protection types (Groves et al. 2000, Merenlender et al. 2004, Chape et al. 2005, Aycrigg et al. 2013, Jenkins et al. 2015, Villamagna et al. 2017). Our method focuses on that covariation, making clear that land protection types are not randomly distributed with respect to each other. Instead, there are identifiable communities of land protection in which unique combinations of managing agencies, mechanisms, and strictness of protection are likely to co-occur. Moreover, the resulting set of land protection communities could not have been predicted without performing cluster analysis, nor could the maps have been produced based on knowledge of a single protection type. In addition, the land protection communities we find are associated with underlying socioenvironmental variables, suggesting some common enabling factors may be at work. Taken together, these aspects of our results make us confident that our approach is providing a meaningful dimension reduction of land protection data while retaining more of the richness of land protection communities than past approaches have allowed. Importantly, while we chose to work on the coterminous United States, everything we did could readily be replicated in other locations and over different scales. Replication of our method is made easier because we used methods well-known to conservation biologists and because our output can be readily mapped. In addition, results can be overlain with data on biodiversity and other features routinely considered in planning and evaluating conservation programs.

Differences among land protection communities go beyond differences in the amount of overall protection, and extend into how strict that protection is, how it is accomplished, and who is responsible for managing protected sites. In our U.S. application, for example, the multi-use open space and public forest clusters are similar at first glance. They both have more than 50% of their area under protection with plenty of protection by large federal agencies. Even so, these clusters differ from each other in protection amount, mechanisms and agencies. Multi-use open space has over 1.5× more protected land, in general, and 2.5× more designated land, in particular. It has 13× the amount of Bureau of Land Management (BLM) managed land. The public forest cluster, however, is more diverse, with more than double the relative abundance of land under easement and land managed by unknown entities, regional districts, local governments, non-government organizations (NGOs), and U.S. Forest Service (USFS). The greater relative contribution of smaller actors in the Public Forest cluster could be due in part to differences in current and historic population size and the amount of land in the public domain. With one-quarter the population density in 1900, the multi-use open space cluster likely had more land in the public domain that was available for easy protection by the federal government at crucial times when land protection was a priority. With 4× the current population density, the public forest cluster has more people to support small actors, such as municipalities, water districts, and NGOs.

These land protection communities show intriguing associations with socioenvironmental variables, shedding light on what landscape features they can protect, how they complement one another and, perhaps, how they came to be found in the locations where they are found

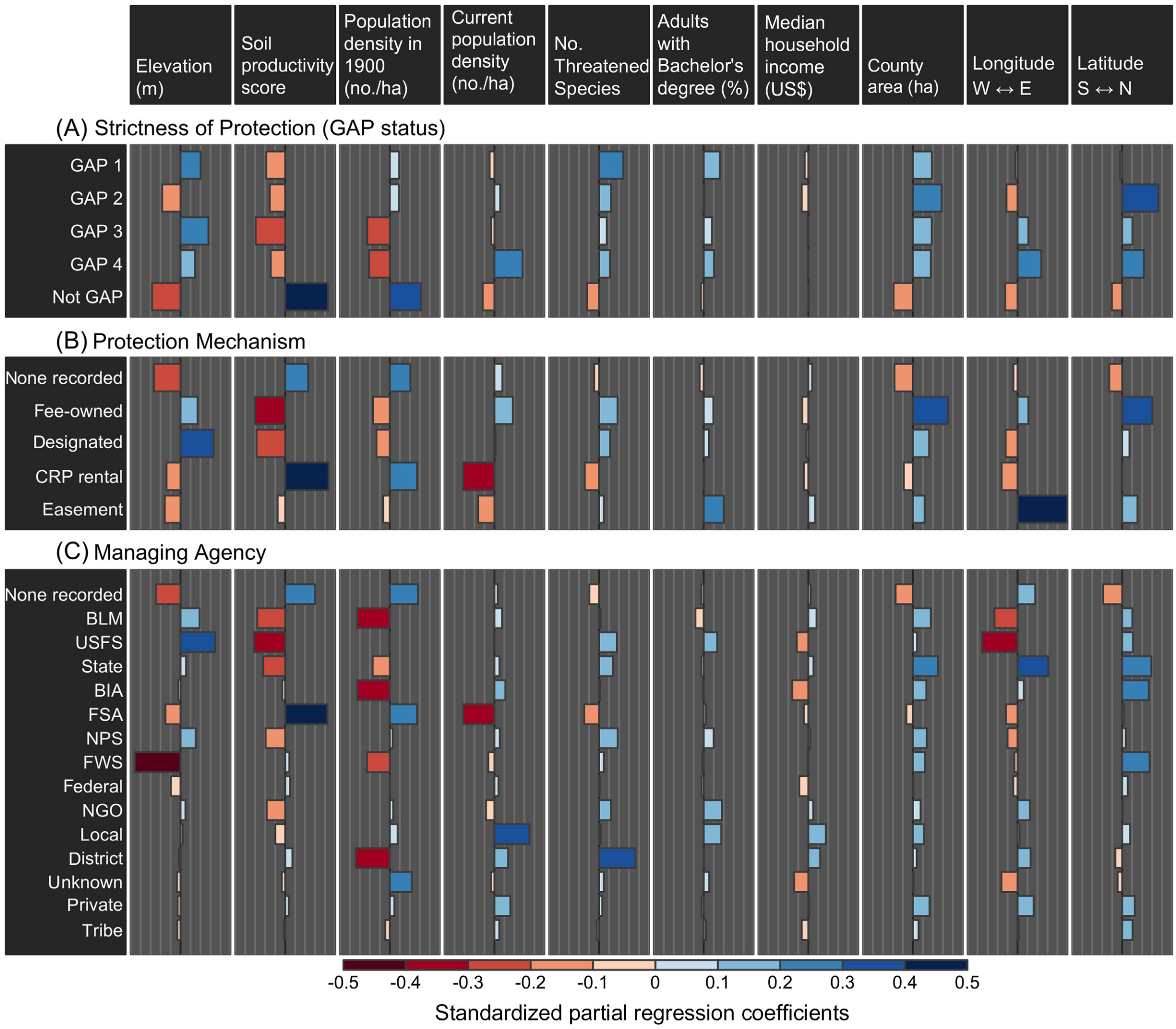

FIG. 5. Standardized partial regression coefficients from three multivariate linear models in which socioenvironmental variables predict the relative abundance of (A) strictnesses of protection, (B) protection mechanisms, and (C) managing agencies. Socioenvironmental variables averaged over a county include average elevation, average soil productivity score, statewide population density in 1900, county population size in 2010, number of IUCN red-listed species in a county, percentage of adult population over age 25 with a bachelor's degree or higher, county median household income, area of county, longitude of county centroid, and latitude of county centroid (decimal degrees). The t tests for all standardized regression coefficients with absolute value greater than 0.12 have P values of less than 0.0001.

today. For example, in terms of broad habitat characteristics, "rocks and ice" are indeed better protected than areas of high soil productivity and low elevation as previously reported for the United States (Scott et al. 2001, Aycrigg et al. 2013) and elsewhere (Joppa and Pfaff 2009). However, two attributes of protection are more abundant in low-elevation areas: GAP 2 (a strict protection) and Fish and Wildlife Service (FWS) management. Multiple factors are likely at play here, but one reason the FWS may be overrepresented in low--elevation areas is because the Emergency Wetlands Resources Act gives FWS responsibility for restoration of wetlands. As a result, wetlands comprise 25% of the Refuge System (U.S. Fish and Wildlife Service 2013). Meanwhile, CRP rental contracts to landowners (mostly farmers) are strongly associated with counties having high soil productivity (and, consequently, high agricultural coverage). Because CRP rental contracts are temporary, they have been ignored in most descriptions of overall land protection. Yet they protect more land in the lower 48 states than either the National Park Service or the Fish and Wildlife Service (Table 1), much of it in the most fertile counties in the country. In terms of threatened or vulnerable species, past studies have found significant gaps in protected area coverage in the United States (Jenkins et al. 2015) and elsewhere (Rodrigues et al. 2004). Instead of asking how many threatened species are unprotected, we asked what type of protection is associated with the number of threatened species in a county. We found that all else being equal, counties with more threatened species have more protection and especially more of the strictest protection (see also Coetzee et al. 2014). Moreover, regional districts disproportionately manage land in counties with large numbers of threatened species, perhaps because most regional districts manage watersheds, and freshwater species are the most likely taxa to be endangered in the United States (Wilcove and Master 2005). This association highlights regional districts as an important potential conservation partner in the growing area of collaborative watershed management (Imperial 2005) and emphasizes the common interests of biodiversity and municipalities in need of clean water (Goldman-Benner et al. 2012). We note however that our understanding of where threatened species are found is incomplete and subject to sampling bias based on accessibility (Dennis and Thomas 2000, Reddy and Dávalos 2003). Our analysis suggests that the location of land protection communities is related to population density in 1900. As conservation became a growing national priority starting in the early 1900s, it was land with low population density (likely held in the public domain and likely in western areas) that was most easily protected by government agencies. This likely explains the strong negative relationship between historic population size and lands protected by BLM, Bureau of Indian Affairs, FWS, states, and districts. We expect that the amount of land in the public domain in 1900 would be a more direct predictor of government protection than historic population size, but we do not have those data. Indeed, the current proportion of a county fee-owned by government agencies is a stronger predictor of cluster membership than any of our other socioenvironmental measures (analysis not shown), but using this measure as a predictor would introduce spurious correlations by including parts of the response variables as a predictor (Brett 2004). As such, a worthwhile priority for future work would be to repeat these analyses using better indicators of early public land allocation that do not overlap the period of protection under consideration. U.S. census count numbers in 1900 were a stronger predictor of low overall protection than current population size or longitude, emphasizing the legacy of social conditions at the time many protection decisions were made decades ago.

There are several caveats to our interpretation of land protection communities in the United States. First, the PAD-US data set is incomplete, especially for local and NGO agencies and easements, but also for some state agencies. Fortunately, much of the variation among clusters is driven by federally managed land (Appendix S1: Fig. S8), for which the data are most complete. It is possible that some of the fuzzy cluster membership shared among clusters, especially the diversified lowlands and public forests clusters (Fig. S5) where easements are more abundant (Fig. 2), could be resolved with more complete easement data. We emphasize that these data are dynamic, and periodic reassessments of protection communities are likely needed as better data become available. This paper establishes the methodology and documents the relevance for doing so. Second, this description of the community of protection is a geographical map of protection that names only those agencies that are directly managing land. The many agencies that advocate for, educate about, facilitate, and monitor land protection are not considered here, but are considered, albeit at smaller spatial scales by other initiatives (e.g., the USFS STEW-MAP project [U.S. Forest Service 2020], the Atlas of Collaborative Conservation in Colorado [*available online*]).[11] Another approach that accounts for conservation activities beyond protected areas is to map the approximate locations of conservation initiatives or plans (Álvarez-Romero et al. 2018, Malhado et al. 2020). Complementary information is also provided by growing literature analyzing social networks among conservation actors (e.g., Ernstson et al. 2010, Ruseva et al. 2016, Yamaki 2016, Guerrero et al. 2020). Third, by aggregating 3,108 counties into just five major clusters, clustering necessarily obscures variation among those counties. As our fuzzy clustering approach makes clear, counties vary in how tightly they adhere to characteristics of the land protection community to which they were matched. Of the five land protection communities we described, the diversified lowlands cluster is the only one that had no strong "core" counties (counties with membership scores close to 1, Fig. 1C). The fuzziness of the diversified lowlands cluster is likely due to the fact that protection seems to be defined not by the dominance of a few, distinct federal land managers, but by a diversity of non-federal land managers. The lack of strong federal protection is likely due to the fact that relatively little land in these counties was held in the public domain (as measured by historic population size in 1900) when the federal government became interested in land protection in the 1900s.

As with any descriptive conservation science study, an obvious question is how might someone use a classification and geographic map of land protection communities? While we believe quantitative methods for describing and mapping conservation institutions like this have many applications, we choose to exemplify potential uses by revisiting the three applications mentioned in the Introduction. We first suggested that an ability to identify and map land protection community types would allow national-scale policymakers to tailor policies and programs to particular regional conservation contexts. Land management programs are increasingly moving towards collaborative models for managing large landscapes (Meretsky and Fischman 2014, Meyer et al. 2014, Bodin 2017). Several formal initiatives are built around the concept of collaborative conservation (Sentinel Landscapes Partnership in the

[11] https://collaborativeconservation.org/program/discover/atlas-of-collaborative-conservation/

United States [Sentinel Landscapes Partnership *n.d.*]; Joint Chiefs' Landscape Restoration Partnership in the United States [U.S. Department of Agriculture Natural Resources Conservation Service 2021]; Migratory Bird joint ventures in the United States [U.S. Fish and Wildlife Service 2021]; Large-Scale Conservation Initiatives in the UK [Large-Scale Conservation Initiatives *n.d.*]; African Forest Landscape Restoration Initiative [African Union Development Agency 2021]). By coordinating their activities with one another and with state and local conservation actors these agencies hope to leverage their investments and scale up conservation efforts. The ability to overlay maps summarizing communities of land protection with an agency's management priorities could help inform a federal agency looking to add an additional landscape to an existing collaborative management program or to build new partnerships in a landscape where they already work.

The second illustrative application we suggested concerned local conservation organizations, such as local land trusts. In the United States, these organizations share resources and materials to help one another replicate land protection models that have proven successful elsewhere (e.g., Yonavjak and Gartner 2011, Land Trust Alliance 2021). Often, resulting communities of practice will form around convenient geographies (e.g., Southeastern Land Trusts, Diablo Trust in Arizona). However, by identifying and mapping land protection communities we can start to identify situations where the conservation context facing land trusts in some locations has more in common with quite distant parts of the country than it does with surrounding areas. For example, the land protection communities of several counties in southern Mississippi have more in common with counties typical of the public forest cluster than with the surrounding counties, probably due to the high coverage of fee-owned land under GAP 3 protection by U.S. Forest Service in southern Mississippi.

The final user group we identified for a classification of land protection communities were conservation scientists researching other topics. Understanding differences in land protection communities can help contextualize results of local scale studies and may suggest how broadly they could be expected to generalize. Our classification can also suggest where, and over what scales, to look if seeking to examine particular phenomena. For example, our focus on how land protection mechanisms covary is immediately relevant to researchers seeking to understand how conservation interventions interact with one another (Lawley and Yang 2015, Lang et al. 2018, Graves et al. 2019). Obviously, our mapping identifies in which counties particular protection types do and do not co-occur. But it also suggests where to look for evidence of interactions across protection types over larger scales as well. For example, counties in the diversified lowlands cluster often surround pockets of counties in the public forest cluster. This pattern lends itself to a number of hypotheses. Ecologically, it may suggest that land protection efforts of private, non-profit, local, and/or state agencies, which are especially abundant in the diversified lowlands cluster, may buffer or aid connectivity to larger tracts of land being protected by federal actors in the public forest cluster. From an economic perspective, it may suggest that investments by federal actors in the public forest cluster are "crowding-in" (or attracting) investments in land protection from those local or state actors (e.g., Parker and Thurman 2011).

Together these are just three examples chosen from among myriad possibilities to highlight the diversity of ways our method for mapping land protection communities could be used by different audiences. Just as viewing species without reference to their ecological community leaves out important insights into ecological dynamics, so too does viewing individual land protection activities without reference to the wider communities of land protection within which these activities take place.

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Literature Cited

African Union Development Agency. 2021. AFR100: the African Forest Landscape Restoration Initiative. African Union Development Agency–NEPAD, Midrand, South Africa. https://afr100.org/

Albers, H. J., A. W. Ando, and M. Batz. 2008. Patterns of multi-agent land conservation: Crowding in/out, agglomeration, and policy. Resource and Energy Economics 30:492–508.

Álvarez-Romero, J. G., et al. 2018. Research advances and gaps in marine planning: Towards a global database in systematic conservation planning. Biological Conservation 227:369–382.

Arias, A. 2015. Understanding and managing compliance in the nature conservation context. Journal of Environmental Management 153:134–143.

Armitage, D., R. de Loë, and R. Plummer. 2012. Environmental governance and its implications for conservation practice. Conservation Letters 5:245–255.

Aycrigg, J. L., A. Davidson, L. K. Svancara, K. J. Gergely, A. McKerrow, and J. M. Scott. 2013. Representation of ecological systems within the protected areas network of the continental United States. PLoS ONE 8:e54689.

Baldwin, R. F., and N. T. Fouch. 2018. Understanding the biodiversity contributions of small protected areas presents many challenges. Land 7. http://dx.doi.org/10.3390/land7040123

Baldwin, R. F., and P. B. Leonard. 2015. Interacting social and environmental predictors for the spatial distribution of conservation lands. PLoS ONE 10:e0140540.

Batáry, P., L. V. Dicks, D. Kleijn, and W. J. Sutherland. 2015. The role of agri-environment schemes in conservation and environmental management. Conservation Biology 29:1006–1016.

Bezdek, J. C. 1981. Pattern recognition with fuzzy objective function algorithms. Springer US, New York, New York, USA.

Bodin, Ö. 2017. Collaborative environmental governance: Achieving collective action in social-ecological systems. Science. 357:eaan1114.

Brett, M. T. 2004. When is a correlation between non-independent variables "spurious"? Oikos 105:647–656.

Campello, R. J. G. B., and E. R. Hruschka. 2006. A fuzzy extension of the silhouette width criterion for cluster analysis. Fuzzy Sets and Systems 157:2858–2875.

Cebeci, Z., F. Yildiz, A. T. Kavlak, C. Cebeci, and H. Onder. 2019. Probabilistic and possibilistic cluster analysis. R package version 0.1.3. https://CRAN.R-project.org/package=ppclust

Chape, S., J. Harrison, M. Spalding, and I. Lysenko. 2005. Measuring the extent and effectiveness of protected areas as an indicator for meeting global biodiversity targets. Philosophical Transactions of the Royal Society B 360:1–14.

Claassen, R., A. Cattaneo, and R. Johansson. 2008. Cost-effective design of agri-environmental payment programs: US experience in theory and practice. Ecological Economics 65:737–752.

Coetzee, B. W. T., K. J. Gaston, and S. L. Chown. 2014. Local scale comparisons of biodiversity as a test for global protected area ecological performance: A meta-analysis. PLoS ONE 9:e105824.

Comay, L. B., R. E. Drafton, C. H. Vincent, and K. Hoover. 2018. Report R45340, federal land designations: a brief guide. Congressional Research Service, Washington, D.C., USA.

Cortes Capano, G., T. Toivonen, A. Soutullo, and E. Di Minin. 2019. The emergence of private land conservation in scientific literature: A review. Biological Conservation 237:191–199.

Crain, B. J., J. N. Sanchirico, K. Kroetz, A. E. Benefield, and P. R. Armsworth. 2020. Species protection in areas conserved through community-driven direct democracy as compared with a large private land trust in California. Environmental Conservation 47:30–38.

Dave, R. N. 1996. Validating fuzzy partitions obtained through c-shells clustering. Pattern Recognition Letters 17:613–623.

Dennis, R. L. H., and C. D. Thomas. 2000. Bias in butterfly distribution maps: The influence of hot spots and recorder's home range. Journal of Insect Conservation 4:73–77.

Donald, P. F., et al. 2019. The prevalence, characteristics and effectiveness of Aichi Target 11's "other effective area-based conservation measures" (OECMs) in Key Biodiversity Areas. Conservation Letters 12:e12659.

Dray, S., et al. 2012. Community ecology in the age of multivariate multiscale spatial analysis. Ecological Monographs 82:257–275.

Dray, S., et al. 2019. adespatial: multivariate multiscale spatial analysis. R package version 0.3-7. https://CRAN.R-project.org/package=adespatial

Dray, S., P. Legendre, and P. R. Peres-Neto. 2006. Spatial modeling: A comprehensive framework for principal coordinate analysis of neighbor matrices (PCNM). Ecological Modelling 196:483–493.

N. Dudley, P. Shadie, and S. Stolton, editors. 2013. Guidelines for applying protected area management categories. IUCN, Gland, Switzerland.

Eigenbrod, F., B. J. Anderson, P. R. Armsworth, A. Heinemeyer, S. Gillings, D. B. Roy, C. D. Thomas, and K. J. Gaston. 2010. Representation of ecosystem services by tiered conservation strategies. Conservation Letters 3:184–191.

Ernstson, H., S. Barthel, E. Andersson, and S. T. Borgström. 2010. Scale-crossing brokers and network governance of urban ecosystem services: The case of Stockholm. Ecology and Society 15:28.

Fishburn, I. S., A. G. Boyer, P. Kareiva, K. J. Gaston, and P. R. Armsworth. 2013. Changing spatial patterns of conservation investment by a major land trust. Biological Conservation 161:223–229.

Fishburn, I. S., P. Kareiva, K. J. Gaston, and P. R. Armsworth. 2009. The growth of easements as a conservation tool. PLoS ONE 4:e4996.

Fovargue, R., M. Fisher, J. Harris, and P. R. Armsworth. 2019. A landscape of conservation philanthropy for US land trusts. Conservation Biology 33:176–184.

Goettsch, B., A. P. Duran, and K. J. Gaston. 2019. Global gap analysis of cactus species and priority sites for their conservation. Conservation Biology 33:369–376.

Goldman-Benner, R. L., S. Benitez, T. Boucher, A. Calvache, G. Daily, P. Kareiva, T. Kroeger, and A. Ramos. 2012. Water funds and payments for ecosystem services: Practice learns from theory and theory can learn from practice. Oryx 46:55–63.

Graves, R. A., M. A. Williamson, R. T. Belote, and J. S. Brandt. 2019. Quantifying the contribution of conservation easements to large-landscape conservation. Biological Conservation 232:83–96.

Groves, C. R., L. S. Kutner, D. M. Stoms, M. P. Murray, J. M. Scott, M. Schafale, A. S. Weakley, and R. L. Pressey. 2000. Owning up to our responsibilities: who owns lands important for biodiversity? Pages 275–300 *in* B. A. Stein, L. S. Kutner, and J. S. Adams, editors. Precious heritage: the status of biodiversity in the United States. Oxford University Press, New York, New York, USA.

Guerrero, A. M., M. Barnes, Ö. Bodin, I. Chadès, K. J. Davis, M. S. Iftekhar, C. Morgans, and K. A. Wilson. 2020. Key considerations and challenges in the application of social-network research for environmental decision making. Conservation Biology 34:733–742.

Guerrero, A. M., R. R. J. Mcallister, and K. A. Wilson. 2014. Achieving cross-scale collaboration for large scale conservation initiatives. Conservation Letters 8:107–117.

Halkidi, M., Y. Batistakis, and M. Vazirgiannis. 2001. On clustering validation techniques. Journal of Intelligent Information Systems 17:107–145.

Hanley, N., S. Banerjee, G. D. Lennox, and P. R. Armsworth. 2012. How should we incentivize private landowners to 'produce' more biodiversity? Oxford Review of Economic Policy 28:93–113.

Hickey, V., and S. L. Pimm. 2011. How the World Bank funds protected areas. Conservation Letters 4:269–277.

Hubbell, S. P. 2001. The unified neutral theory of biodiversity and biogeography. Princeton University Press, Princeton, New Jersey, USA.

Imperial, M. T. 2005. Using collaboration as a governance strategy: Lessons from six watershed management programs. Administration & Society 37:281–320.

IUCN-WCPA. 2019. Guidelines for recognising and reporting other effective area-based conservation measures. IUCN, Gland, Switzerland.

Jackson, H. B., K. Kroetz, J. Sanchirico, A. Thompson, and P. Armsworth. 2020. Protected area, easement, and rental contract data reveal five communities of land protection in the United States. Dryad, data set. https://doi.org/10.5061/dryad.vt4b8gtqz

Jenkins, C. N., K. S. Van Houtan, S. L. Pimm, and J. O. Sexton. 2015. US protected lands mismatch biodiversity priorities. Proceedings of the National Academy of Sciences USA 112:5081–5086.

Joppa, L. N., and A. Pfaff. 2009. High and far: biases in the location of protected areas. PLoS ONE 4:e8273.

Kabii, T., and P. Horwitz. 2006. A review of landholder motivations and determinants for participation in conservation covenanting programmes. Environmental Conservation 33:11–20.

Kamal, S., M. Grodzińska-Jurczak, and G. Brown. 2015. Conservation on private land: a review of global strategies with a proposed classification system. Journal of Environmental Planning and Management 58:576–597.

Keeley, A. T. H., P. Beier, T. Creech, K. Jones, R. H. G. Jongman, G. Stonecipher, and G. M. Tabor. 2019. Thirty years of connectivity conservation planning: an assessment of factors influencing plan implementation. Environmental Research Letters 14:103001.

Keppel, G., C. Morrison, D. Watling, M. V. Tuiwawa, and I. A. Rounds. 2012. Conservation in tropical Pacific Island countries: Why most current approaches are failing. Conservation Letters 5:256–265.

Kreuter, U. P., D. W. Wolfe, K. B. Hays, and J. R. Conner. 2017. Conservation credits: evolution of a market-oriented approach to recovery of species of concern on private land. Rangeland Ecology and Management 70:264–272.

Kroetz, K., J. N. Sanchirico, P. R. Armsworth, and H. S. Banzhaf. 2014. Benefits of the ballot box for species conservation. Ecology Letters 17:294–302.

Land Trust Alliance. 2016. National land trust census report. Land Trust Alliance, Washington, D.C., USA.

Land Trust Alliance. 2021. Land Trust Alliance: saving the places people love. Land Trust Alliance, Washington, D.C., USA. https://www.landtrustalliance.org/

Lang, C., P. Prendergast, and S. Pearson-Merkowitz. 2018. How does municipal policy affect state and local actions? Evidence from land conservation spending. Resource and Energy Economics 54:23–36.

Large-Scale Conservation Initiatives. n.d. Large-Scale conservation initiatives. http://www.geodata.soton.ac.uk/landscape_scale/

Lawley, C., and W. H. Yang. 2015. Spatial interactions in habitat conservation: evidence from prairie pothole easements. Journal of Environmental Economics and Management 71:71–89.

Legendre, P., and E. D. Gallagher. 2001. Ecologically meaningful transformation for ordination of species data. Oecologia 129:271–280.

Legendre, P., and L. Legendre. 2012. Numerical ecology. Third edition. Elsevier, Amsterdam, The Netherlands.

Lerner, J., J. Mackey, and F. Casey. 2007. What's in Noah's wallet? Land conservation spending in the United States. BioScience 57:419–423.

Malhado, A. C. M., J. Santos, R. A. Correia, J. V. Campos-Silva, D. Teles, M. H. Costa, P. Jepson, and R. J. Ladle. 2020. Monitoring and mapping non-governmental conservation action in Amazonia. Land Use Policy 94:104556.

Mansourian, S., and N. Dudley. 2008. Public funds to protected areas. WWF International, Gland, Switzerland.

Martin, L. E., M. G. Sorice, and U. P. Kreuter. 2011. Understanding and influencing urban residents' knowledge about wildland management in Austin, Texas. Urban Ecosystems 16:33–51.

Merenlender, A. M., L. Huntsinger, G. Guthey, and S. K. Fairfax. 2004. Land trusts and conservation easements: Who is conserving what for whom? Conservation Biology 18:65–75.

Meretsky, V. J., and R. L. Fischman. 2014. Learning from conservation planning for the US National Wildlife Refuges. Conservation Biology 28:1415–1427.

Meyer, S. R., C. S. Cronan, R. J. Lilieholm, M. L. Johnson, and D. R. Foster. 2014. Land conservation in northern New England: Historic trends and alternative conservation futures. Biological Conservation 174:152–160.

Mills, M., et al. 2019. How conservation initiatives go to scale. Nature Sustainability 2:935–940.

Organisation for Economic Cooperation and Development. 2020. A comprehensive overview of global biodiversity finance. OECD. https://www.oecd.org/environment/resources/biodiversity/report-a-comprehensive-overview-of-global-biodiversity-finance.pdf

Ostrom, E. 1990. Governing the commons: the evolution of institutions for collective action. Cambridge University Press, Cambridge, UK.

Palomo, I., B. Martín-López, M. Potschin, R. Haines-Young, and C. Montes. 2012. National Parks, buffer zones and surrounding lands: Mapping ecosystem service flows. Ecosystem Services 4:104–116.

Parker, D. P., and W. N. Thurman. 2011. Crowding out open space: the effects of federal land programs on private land trust conservation. Land Economics 87:202–222.

Rao, C. R. 1995. A review of canonical coordinates and an alternative to correspondence analysis using Hellinger distance. Qüestiió 19:23–63.

Reddy, S., and L. M. Dávalos. 2003. Geographical sampling bias and its implications for conservation priorities in Africa. Journal of Biogeography 30:1719–1727.

Redford, K. H., et al. 2003. Mapping the conservation landscape. Conservation Biology 17:116–131.

Rissman, A. R., and A. M. Merenlender. 2008. The conservation contributions of conservation easements: analysis of the San Francisco Bay area protected lands spatial database. Ecology and Society 13:25.

Rodrigues, A. S. L., et al. 2004. Effectiveness of the global protected area network in representing species diversity. Nature 428:640–643.

Rousseeuw, P. J. 1987. Silhouettes: a graphical aid to the interpetation of validation of cluster analysis. Journal of Computational and Applied Mathematics 20:53–65.

Ruseva, T. B., J. R. Farmer, and C. Chancellor. 2016. Networking for conservation: social capital and perceptions of organizational success among land trust boards. Ecology and Society 21:50.

Scott, J. M., R. J. F. Abbitt, and C. R. Groves. 2001. What are we protecting? the United States conservation portfolio. Conservation Biology in Practice 2:18–19.

Scullion, J. J., K. A. Vogt, A. Sienkiewicz, S. J. Gmur, and C. Trujillo. 2014. Assessing the influence of land-cover change and conflicting land-use authorizations on ecosystem conversion on the forest frontier of Madre de Dios, Peru. Biological Conservation 171:247–258.

Sentinel Landscapes Partnership. n.d. The Sentinel Landscapes Partnership: where defense, agriculture, and conservation communities work together to empower private landowners. https://sentinellandscapes.org/

Shwartz, A., et al. 2017. Scaling up from protected areas in England: The value of establishing large conservation areas. Biological Conservation 212:279–287.

Simmons, B. A., K. A. Wilson, and A. J. Dean. 2020. Landholder typologies illuminate pathways for social change in a deforestation hotspot. Journal of Environmental Management 254:109777.

Smith, A. C., N. Koper, C. M. Francis, and L. Fahrig. 2009. Confronting collinearity: comparing methods for disentangling the effects of habitat loss and fragmentation. Landscape Ecology 24:1271–1285.

Stroman, D. A., and U. P. Kreuter. 2015. Factors influencing land management practices on conservation easement protected landscapes. Society & Natural Resources 28:891–907.

Stroman, D. A., U. P. Kreuter, and J. Gan. 2017. Balancing property rights and social responsibility: perspectives of conservation easement landowners. Rangeland Ecology and Management 70:255–263.

Tobler, W. 1970. A computer movie simulating urban growth in the Detroit region. Economic Geography 46:234–240.

U.S. Department of Agriculture Farm Services Agency. 2018. CRP enrolment and rental payments by county, 1986-2018. https://www.fsa.usda.gov/

U.S. Department of Agriculture Natural Resources Conservation Service. 2021. Joint Chief's Landscape Restoration Partnership. USDA NRCS, Washington. D.C., USA. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/programs/initiatives/?cid=stelprdb124

U.S. Fish and Wildlife Service. 2021. Migratory Bird Program. U.S. Fish and Wildlife Service, Washington, D.C., USA. https://www.fws.gov/birds/index.php

U.S. Fish and Wildlife Service. 2013. National wildlife refuge system land protection projects: an assessment of land protection projects; a plan for strategic growth. U.S. Fish and Wildlife Service, Washington, D.C., USA.

U.S. Forest Service. 2020. STEW-MAP: The Stewardship Mapping and Assessment Project. U.S. Forest Service, Northern Research Station, Madison, Wisconsin, USA. https://www.nrs.fs.fed.us/STEW-MAP/

U.S. Geological Survey Gap Analysis Project. 2016. Protected areas database of the United States (PAD-US 1.4). USGS Gap Analysis Program (GAP). http://dx.doi.org/10.5066/F7G73BSZ

U.S. Geological Survey Gap Analysis Project. 2018. Protected areas database of the United States (PAD-US 2.0). USGS Gap Analysis Program (GAP). http://dx.doi.org/10.5066/P955KPLE

Villamagna, A. M., B. Mogollon, and P. L. Angermeier. 2017. Inequity in ecosystem service delivery: socioeconomic gaps in the public-private conservation network. Ecology and Society 22:16.

Wilcove, D. S., and L. L. Master. 2005. How many endangered species are there in the United States? Frontiers in Ecology and the Environment 3:414–420.

Yamaki, K. 2016. Role of social networks in urban forest management collaboration: A case study in northern Japan. Urban Forestry & Urban Greening 18:212–220.

Yonavjak, L., and T. Gartner. 2011. Gaining ground: Increasing conservation easements in the US south. World Resources Institute Brief 7.

Zhu, L. L., C. M. Zhang, and Y. Y. Cai. 2018. Varieties of agri-environmental schemes in China: A quantitative assessment. Land Use Policy 71:505–517.

Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.2322/full

Data Availability

Data are available (Jackson et al. 2020) in the Dryad Digital Repository: https://doi.org/10.5061/dryad.vt4b8gtqz