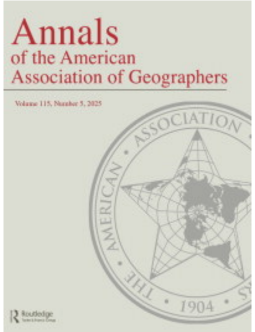

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America the Beautiful: Meeting "30 × 30" Conservation Goals Through Connected Protected Areas

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Protected areas are a primary instrument for biodiversity conservation, and area-based targets have become a hallmark of global efforts with the 2022 Kunming-Montreal Global Biological Framework recommending at least 30 percent of land and water be protected by 2030. In parallel, the United States has implemented "America the Beautiful," a call for local, state, and regionally led efforts to conserve, connect, and restore 30 percent of U.S. lands and waters by 2030. Achieving these goals is complicated, however, by the multiple policy scales at which conservation decisions are made and governed and the limited guidance provided on how gains to protected and connected areas should be evaluated. We assess the connectedness of U.S. protected areas at multiple scales and find that less than 3 percent of the United States is protected and connected. Connectedness increases when the area under investigation is partitioned into smaller policy units (e.g., counties), a product of the modifiable areal unit problem. Similarly, connectedness values increase by an order of magnitude when assessed relative to the protected area network rather than considering all land area. Both findings support the need for standardized reporting frameworks and highlight the challenges in coordinating conservation goals across administrative units. *Key Words: connectivity, landscape ecology, landscape metrics, scale, spatial planning.*

Protected areas (PAs)—locations where human presence is limited to preserve natural, ecological, and cultural value—are a primary instrument for biodiversity conservation and one component of larger efforts to slow mass extinction of wildlife and curb global warming. Area-based targets for protection have become a hallmark of global conservation efforts and provide concrete, measurable goals against which governments and organizations can be held accountable. For example, the 2022 Kunming-Montreal Global Biodiversity Framework (GBF) was adopted by nearly 200 countries and contains the keynote target to protect at least 30 percent of global land and water by 2030 (Convention on Biological Diversity 2023). This target, colloquially known as 30 by 30 (or 30 × 30), has already resulted in actions to protect more land around the world. In parallel, the United States implemented "America the Beautiful" (ATB) through an executive order (Biden 2021), which is a call for local, state, and regionally led efforts to conserve, connect, and restore 30 percent of U.S. lands and waters by 2030. These 30 × 30 targets are intended to elevate conservation beyond the 17 percent targets established by the Aichi convention in 2010 and better address warnings that humankind needs to protect half of Earth's surface to stave off mass extinction (Odum and Odum 1972; Noss et al. 2012; O'Leary et al. 2016; Wilson 2017).

Commitments from countries to protect additional land area is a start, but establishing isolated reserves is not sufficient for conserving biodiversity. Protected areas must be well connected to achieve biodiversity outcomes and effectively increase the resilience of conservation networks (Rudnick et al. 2012). Habitat areas that are connected directly or are near enough for species to disperse between them are key for population viability because they facilitate movement and gene flow (Gilbert-Norton et al. 2010; Krosby et al. 2010; Minor and

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Lookingbill 2010) and improve the chances that species will be able to migrate and repopulate areas in response to climate change (DeFries et al. 2005; Heller and Zavaleta 2009). Together, these benefits reduce extinction risks and minimize the effects that climate and environmental variability might have on small populations (Brown and Kodric-Brown 1977; Newmark 1996).

Both the Kunming-Montreal GBF and the U.S. ATB plan underscore protecting land through "well-connected" areas, but actually achieving these targets has proven difficult in the past. When these efforts fail (see, e.g., Brondízio et al. 2019; Díaz et al. 2019; Secretariat of the Convention on Biological Diversity 2020), it is generally attributed to breakdowns in implementation, monitoring, and reporting rather than apathy or lack of resources. Reinforcing this point, the ATB plan explicitly acknowledges that the means for evaluating and monitoring the country's progress toward this ambitious and urgent goal have not yet been determined. Another factor hindering efforts is that targets such as 30×30 are often adopted at the national level, but decisions about how much and which land to preserve are often left to local, regional, and tribal governments, or even individual landowners. This mismatch in the top-down scale of policy creation versus the bottom-up scale of implementation makes it difficult to align action with goals and can complicate reporting structures. For example, the United States currently lacks a baseline understanding of protected area connectivity, which is key for ultimately achieving biodiversity targets (Dreiss and Malcom 2022) and makes it difficult to design network improvements at local scales and nearly impossible to assess and report progress toward larger conservation agenda goals. A solid understanding of baseline protected and connectedness along with practical and meaningful ways to measure and report progress toward conservation targets are needed (Geldmann et al. 2021).

The objective of this study is to establish a baseline understanding of PA status and connectivity at multiple policy and administrative scales, and then assess how the administrative level of analysis adopted could affect area-based reporting metrics. This analysis represents an important first step in achieving policy goals while also developing an assessment framework for measuring, monitoring, and managing the connectivity of the PA network of the United States. We begin by highlighting the importance of landscape connectivity in conservation planning. To assess connectivity in the United States, we then compile a database of PAs that support biodiversity conservation and use this database to compute PA amount and connectedness at four administrative levels relevant for policymaking including: (1) the continental United States (CONUS); (2) the twelve Department of Interior (DOI) regions (which are based on watersheds but generally drawn along state/county lines to simplify coordination); (3) the fifty-six states and territories including Puerto Rico, the Virgin Islands, and the Pacific Island territories of Guam, American Samoa, and the Northern Mariana Islands; and (4) the 3,113 counties that comprise the fifty states and Puerto Rico. We also analyze (5) the twenty-one Environmental Protection Agency (EPA) Level 2 ecoregions as these units are relevant for biodiversity preservation. We assess the percentage of each unit that is protected and connected, demonstrate how the focal scale affects measurements, and indicate where deficiencies in connectivity result from network design, which suggest where future improvements can be made. We end with a discussion of how connectivity efforts and measures can be improved in support of ATB and global targets.

Landscape Connectivity in Conservation Planning

Landscape, or habitat, connectivity is a central and explicitly spatial component of conservation planning (Boitani et al. 2007; Jennings et al. 2020; Beger et al. 2022) that has long been recognized as key for successful habitat restoration and preservation. Landscape connectivity is the degree to which the landscape facilitates or impedes movement among resource patches (Taylor et al. 1993; With, Gardner, and Turner 1997). The composition and spatial arrangement of habitat patches affect species movement, ultimately influencing population dynamics and community structure (Taylor, Fahrig, and With 2006). Landscapes with high connectivity facilitate movement of organisms among habitat patches (Taylor et al. 1993), whereas those with low connectivity impede movement (Figure 1). The reasons for movement vary but often involve dispersal for reproduction, seasonal migrations, or establishing new food, breeding, or nesting sites (Frazier et al. 2021; Fahrig et al. 2022). Additionally, movement

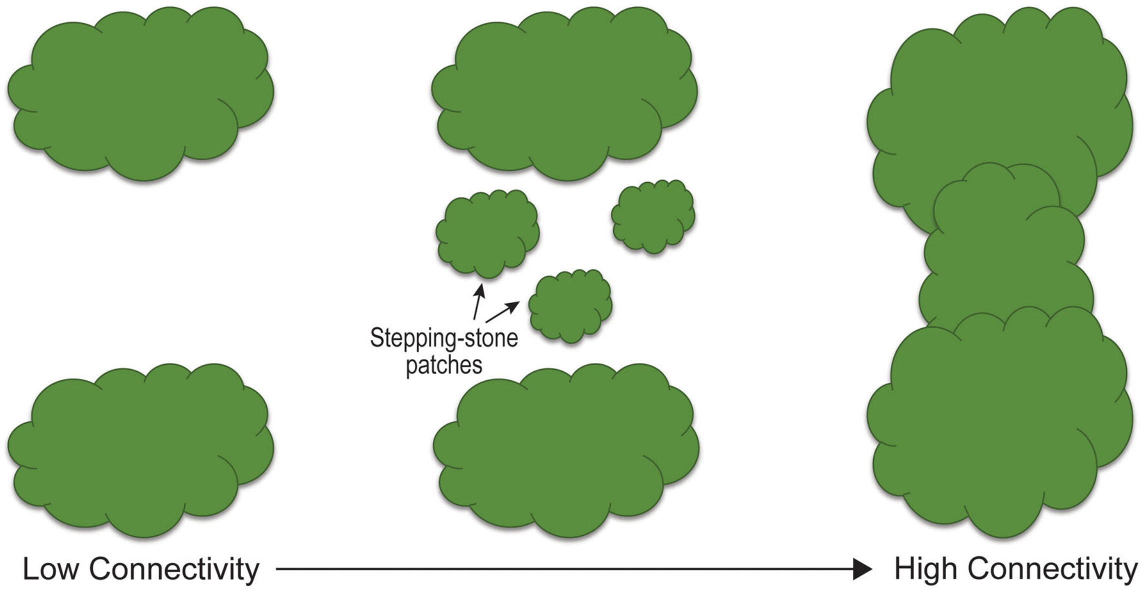

Figure 1. Conceptualization of connectivity from fragmented and isolated habitat patches (left) to well-connected patches (right). Small patches connecting larger patches are referred to as stepping-stone patches (middle).

increases individual fitness by supporting reproduction (Fahrig et al. 2022), linking successful movement to natural selection through greater population abundance, distribution, and persistence (Bowne and Bowers 2004).

In recent decades, habitat fragmentation has been increasing due to conversion of natural land covers to urban, agriculture, and other developed uses, thereby reducing landscape connectivity. In fragmented landscapes, local populations can become isolated and unable to disperse to other suitable habitat for vital activities. This fragmentation can result in local extinctions (Fahrig and Merriam 1994) as species might only be able to survive within larger patch networks that can be reached by dispersing individuals (Adler and Nuernberger 1994; Hanski 1999; Bowne and Bowers 2004). Research has shown that individual PAs are often too small to harbor stable and resilient populations, particularly for wide-ranging species or large carnivores (Di Minin et al. 2013; Dutta et al. 2016).

Because PAs are a cornerstone of efforts to conserve biological diversity (Soulé and Terborgh 1999; Gaston et al. 2008; Maxwell et al. 2020), ensuring there is connectivity among them is essential to promoting species movement and preventing local extinctions. Well-designed PA networks that foster connectivity are also needed to preserve healthy ecosystems and safeguard the delivery of ecosystem services (Saura et al. 2017). Although scientific evidence on the importance of PA connectivity has translated loosely into global commitments, the concept remains underexplored, and there are very few studies that have quantified the spatial connectivity of terrestrial PA networks (Saura et al. 2017) or examined how the spatial scale at which PA network connectivity is measured and monitored could affect administration and design. This gap in the existing literature relates to the modifiable areal unit problem (MAUP; Openshaw 1984), which is a general term for the statistical biases that are generated when the size, shape, or scale of geographic units is altered. As spatial data lends itself to aggregation, these types of fallacies can be unintentionally introduced into geographic analyses. This study also addresses how neglecting nuances in the measurement of spatial relationships could affect real-world outcomes and adds this important spatial perspective to the body of knowledge on PA-based conservation. Together, these contributions provide support for including explicit connectivity targets into global agreements.

Methods

We constructed a database of terrestrial PAs for the United States, Mexico, and Canada using the U.S. Protected Areas Database (U.S. Geological Survey PAD-US v2.1) and the World Database of Protected Areas (WDPA, May 2021). We selected PAs with permanent protection for conversion of natural land cover and managed for the preservation of biological diversity without being subject to extractive uses. These areas are attributed as GAP Status 1 and 2 in the PAD-US. The WDPA was used to supplement PAs that are outside the official administrative boundaries of the United States but can be used as "stepping stone" patches to connect PAs within the administrative unit of analysis (described later).

We removed all PAs smaller than 1 km^2 (based on a Mollweide projection) and simplified polygons to a 100-m tolerance to improve computational efficiency following prior studies (Saura et al. 2017; Saura et al. 2018). We selected PAs for each unit at each level of analysis (e.g., each county, state/territory, DOI region, ecoregion, and CONUS) using administrative boundary files from the U.S. Census, DOI, and EPA. We buffered each unit by 230 km based on typical species' dispersal distances (Bowman, Jaeger, and Fahrig 2002; Minor and Lookingbill 2010; Santini et al. 2013) to allow for transboundary "stepping stone" connectivity that might contribute to connectivity between the PAs within a unit. For each unit, we calculated minimum pairwise distances between all PA edges, creating distance matrices for each of the 3,113 counties, fifty-six states and territories, twelve DOI regions, twenty-one ecoregions, and CONUS, which are used in the calculations that follow. Full data preprocessing details are in the Supplemental Material.

"Protected and Connected" Analyses

The amount of protected and connected land for each unit at each analysis level was computed using the %*Protected* and protected-connected (*ProtConn*) metrics (Saura et al. 2017; Saura et al. 2018). *ProtConn* is a graph-based, landscape metric that measures the percentage of a region covered by areas that are both protected and connected (Hughes et al. 2023) in terms of species dispersal capabilities. *ProtConn* has been used in global assessments of connectedness of ecoregions and country-level targets (Saura et al. 2017; Saura et al. 2018, 2019) and is one of two connectivity metrics recommended for global target reporting by the Protected Planet Report (UNEP-WCMC and IUCN 2021). Although *ProtConn* does not consider the condition of the intervening landscape between protected patches (Naidoo et al. 2019), it does capture both structural and functional connectivity as links between PAs are weighted by the probability of dispersal from one protected patch to another.

We first computed the percentage of the landscape that is protected in each unit as:

$$\%Protected = 100 \times \frac{\sum_{i=1}^{n} a_i}{A_L} \tag{1}$$

where a_i is the area of each individual PA patch i, and A_L is the total area of the focal unit. We then assessed the percentage of the total unit area that is both protected and connected using *ProtConn* (Saura et al. 2017; Saura et al. 2018):

$$ProtConn = 100 \times \frac{ECA}{A_L} \tag{2}$$

where *ECA* is the equivalent connected area, or size a single PA would need to be to provide the same area of reachable protected land as the entire network of PAs in the unit. Full details of ECA are included in the Supplemental Material. The computation of ECA includes a user-defined dispersal distance, which represents how far a species can disperse to another PA patch. We considered three dispersal distances of 1, 10, and 100 km to account for a large range of terrestrial vertebrates (Stevens et al. 2014) consistent with prior studies (Minor and Lookingbill 2010; Santini, Saura, and Rondinini 2016; Saura et al. 2017).

The amount of land that is protected but not connected (i.e., isolated) in the network is the inverse of *ProtConn*:

$$ProtUnconn = \%Protected - ProtConn \tag{3}$$

Metric Partitioning for Network Assessment

ProtConn can be partitioned into the proportion of the network connected via different conditions including through PAs [*Prot*], unprotected areas [*Unprot*], and transboundary areas [*Trans*]:

$$ProtConn = ProtConn[Prot] + ProtConn[Unprot] + ProtConn[Trans] \tag{4}$$

The amount of land that is protected and connected but for which connectivity occurs through unprotected areas (*ProtConn[Unprot]*) is relevant for understanding where species might be vulnerable when moving and migrating between patches.

ProtConn can be adjusted to give the percentage of the PA network that is connected, rather than the percentage of all land in the unit ($ProtConn_{Net}$; akin to *RelConn* in Saura et al. 2017). We present a similar adjustment of *ProtUnconn*, called $ProtUnconn_{Net}$, that builds from this concept of relative connectivity (Saura et al. 2017) and assesses the land that is unconnected relative to the amount of land in the PA network. Although having higher *ProtConn* at the expense of lower relative connectivity is preferable from a conservation standpoint (Saura et al. 2017), understanding where there might be high relative connectivity is important for units that might have an optimized starting point for adding new PAs, especially when establishing baselines for future monitoring and progress assessment.

$$ProtConn_{Net} = 100 \times \frac{ECA}{\sum_{i=1}^{n} a_i} \tag{5}$$

$$ProtUnconn_{Net} = \%Protected \ - ProtConn_{Net} \tag{6}$$

Both *ProtConn* and *ProtUnconn*, and their relative adjustments $ProtConn_{Net}$ and $ProtUnconn_{Net}$, can be partitioned into fractions representing the proportion of the network that is connected via unprotected land or transboundary regions. These variants represent the various structural reasons that a network could be unconnected, including fragmentation by the sea, outland areas, or network design, and can be used to understand what is causing network deficiencies. We compute $ProtUnconn_{Net}$*[Design]*, which represents the portion of the PA network that is unconnected due to arrangement of PAs inside an administrative area. This measure can be loosely interpreted as the portion of PA connectedness for which an administrative unit can be held accountable. Full equations for $ProtUnconn_{Net}$*[Design]* and other variants of *ProtConn* are in the Supplemental Material. Full details of *ProtConn* with illustrative examples can be found in Saura et al. (2017; Saura et al. 2018).

For all metrics, we present individual-level findings as well as summarized results across analysis levels using area-weighted averages. All data processing was completed in R using the *sf* package and Python using the *arcpy* package. Analyses were completed using the Conefor 2.6 (Saura and Torné 2009) command-line interface for Windows and R. Links to the publicly available code are given in the Data Availability section.

Results

We first provide descriptive results for the amount of land that is protected (*%Protected*) to report on progress toward 30 × 30 and provide context for protected and connected findings. Less than 8 percent of CONUS is protected through areas managed for biodiversity, meaning an additional 22 percent of CONUS land area needs to be conserved before 2030 to reach 30 × 30 targets. Globally, about 17 percent of terrestrial land is protected (UNEP-WCMC and IUCN 2021), putting CONUS well below other areas. Alaska is the only state or DOI region that has already met the 30 × 30 target (35.7 percent protected; Figure 2A,C). California is the next closest with 22.6 percent of its land protected. Twenty-nine states and territories have less than 5 percent of their land protected, and seven Midwestern states have less than 2 percent of their land protected: Texas, Kansas, Nebraska, Iowa, Ohio, Indiana, and Kentucky (Figure 2C).

Geographically, more land is protected in the western United States and northern Great Lakes compared to other parts of the country. These biases are particularly noticeable at the county level, where clusters emerge for counties protecting at least 30 percent of land (Figure 2D). Other clusters are evident in the upper Great Plains, central Arkansas, Appalachians, mid-Atlantic coast, upstate New York, and southern Florida. They typically coincide with the locations of U.S. National Forests and Grasslands, which steward an impressive portfolio of protected land in the public trust. Notably, though, many counties in the Midwest and Texas have no land protected (Figure 2D, white areas).

As noted, protected land must also be well connected to facilitate biodiversity outcomes. When a PA network is completely connected, all patches are reachable by a species with a given dispersal capability, and *ProtConn* will equal *%Protected*. Target *ProtConn* values for ATB are therefore 30 percent (or greater). *ProtConn* results show that just 3 percent or less of CONUS land is protected and connected (Table 1, top left), even when considering the largest dispersal capability (100 km), which is arguably beyond the typical movement behavior of many terrestrial species in the United States, including mammals (Bowman, Jaeger, and Fahrig 2002; Minor and Lookingbill 2010; Schloss, Nuñez, and Lawler 2012; Saura et al. 2017). Prior studies using *ProtConn* with a 100-km dispersal distance found

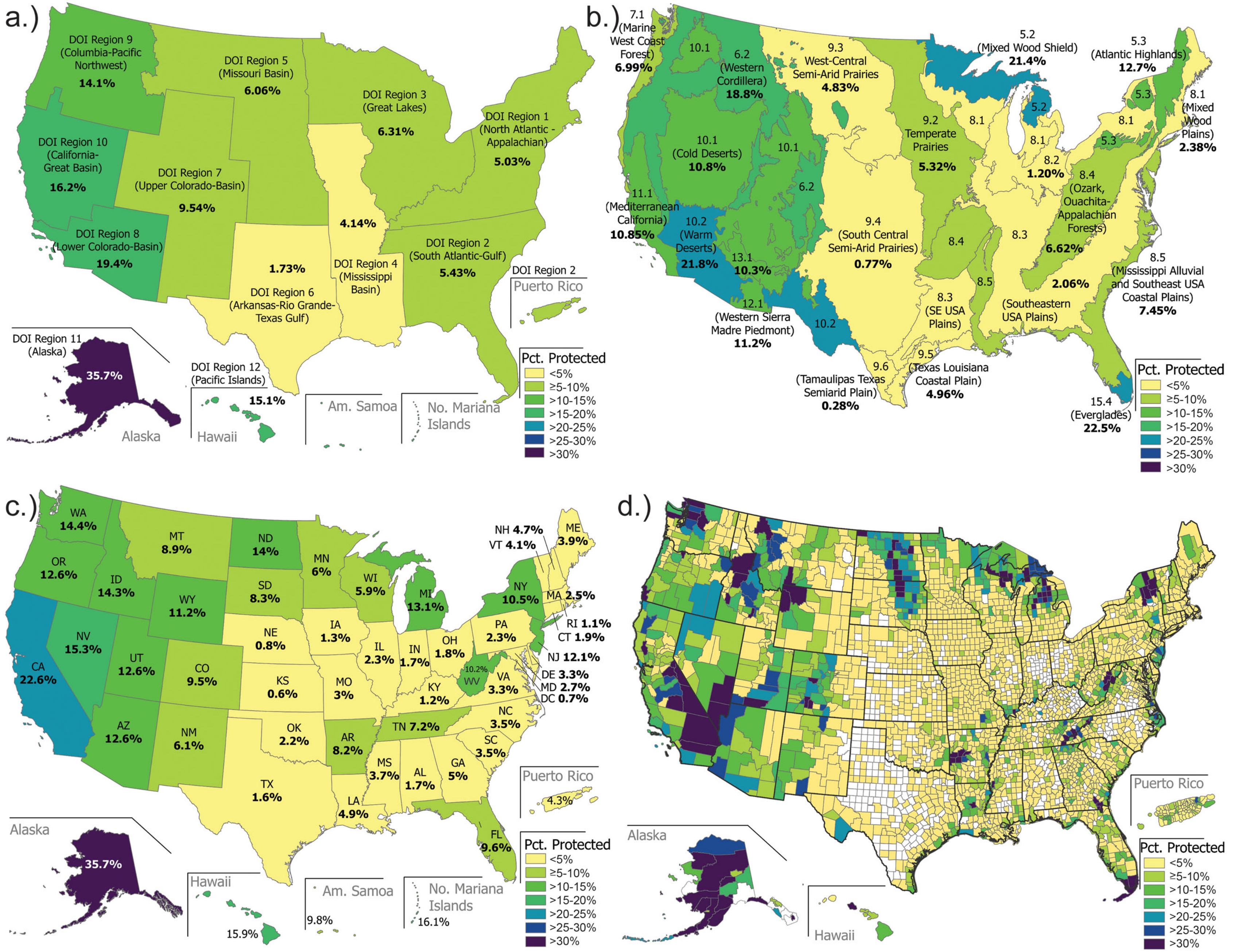

Figure 2. Protected area results for (A) Department of Interior (DOI) regions; (B) Level 2 ecoregions; (C) states and territories; and (D) counties. Units with no color have no land protected (GAP Status 1 or 2).

Table 1. Percentage of land in the contiguous United States that is protected and connected, measured at three dispersal distances for five analysis levels

	Percent of land that is protected and connected (*ProtConn*)			Percent of the protected area network that is connected ($ProtConn_{Net}$)		
Analysis level	1-km	10-km	100-km	1-km	10-km	100-km
CONUS	0.8%	1.2%	3.0%	9.5%	15.6%	38.1%
DOI Regions[a]	2.0%	2.8%	5.2%	25.0%	35.0%	65.8%
Ecoregions[a]	2.0%	2.9%	5.2%	25.2%	36.3%	65.9%
States and territories[a]	2.8%	3.9%	6.3%	36.1%	49.6%	80.3%
Counties[a]	6.1%	7.0%	8.1%	73.5%	84.0%	96.2%
	Percent of land that is protected and unconnected (*ProtUnconn*)			Percent of the protected area network that is inconnected ($ProtUnconn_{Net}$)		
Analysis level	1-km	10-km	100-km	1-km	10-km	100-km
CONUS	7.1%	6.7%	4.9%	90.7%	84.5%	61.9%
DOI regions[a]	5.9%	5.1%	2.7%	75.0%	65.0%	34.2%
Ecoregions[a]	5.9%	5.0%	2.7%	74.8%	63.7%	34.1%
States and territories[a]	5.0%	4.0%	1.6%	63.9%	50.4%	19.7%
Counties[a]	2.2%	1.3%	0.3%	26.5%	16.0%	3.8%

Note: CONUS = continental United States; DOI = Department of Interior.
[a]Area-weighted averages for all units within CONUS. Full results including Alaska and Pacific Island territories are included in Supplemental Table S.1 and Figure S.1.

that 9.7 percent of global land area is protected and connected (Saura et al. 2017), which again places CONUS well below the global average.

ProtConn increases considerably when the area under investigation is partitioned into smaller analysis units (i.e., DOI regions, ecoregions, states and territories, counties), as it is easier to deploy a connected network across smaller areas (Saura et al. 2018). These reporting differences occur because the relative area covered by the PA network increases as unit area decreases. These differences, however, highlight the importance of standardizing reporting units so values are not inflated (Table 1). There are also considerable differences when comparing *ProtConn* (or *ProtUnconn*) to its relative counterpart $ProtConn_{Net}$ (or $ProtUnconn_{Net}$; Table 1, right). Values increase by an order of magnitude from a relative standpoint (Table 1, top right), yet connectivity is still quite low. These relative versions can provide indications of connectivity at local scales but should not be used for overall reporting.

Although the aggregate results for CONUS-level *ProtConn* are concerning, certain individual units have connected their PA networks more successfully than others. Alaska has almost 26 percent of its land preserved in a well-connected PA network at 100-km dispersal distance, and California has about 19 percent of its land protected and connected at 100-km dispersal (Supplemental Figure S.1C). Nine states and territories (Idaho, Michigan, Nevada, New Jersey, North Dakota, Utah, Washington, Hawaii, and the Northern Mariana Islands) all have more than 10 percent of their land preserved in well-connected PAs at 100-km dispersal. Gains can be made, however, in the seventeen states with less than 2 percent of their land protected and connected (Supplemental Figure S.1C).

Even when small amounts of land are protected, a PA network can and should be optimized for connectivity to support movement and migration. Results for $ProtConn_{Net}$ and $ProtUnconn_{Net}$ show that most PA networks in the United States, regardless of their size, are highly unconnected (Table 1, right). For instance, at 1-km dispersal distance, the CONUS network is almost 90 percent unconnected, meaning most reserves are isolated and not reachable by species that can only disperse up to 1 km. At 10-km dispersal, that number improves only by about 5 percent.

Understanding why PAs are unconnected can aid in developing effective solutions and interventions. The amount of the network that is unconnected due to the network design ($ProtUnconn_{Net}[Design]$) is an important metric when implementing policies such

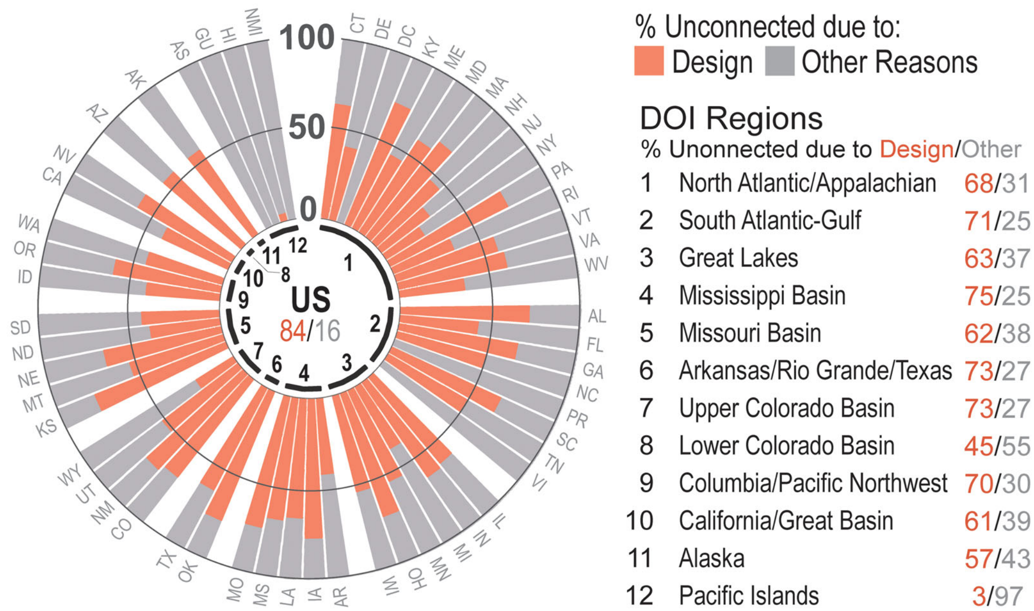

Figure 3. Portion of the protected area network for states and territories (left) and Department of Interior (DOI) regions (right) that is unconnected due to design. *Note:* American Samoa (AS) does not have any protected land that is unconnected.

as ATB. We find that for most states and DOI regions, the unconnected aspects of the network are, in fact, due to the design of the network rather than fragmentation that occurs due to natural barriers like the sea or administrative partitioning (Figure 3). For thirty-one states and territories, network design is responsible for more than half of the network unconnectedness. These areas can be improved, however, with strategic PA placement.

Even in a well-designed and connected network, species might still need to move through unprotected land to reach functionally "connected" PAs, represented by *ProtConn[Unprot]*. Visualizing the intersection of %*Protected* and *ProtConn[Unprot]* can show where PA amounts are high but species likely have to move through exposed or highly modified areas to reach another PA (Figure 4). The western United States, which had high %*Protected* (Figure 2) also has low *ProtConn[Unprot]* (shown in yellow in Figure 4), which means most connectivity is through PAs, safeguarding species. Blue areas, notably in the Midwest and Northeast, indicate areas where %*Protected* is low, and connectivity between PAs requires traversing unprotected land. Green-hued areas have a high percentage of land protected that is functionally connected, but that connectedness requires species to travel through unprotected areas. These regions are places where small investments to add well-positioned PAs could have an outsized impact on connectivity and conservation.

Discussion

Protecting land while also ensuring it is functionally connected to support biodiversity outcomes are interlinked goals that must be pursued in tandem. The Kunming-Montreal GBF and the U.S. ABF plan both recognize and prioritize this dual need. As these agreements evolve from "target setting" to "target getting," it is an opportune time to establish "protected and connected" baselines against which progress toward 30×30 can be measured and frameworks that facilitate monitoring and reporting. To date, there has been little guidance on these items, so this study contributes to these needs in two ways. First, it provides a foundational understanding of how much land in the United States is currently protected and connected as a means for comparing the United States to other areas of the world and also measuring future improvements to the PA network. Second, the study demonstrates how the administrative level at which monitoring and reporting is completed will affect measurements of

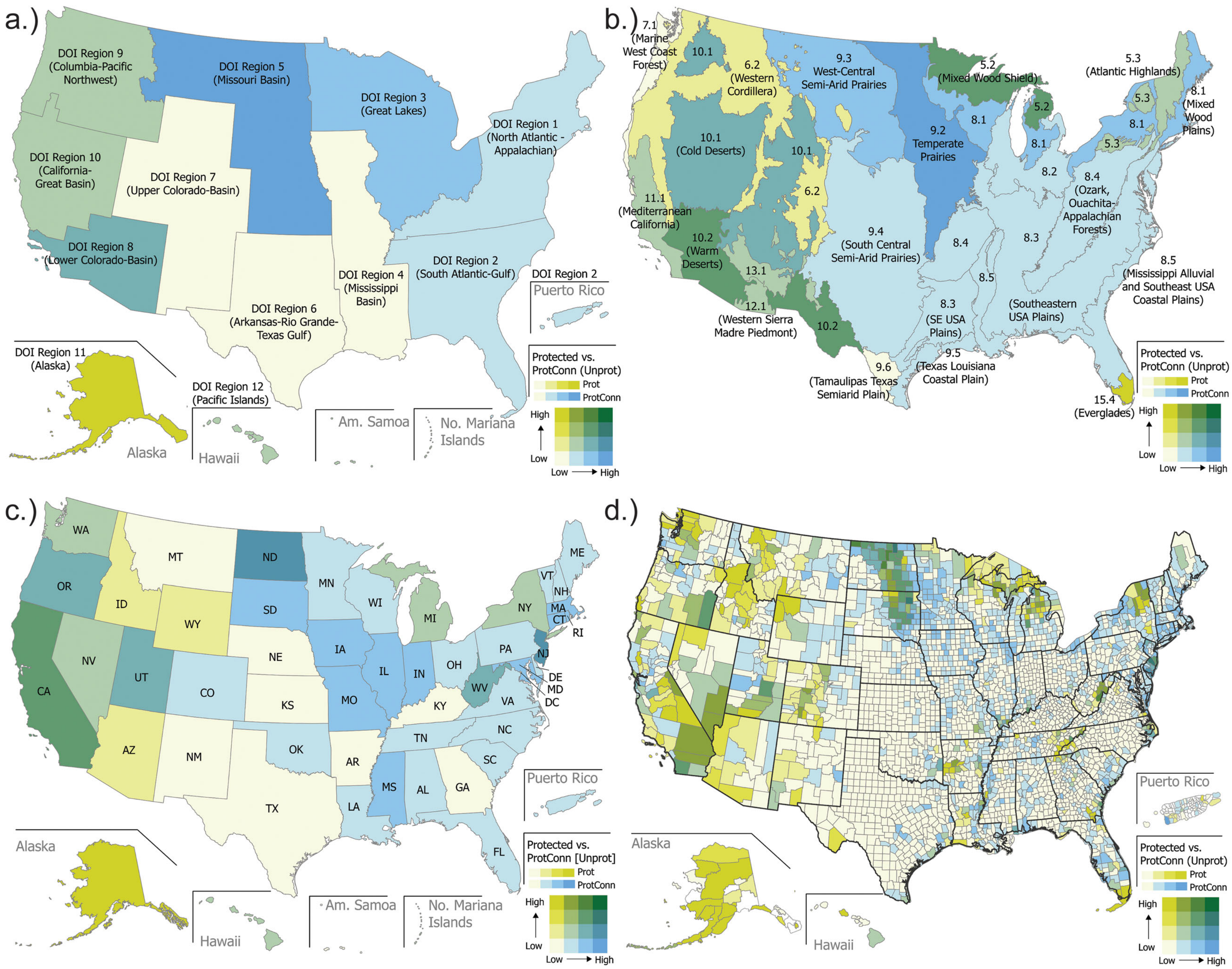

Figure 4. Bivariate choropleth maps for the intersection of %*Protected* and *ProtConn[Unprot]*. Breakpoints for %*Protected* are (low to high) 10, 20, 30, and > 30 percent. Breakpoints for *ProtConn[Unprot]* are (low to high) 25, 50, 75, and > 75 percent. Bright blue indicates areas with low protection (less than 10 percent area), with connectivity mostly through unprotected areas. Bright yellow indicates areas with high protection, with connectivity mostly through protected areas. *Note:* DOI = Department of Interior.

connectedness and stresses the need for standardized reporting frameworks not only for the United States but also for international signatories of the GBF.

The findings from this study highlight the need to protect more land in the United States that is functionally connected. With less than 8 percent of CONUS land protected for biodiversity, and only 3 percent of that land protected and connected (at 10-km dispersal), the United States is well behind the global tallies of 17 percent protected and 9.7 percent protected and connected (Saura et al. 2019). Given these results, focusing on optimizing new PAs in locations that will improve network connectivity rather than simply adding isolated or fragmented areas can help achieve 30×30 targets. Various algorithms have been developed specifically for this purpose (Christensen, Ferdaña, and Steenbeek 2009; Andrello et al. 2015; Hanson et al. 2019), and can be leveraged to help with optimization. Given the high social, political, and sometimes financial costs for acquiring, upgrading (i.e., strengthening the management level on tracts by reducing allowable uses), and directly managing public lands for biodiversity outcomes, efforts to preserve ecosystems on private lands are increasingly necessary for creating functionally connected PA networks (Bargelt, Fortin, and Murray 2020; Dreiss and Malcom 2022; Chapman, Boettiger, and Brashares 2023). These efforts, which are sometimes referred to as other effective area-based conservation measures (OECMs), have the potential to lead to important gains for biodiversity conservation and climate mitigation objectives, particularly where existing PAs and public lands do not coincide with biodiversity hot spots or important migratory corridors. Moving forward, private efforts and OECMs will likely be critical for optimizing network design. Valuation tools also exist to support this purpose (Nolte 2020) and can be used to help prioritize these parcels for protection.

The findings from this study also highlight the discrepancies that can result from varied reporting structures and the importance of establishing clear reporting levels and norms for measuring and monitoring network gains. Connectedness values were an order of magnitude larger when connectivity was assessed in terms of the PA network (Table 1, right) rather than the entire land area (Table 1, left). These disparities highlight the potential for differential administrative reporting strategies if clear guidelines are not set, even when a common metric such as *ProtConn* is adopted. Because the onus for identifying and conserving land in the ATB plan is distributed across many different levels of administration, including states, local governments, Indigenous territories, and private landowners, interagency coordination and collaboration will be needed to not only ensure that added PAs meet ecosystem needs (Dreiss and Malcom 2022; Keeley et al. 2022) but that measurement and reporting norms are established and followed.

We advocate for connectedness to be computed at the national level rather than aggregated from smaller administrative units. First, as demonstrated earlier, aggregation of areal units can inflate values due to the statistical biases introduced through MAUP. As the size of the areal units (e.g., states) are partitioned into smaller and smaller units (e.g., counties), the metric value can naturally grow simply because the area of PAs is greater relative to the total land area of the unit, and the number of PAs that are considered connected also increases (Figure 5). Second, distributing reporting responsibilities to counties, states, or even DOI regions could lead to fragmentation of governance and siloed attempts to increase connectivity in small areas without considering the impacts of PA additions to the network as a whole beyond the unit. For instance, even though *ProtConn* incorporates protected areas from neighboring units as "stepping stones," when computed at small scales (e.g., counties), the metric will not reflect changes in a national-scale PA network. Reporting connectedness values at the national level is also compatible with GBF reporting. Third, the amount of habitat that needs to be conserved in each region will vary, and assigning reporting at finer levels runs the risk of places designating protected land solely for the sake of meeting targets rather than optimally siting the network to serve the areas with the greatest need. Site selection is equally important as reaching targets for achieving conservation outcomes (Margules and Sarkar 2007; Dinerstein et al. 2017).

There are two caveats to our recommendation. First, national-level reporting is complicated when a country contains "outland" areas that are unconnected to the mainland by the sea, such as Hawaii and Puerto Rico, or separated by another country, such as Alaska is disconnected from the United States through Canada. These outland areas can result in spuriously lowered connectedness. Second, successful biodiversity conservation is strongly linked to ecoregions or migration pathways that often span

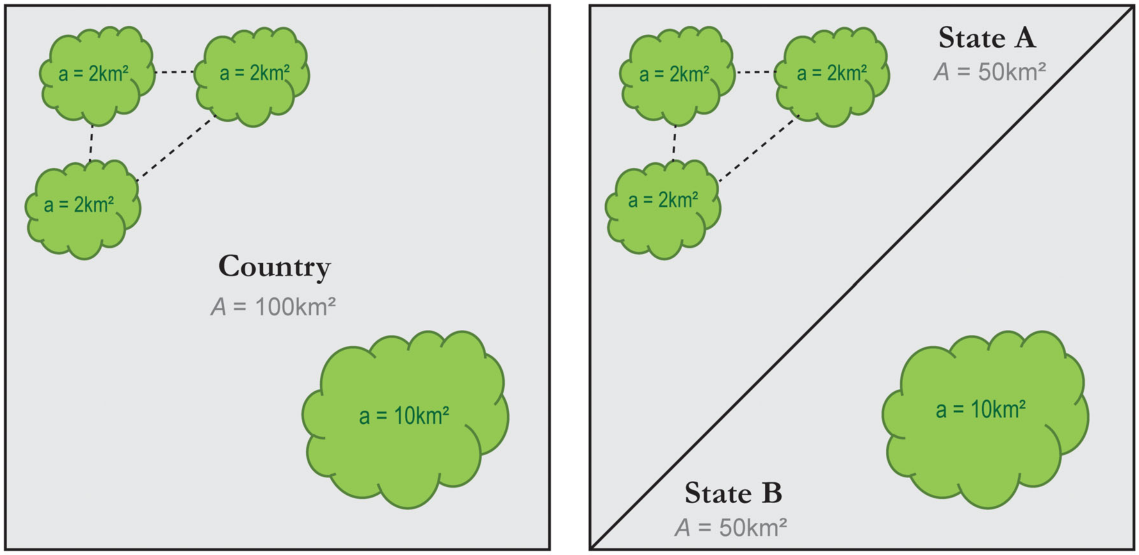

Figure 5. A hypothetical country (left) with four protected areas (PAs) that is equally divided into two states, A and B (right). At the country level, the three small PAs (each with area *a*) in the upper left are near each other and considered connected (distance decay terms ≈ 1; see Equation 3C in Supplemental Material), and the singular large PA in the bottom right is unconnected from the other three (distance decay term ≈ 0). When *ProtConn* is computed at the country level, the PA network covers 16 percent of the total land area (*a*), but only 11.1 percent of the land is both protected and connected. When the country is partitioned into its two states (left), the area covered by the PA network in State A is 12 percent, and the network is 9.8 percent connected. In State B, the area covered by the PA network is 20 percent, and the network is also fully connected (20 percent) because there is only a single PA. A weighted average of the two states indicates that *ProtConn* is 14.9 percent when computed using the state-level units compared to 11.1 percent using the country-level unit.

multiple states or countries, and there can be mismatches between the ecological units relevant for conservation and the administrative units relevant for policymaking (Henle et al. 2010). Partitioning metrics for an ecologically relevant unit to an administrative unit could fail to capture how well a unit is coordinating with other units or balancing ecosystem needs. Integrating ecoregion-level analyses into country-level reporting will better align the realities of federal and state administration of the PA systems with the ecological processes relevant to biodiversity conservation. Creating administrative pathways to planning and monitoring PAs at an ecosystem scale has the additional advantage of opening channels to localized expertise about species, landscapes, land-use practices, and political environments.

Other Considerations for Moving Connectivity Research Forward

Connectivity can be measured in multiple ways (see reviews by Kindlmann and Burel 2008; Keeley, Beier, and Jenness 2021), and there has been limited empirical guidance for which metrics should be used for target reporting, both in the United States and globally (Yang, Kedron, and Frazier 2024). The GBF recommends two metrics—*ProtConn* and *PARC-Connectedness* (Drielsma, Ferrier, and Manion 2007)—and we adopted *ProtConn* here because *PARC-Connectedness* does not evaluate connectivity from one PA to another and confounds the proportion of PA with primary vegetation from land cover (Theobald et al. 2022). *ProtConn* is also easier to compute and can be computed at different levels, whereas *PARC-Connectedness* is a global measure. *ProtConn* does have limitations, though (Saura et al. 2018). First, it does not consider land use heterogeneity or account for movement costs (e.g., over human-modified areas; Parks et al. 2020; Ward et al. 2020; Figure 6). The use of *ProtConn[Unprot]* (see Figure 4) can help capture where species might be vulnerable as they move through unprotected lands, but incorporating more spatially explicit measures of the permeability of the land around PAs, through, for example, human footprint layers (e.g., Venter et al. 2016; Theobald et al. 2020), can help better capture the functional connectivity of a landscape for species movement (Belote et al. 2016; Belote and Wilson 2020). Second, *ProtConn* is computationally

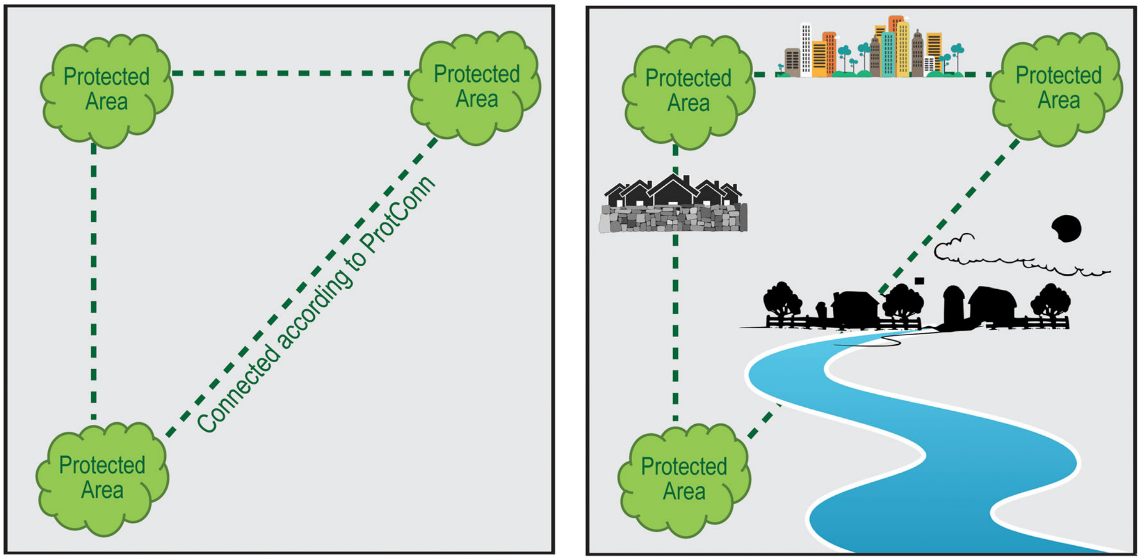

Figure 6. Conceptual illustration of how *ProtConn* may consider a set of protected areas "connected" based only on their areas and distance (left), without considering the condition of the intervening land. The situation in the real world (right) could include natural or anthropogenic barriers to movement between protected areas that are considered connected.

intensive, and Yang, Kedron, and Frazier (2024) showed that simpler metrics could be reasonable substitutes in certain reporting contexts. Third, *ProtConn* cannot identify where more effective PA management or administrative coordination is necessary (Saura et al. 2018). Thus, results derived from *ProtConn* should be regarded as liberal estimates of connectedness, as incorporating the suitability or permeability of interposing areas would likely decrease the amount of land considered protected and connected. As human pressures reduce the quality of PAs and transitional areas (Geldmann et al. 2019), it will be important to identify and adopt metrics that account for species-specific dispersal and movement costs when planning specific functions of the PA network. A single-metric approach like *ProtConn* is attractive, but monitoring and benchmarking will be improved if that metric is complemented by species- and resistance-based metrics and local knowledge.

Moving beyond metrics, we continue to lack a solid scientific understanding of how much connectivity is needed to achieve desired global biodiversity impacts. Climate change will continue to shift ecosystems (Williams, Jackson, and Kutzbach 2007; Fitzpatrick and Dunn 2019) and undermine the effectiveness of existing PAs (Dobrowski et al. 2021). Policies must prioritize the protection of areas that can act as refugia or corridors for migrating species (Carroll et al. 2018; Michalak et al. 2018; Graham et al. 2019; Stralberg, Carroll, and Nielsen 2020). Accurately predicting which ecoregions will change and at what rates is key to guiding PA network expansion. Recent findings project large climatic shifts across the northern midlatitudes in the United States (Cui et al. 2021), and these shifts will invariably affect PAs. PA network design must also consider where and how species will need to migrate to locate new areas of suitable climate. Efforts to forecast where PAs are needed in the future should also consider the potentially negative consequences of connectivity (Keeley et al. 2022), such as fostering the spread of invasive species.

PAs often serve a dual role both as refuges for biodiversity conservation and also places for human enjoyment and other ecosystem services. Ensuring "more equitable access to nature and its benefits for all people in America—no matter their zip code" is an explicit goal of the ATB plan (Biden 2021), so that all residents can benefit from cleaner air, water, and the other benefits that nature provides. Although we did not explicitly analyze access to PAs, our results do permit some general observations. The county-level PA map (Figure 2D) shows that there are areas of the country, notably in the Midwest and Great Plains, that do not have any PAs. Future site prioritization work should consider benefits to both people and biodiversity, and determine whether both goals can be part of prioritizations. It is important to also meter these discussions with an understanding that parks and PAs will often attract development at their boundaries as people are drawn to the natural, scenic, cultural, or recreational amenities (Joppa, Loarie, and Pimm 2008; Radeloff et al. 2010; Vukomanovic et al. 2020). This development can jeopardize the effectiveness of PAs for biodiversity conservation (Gimmi et al. 2011). Building in buffers around ecologically sensitive areas or habitat for endangered and threatened species can help alleviate these pressures while safeguarding the range of ecosystem services provided by protected areas.

Conclusions

This is the first study to present connectedness results for PAs in the United States at multiple, policy-relevant scales where PA network design is being administered. We found that while the percentage of land that is protected and connected increases with decreasing levels of analysis, values at all scales are below the Aichi and Kunming-Montreal GBF targets and below global, country-level amounts. We found that these deficiencies are largely due to PA network design, and because network design is within the purview of counties, states, regional agencies, tribal governments, and local stakeholders, it is possible to ultimately increase PA connectedness in the United States. Increasing connectedness, however, will depend on cooperative spatial planning that spans administrative boundaries and integrates multiple levels of government and private stakeholders. The scale mismatches between ecological processes and administrative units along with the nested nature of administrative units will require better network governance, coordination, and interagency collaboration to ensure PA additions meet cross-scale ecosystems.

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Data Availability Statement

All data used in the analysis are publicly available through the U.S. Protected Areas Database (https://www.usgs.gov/programs/gap-analysis-project) and the World Database of Protected Areas (https://www.protectedplanet.net). Our code is available through an Open Science Framework Repository called "U.S. Protected Area Connectivity" (https://osf.io/sm9nr/). The county-level analyses also used code that is openly available on GitHub through connectscape.github.io/Makurhini/.

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