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Achieving conservation targets by jointly addressing climate change and biodiversity loss

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Abstract

Unprecedented rates of climate change and biodiversity loss have galvanized efforts to expand protected areas (PAs) globally. However, limited spatial overlap between the most important landscapes for mitigating climate change and those with the highest value for biodiversity may impede efforts to simultaneously address both issues through new protections. At the same time, there is a need to understand how lands with high conservation value align with existing patterns of land management, both public and private, which will inform strategies for developing new conservation areas. To address these challenges, we developed three composite indices to identify the highest conservation value lands across the conterminous United States (CONUS) and Alaska, drawing on a suite of key ecological and environmental indicators. Two indices characterize the most important conservation lands for addressing climate change (based on climate accessibility, climate stability, and total carbon storage) and biodiversity (based on species richness, ecological integrity, and ecological connectivity), while a third, combined index simultaneously addresses both conservation challenges. We found that existing PAs in the United States have relatively low overlap with the highest conservation value lands, regardless of the index used (10%–13% in CONUS, 27%–34% in Alaska), suggesting limited effectiveness of current protections but substantial opportunity for expanding conservation into high-value, unprotected areas. In unprotected landscapes, the highest value lands for addressing climate change generally diverged from those identified as most important for protecting biodiversity (22%–38% overlap, depending on index and geography). Our combined index reconciled these spatial trade-offs through high overlap with both the climate and biodiversity indices (66%–72%). Of the unprotected high conservation value lands identified by each of our three indices, we found ≥70% are privately managed in CONUS, while 16%–27% are privately managed in Alaska, underscoring the need to engage private landowners and land trusts in efforts to substantially increase the total footprint of conservation lands in the United States. Our findings highlight the importance of balancing climate and biodiversity objectives when identifying new lands for conservation and provide guidance on where to target new protections to simultaneously address both goals. To facilitate planning using the indices, we developed an interactive web application.

KEYWORDS
30 × 30, composite indices, connectivity, conservation planning, landscape ecology, protected areas

INTRODUCTION

Globally, climate change and unprecedented biodiversity loss constitute two of the most pressing challenges of the Anthropocene (IPBES, 2019; Ripple et al., 2021; Rockström et al., 2009). Strategies to address these two crises are often developed and implemented separately, despite growing awareness that they are deeply interconnected (Lade et al., 2020; Pörtner et al., 2021). Climate change itself is a significant threat to global biodiversity (Bellard et al., 2012; Warren et al., 2018), while protecting biodiversity and maintaining intact ecosystems can bolster carbon storage, climate stability, and system resilience to climate impacts (Anderegg et al., 2018; Chen et al., 2018; García-Palacios et al., 2018; Isbell et al., 2015; Pires et al., 2018). Resolving these major challenges of climate change and biodiversity loss will require coherent, integrated approaches to conservation that account for their interdependence (Arneth et al., 2020; Pettorelli et al., 2021).

In the United States and elsewhere, expanding the network of protected areas (PAs) is a key strategy for both mitigating climate change (Dinerstein et al., 2019) and slowing biodiversity loss (Noss et al., 2012). There have been increasing calls for new protection targets that expressly acknowledge these dual benefits, including the draft post-2020 Global Biodiversity Framework (CBD, 2021), the Half-Earth initiative (Wilson, 2016), and the Biden administration's recent commitment to protect 30% of U.S. lands by 2030 ("30 × 30"; Executive Order No. 14008, 2021). With approximately 12% of lands currently protected (Dreiss & Malcom, 2022), achieving the ambitious 30 × 30 target in the United States will require expanding current protections by approximately 177 million ha (i.e., 18% of the total U.S. land area of 984 million ha).

In the United States, meeting these PA targets in a manner that best addresses both biodiversity loss and climate change requires strategic prioritization at a national scale. This represents a departure from how PAs have historically been established—for example, opportunistically, based on scenic value, and in remote, low-cost landscapes unsuitable for other uses, such as agriculture (Joppa & Pfaff, 2009; Pressey et al., 1993; Venter et al., 2018). PAs have rarely been selected to strategically conserve biodiversity and maintain ecosystem functioning (Dickson et al., 2017; Watson et al., 2016). As a result, existing PAs within the United States are likely inadequate for stemming biodiversity loss (Belote et al., 2017; Jenkins et al., 2015). Indeed, the majority of vulnerable and endemic species are not well represented within PAs in the United States (Dietz et al., 2020; Jenkins et al., 2015).

The existing PA network may also be insufficient to meet the mounting challenges of climate change. Both within the United States and worldwide, PAs are experiencing heightened displacement of historic climatic conditions (Batllori et al., 2017; Elsen et al., 2020) as well as the emergence of novel conditions (Hoffmann et al., 2019; Wiens et al., 2011). The U.S. national park network, in particular, is facing disproportionately higher climate velocities than the United States as a whole (Gonzalez et al., 2018). Range shifts and the likely reshuffling of biotic communities (Chen et al., 2011; Williams & Jackson, 2007) further challenge the static geographic boundaries of PAs. These dynamics may ultimately undermine the efficacy of area-based targets (Dobrowski et al., 2021) unless the accessibility of climatic conditions, climatic refugia, and connectivity are expressly considered in expanding the PA network (Lawler et al., 2020; Stralberg et al., 2020).

Prioritizing which landscapes to protect given these pressing needs remains a considerable challenge due to the range of benefits that a given landscape may provide (e.g., carbon storage, wildlife habitat, and ecological connectivity), and the fact that these benefits do not always overlap in space (Di Marco et al., 2018; Soto-Navarro et al., 2020). In some contexts, this lack of overlap may force trade-offs between biodiversity and climate-related objectives. For instance, the spatial correlation between carbon storage and species richness can be limited at scales relevant to conservation planning (Di Marco et al., 2018), and protecting some imperiled species may be incompatible with maximizing carbon storage (Littlefield & D'Amato, 2022). These trade-offs may lead to poor allocation of resources in some contexts if prioritizing carbon storage is presumed to universally maximize biodiversity benefit (Beaudrot et al., 2016; Phelps et al., 2012; Seddon et al., 2020), though in other contexts (e.g., where there is strong concordance between biodiversity and carbon), "win–wins" may be achievable (Brandt et al., 2014; Law et al., 2021; Lecina-Diaz et al., 2018).

Given these potential trade-offs as well as the mismatch between existing PAs and conservation objectives, there is a growing need for spatially explicit indices of conservation value that address the combined challenges of climate change and biodiversity loss (Carroll & Ray, 2021; Soto-Navarro et al., 2020). More specifically, such measures should expressly integrate both climate change mitigation (e.g., via carbon storage in natural landscapes) and adaptation (e.g., by ensuring accessibility of climatic conditions) as well as both current patterns of biodiversity and the prerequisites to accommodate new patterns in the future (e.g., ecological connectivity). Importantly, measures of conservation value must span all ownerships, as meeting area-based targets will likely require increased formal protection of public lands as well as new conservation actions on private lands (e.g., via voluntary conservation easements or private reserves; Kamal et al., 2015). Indeed, the contributions of private lands to conservation objectives and their complementarity with protected public lands can be substantial (Chapman et al., 2021; Graves et al., 2019). In evaluating the potential for currently unprotected public and private lands to address climate change and stem biodiversity loss, the overall benefits of meeting ambitious conservation targets such as 30 × 30 may be maximized.

Here, we draw on a set of key climate change and biodiversity indicators and combine these indicators into three composite indices that quantify the conservation value of all lands across two distinct spatial extents: the conterminous United States (CONUS) and Alaska. Two indices focus on conservation values relevant to either climate change or biodiversity separately, while the third balances both sets of conservation objectives in a combined index. We use these indices to (1) assess how well currently protected landscapes align with high conservation value lands identified by each index; (2) quantify the spatial trade-offs between addressing climate change and biodiversity loss when prioritizing new conservation actions on currently unprotected lands; and (3) compare the relative contribution of public, private, and tribal lands to currently unprotected landscapes with high conservation value.

METHODS

We compiled a parsimonious set of six ecological and environmental indicators and combined them into three composite indices. Our climate index incorporates information on contemporary carbon storage as well as the expected change in local and regional climate conditions, thus capturing the potential for a given landscape to help mitigate the impacts of climate change (Fargione et al., 2018; Griscom et al., 2017) and to act as a refuge against dramatic fluctuations in temperature and precipitation (Belote et al., 2018; Hamann et al., 2015). Our biodiversity index incorporates species richness and threat status along with estimates of the ecological integrity of landscapes and their ability to support connectivity, thus emphasizing the conservation of both species themselves and the biophysical environments required to support them (Soto-Navarro et al., 2020). Finally, we develop a combined index incorporating all climate and biodiversity indicators to identify high-value landscapes that reconcile trade-offs between these two major conservation objectives. We derived indicators from the most recent and highest resolution spatial data available, with the goal of minimizing coverage gaps across CONUS and Alaska. All indicators were represented as rasters (Table 1).

Climate indicators

To estimate total carbon storage (above- and belowground biomass and soil organic carbon [SOC]), we used a global, 300-m resolution dataset of terrestrial carbon storage (circa 2010) developed by Noon et al. (2021; see also Goldstein et al., 2020). Biomass carbon values were derived from land cover-specific maps of aboveground biomass (from satellite imagery) and belowground biomass (from regression-based models of root-to-shoot ratios), harmonized across ecosystems (Spawn et al., 2020), and supplemented with other estimates for particular coastal systems. Similarly, SOC values to 30-cm depth for terrestrial systems were derived from the global SoilGrids 2.0 database (Poggio et al., 2021) and supplemented with other estimates (e.g., for mangroves; Sanderman et al., 2018). Note that the total carbon layer quantifies existing carbon stocks but does not explicitly capture the potential for ongoing sequestration, another important metric for achieving net-zero emissions goals.

Climate accessibility estimates the minimum distance an organism has to migrate to colonize future climate conditions that match its current climate habitat, with smaller distances representing greater accessibility. This indicator, therefore, captures how well a landscape may enable species to track suitable climatic conditions

TABLE 1 Description of indicators included in each of the three composite indices. See text for data sources.

Indicator	Description	Index: Climate	Biodiversity	Combined
Total carbon storage	Total amount of carbon stored in aboveground biomass, belowground biomass, and soil organic carbon. Total carbon storage provides an estimate of how well a given location may help mitigate climate change by keeping carbon out of the atmosphere.	X		X
Climate accessibility	Degree to which current climate conditions will be locally accessible in the future (by the year 2055). Areas of high climate accessibility will support species tracking suitable climatic conditions through both local and long-distance movements.	X		X
Climate stability	Similarity between present and future (2055) climate at a given location. Areas with relatively stable climatic conditions may serve as climatic refugia.	X		X
Species richness	Richness of vertebrate species (Alaska) or imperiled species (CONUS) using a given location. Areas of higher species richness may warrant higher degrees of protection, particularly in the face of stressors associated with climate change.		X	X
Ecological integrity	Degree to which a given location remains in its natural state without human influences (e.g., agriculture and development). Areas with high ecological integrity have a high capacity to support natural ecological and evolutionary processes, more so than areas heavily modified by human activity.		X	X
Ecological connectivity	A measure of the ability of a landscape to support the natural movement of organisms, to enable gene flow, and to provide linkages between areas of high-quality habitat and suitable climatic conditions.		X	X

Abbreviation: CONUS, conterminous United States.

through local and long-distance movements (Littlefield et al., 2019). We derived climate accessibility as the opposite of climate velocity (i.e., $-1 \times$ climate velocity), where climate velocity is a measure of the instantaneous velocity of climate change at a location on the landscape (Carroll et al., 2015). The climate velocity metric used here was originally developed by Hamann et al. (2015). This metric integrates 11 climate variables via principal components analysis (PCA) and calculates velocity based on the distance between sites with matching present (averaged from 1981 to 2010) and future climate conditions (averaged from 2041 to 2070). Here, we use a 1-km resolution backward climate velocity layer based on the RCP8.5 emissions scenario.

We defined climate stability as the similarity between present and future climate (same date ranges as above) at a given location, thus quantifying the potential for a location to provide a refuge against substantial departures from current climatic conditions or act as a stepping stone as ranges shift in response to climate change (Ackerly et al., 2010). We derived our estimate of climate stability as the opposite of climate dissimilarity (i.e., $-1 \times$ climate dissimilarity), where climate dissimilarity conveys how different the future climate at a given location will be from its present climate conditions (Mahony et al., 2017; Williams et al., 2007). Specifically, we took the inverse of the climatic dissimilarity map (1-km resolution) developed by Carroll et al. (2018) (see also Belote et al., 2018; Hamann et al., 2015), which is based on 11 climate variables under the RCP8.5 emission scenario integrated via PCA. Climate stability and climate accessibility capture complementary aspects of landscape resilience to climate change (see Appendix S3: Figures S1 and S2), with stability depending on the amount of change at a given location and accessibility being a function of how far organisms will have to move to keep up with changing climates. For instance, a given location may experience substantial local change in climate between present day and mid-century (i.e., low climate stability), but if that location's climate habitat at mid-century matches the present-day climate habitat of nearby locations, climate accessibility may be high.

Biodiversity indicators

Species richness is a core component of most definitions of biodiversity (DeLong, 1996; Soto-Navarro et al., 2020). Although there are limitations to using richness as a standalone metric to prioritize sites for conservation (e.g., prioritizing richness does not necessarily maximize species representation across sites; Astudillo-Scalia & Albuquerque, 2020), when combined with other indicators that capture the ecological integrity and resilience of landscapes, species richness provides a valuable metric for quantifying the contributions of a site to overall biodiversity and ecosystem functioning (Astudillo-Scalia & Albuquerque, 2020; Fleishman et al., 2006). Because of differences in data availability between CONUS and Alaska, we used two estimates of species richness. For CONUS, we used a modeled layer of imperiled species richness (Hamilton et al., 2022; NatureServe, 2020), which integrates habitat suitability maps for 2216 of the nation's most imperiled species, including vertebrates (birds, mammals, amphibians, reptiles, freshwater fishes; 309 species), freshwater invertebrates (228 species), pollinators (43 species), and vascular plants (1636 species). The 990-m resolution layer includes species designated by NatureServe as imperiled or critically imperiled as well as species listed as threatened or endangered under the Endangered Species Act. Because this data layer is currently available only for CONUS, we estimated vertebrate species richness separately for Alaska based on 500-m resolution species range data from the USGS Gap Analysis Project (GAP; Gotthardt et al., 2014). We calculated species richness by overlaying GAP range maps for 330 terrestrial vertebrate species in Alaska, including birds (255 species), mammals (72 species), and amphibians (3 species), following Soto-Navarro et al. (2020).

Ecological integrity describes the degree to which a given location remains in a natural state (i.e., unmodified by human land use; Plumptre et al., 2021). Areas with high ecological integrity are minimally influenced by human activities and have a high capacity to support natural evolutionary and ecological processes (Angermeier & Karr, 1996; Parrish et al., 2003). We calculated ecological integrity as $1 - L$, where L is the intensity of human land use at a given location. We derived estimates of land use intensity separately for CONUS (circa 2017) and Alaska (circa 2014) based on the procedure originally described by Theobald (2010, 2013) and following the methods described in CSP (2019). Briefly, we compiled spatial data layers on several categories of human disturbance, including urban, transportation, energy, and agricultural impacts, and assigned each a value between 0 and 1, depending on the intensity and extent of human land use represented by a given disturbance type. We then combined these categories of human disturbance into a single L layer describing the intensity of human land use at each pixel across the landscape. Details of the datasets and procedures used to develop the L layers are given in Appendix S1. Given differences in the availability of data, ecological integrity was calculated at a 90-m resolution for CONUS and at a 270-m resolution for Alaska.

Ecological connectivity describes the ability of a landscape to support the natural movement of organisms (e.g., through dispersal or migration), to enable gene flow, and to provide linkages between areas of high-quality habitat (Crooks & Sanjayan, 2006; Dickson et al., 2019). Connectivity is also key to supporting adaptation to climate change by allowing species to track favorable climate conditions (Heller & Zavaleta, 2009; Littlefield et al., 2019). To map ecological connectivity across CONUS and Alaska, we applied a circuit theory-based approach (Dickson et al., 2019; McRae et al., 2008) using Omniscape software (Landau et al., 2021) to implement omnidirectional connectivity models for each geographic extent at a 1-km resolution and using a moving window radius of 100 km (McRae et al., 2016). Following Dickson et al. (2017), we derived resistance surfaces for the connectivity models by rescaling our human land use intensity (L) layers for CONUS and Alaska (described above) and incorporating a modest penalty for steep slopes, which may present barriers to movement for many terrestrial organisms. We parameterized source strength (i.e., the likelihood that animal movement may originate from a given location) as proportional to the number of mammal species estimated to occur in a given location. We focused on mammals here (rather than, say, birds) as a representative group of terrestrial species spanning a large range of body sizes whose movement can reasonably be assumed to depend on human land use intensity and topography (factors that may be less critical in driving movement decisions by volant species). We estimated mammal richness by overlaying mammal species range maps and generated richness layers separately for CONUS and Alaska due to differences in data availability and quality. For CONUS, we compiled International Union for Conservation of Nature (IUCN) range maps for mammals (408 species) and restricted these ranges based on recently published maps of IUCN habitat, following the methods by Jung et al. (2020). We produced richness maps for CONUS at 2-km resolution, as recommended for IUCN range data (KBA, 2019). For Alaska, we used the 500-m resolution GAP mammal species range data described above.

Derivation of composite indices

As noted above, we developed three composite indices using combinations of the climate and biodiversity indicators just described, with each index addressing a unique set of conservation values. The "climate index" combines the three climate indicators (total carbon storage, climate accessibility, and climate stability), the "biodiversity index" combines the three biodiversity indicators (species richness, ecological integrity, and ecological connectivity), and the "combined index" incorporates all six indicators to provide a comprehensive assessment of conservation value across CONUS and Alaska. Because several indicators were derived separately for CONUS and Alaska (due to differences in dataset availability between these two geographic regions; see above), we calculated each of the three indices separately for CONUS and Alaska, yielding six different models. The process for deriving each of these models was identical, but the underlying set of indicators differed in each case.

To place all indicators on the same scale, we first standardized each indicator by converting to *z*-scores (i.e., mean centering and dividing by one standard deviation) and then resampled all indicators to 90-m resolution (i.e., that of the highest resolution indicator) in Google Earth Engine (GEE; Gorelick et al., 2017), using GEE's default nearest neighbor algorithm. We then derived each composite index (in GEE) as the weighted linear sum of indicator variables, such that

$$y_i = \sum_{j=1}^{J} x_{ij} w_j,$$

where y_i is the value of the index at location i, x_{ij} is the (standardized) value of indicator j at location i, and w_j is the weight applied to indicator j (Malczewski, 2000).

Lacking any a priori justification for elevating the influence of one indicator over another, we treated all indicators as equally influential in determining the resulting index value. Intuitively, it may seem that giving all indicators equal weight (w_j) would lead to indicators having equal influence on the values of the composite index. However, this has been shown not to be the case when indicators are correlated with each other, as many environmental variables are (Becker et al., 2017; Paruolo et al., 2013). The application of equal weights can lead to a nonintuitive outcome in which certain indicators are more strongly correlated with the resulting index values than are other indicators. We therefore strove to equalize indicator influence itself, which we define as the degree to which a single indicator can explain observed variation in the composite index (calculated as the Pearson correlation ratio between values of a single indicator and values of the composite index; see Appendix S2). In our view, ensuring equal influence across indicators allows for an intuitive interpretation of the relationship between each indicator and the composite index, that is, one in which each indicator plays an equal role in determining that model's outcome. We adapted a method developed by Becker et al. (2017) using an optimization routine to determine the set of weights (w_j) that lead to equal influence across all indicators. This approach is described in detail in Appendix S2 and was applied separately for each index. Appendix S2: Table S1 illustrates the utility of this approach by comparing the influence values for each indicator when using optimized weights to those derived when using equal weights (i.e., all weights set to 1).

Assessing PA effectiveness and conservation opportunities

As a simple measure of their potential effectiveness, we examined the degree to which existing PAs overlap with the highest conservation value lands identified by each of our three indices. We first calculated the top quartile (25th percentile) value for each of the three indices (composite, climate, and biodiversity) and created new layers consisting of only those pixels within the top quartile for each index (hereafter "high-value lands"). We then delineated existing PAs based on the U.S. Geological Survey's Protected Areas Database of the United States (PAD-US, v2.1; USGS, 2020) and calculated the proportion of high-value lands for each index occurring within existing PAs. We considered all lands in PAD-US categorized as GAP 1 or GAP 2 to be protected, including both public lands (i.e., federal, state, and local PAs) and private lands with voluntary conservation easements (as compiled by the National Conservation Easements Database and integrated into PAD-US 2.1). GAP 1 and 2 lands are both permanently protected from conversion, allowing only natural disturbances (GAP 1) or some management interventions (e.g., wildfire suppression; GAP 2) (USGS, 2020). It is important to note that, under this definition, not all public lands are considered protected. For instance, we considered designated wilderness areas within National Forests to be protected (based on GAP status), whereas other National Forest lands without such special designation were considered unprotected, given that they are potentially subject to resource extraction. Conversely, not all "unprotected lands" (i.e., lands not classified as GAP 1 or 2) are necessarily at risk of conversion or of decreased conservation value. Indeed, important conservation work occurs outside of formal PAs, notably on tribal lands where Indigenous communities have made substantial contributions to climate and biodiversity through land stewardship (Ricketts et al., 2010; Schmidt & Peterson, 2009; Schuster et al., 2019). Thus, our classification of a landscape as protected or not solely reflects the GAP status applied in PAD-US.

To compare the spatial footprint of potential conservation opportunities identified by each of our three composite indices, we started with the high-value lands described above (i.e., only pixels in the top 25% of values for each index) and removed the subset of pixels overlapping with existing GAP 1 and 2 PAs to produce a "high-value unprotected land" layer for each index. We then summarized the amount of high-value unprotected lands falling into each of four land management categories. "Federal lands" were those categorized in PAD-US as either federally managed or jointly managed by the U.S. government and a local government entity. "Other public lands" were those categorized in PAD-US as managed at the state, local, or district level. "Tribal lands" were identified using the U.S. Census Bureau's American Indian/Alaska Native/Native Hawaiian (AIANNH) Areas Shapefile for 2019 (U.S. Census Bureau, 2019). We classified all polygons in this dataset as tribal lands, but acknowledged that tribal ownership and management of lands in the United States is complex and that this coarse definition of tribal lands overlooks important distinctions in land use and management by tribes while likely excluding many areas (e.g., on federal or state lands) currently used and managed by tribal communities. However, it was beyond the scope of this study to compare conservation values on multiple types/categories of tribally managed lands. We considered all other locations across CONUS and Alaska not included in the above three categories to be "privately managed lands." We did not distinguish between private land uses, and thus the "privately managed lands" category includes landscapes across a spectrum, from open spaces to industrial uses. We calculated the total area of high-value unprotected lands identified by each index falling within each land management category and summarized these values as a proportion of (1) all high-value unprotected lands identified by a given index and (2) total unprotected land area in a given management category.

We performed all analyses separately for CONUS and Alaska given differences between these two focal geographies in the underlying indicator layers used to derive the composite indices (see above). Analyses were conducted in GEE and Python using the earthengine-api Python package (v0.1.246). Figures were produced in R (R Core Team, 2021) using the ggplot2 package (Wickham, 2016). Data layers for all six environmental indicators and three composite indices are available to view at https://csp-inc.github.io/ClimateAtlas/.

RESULTS

At the broadest scales, our three indices tended to highlight similar regions across CONUS and Alaska as being of high conservation value (Figures 1 and 2), though considerable areas of mismatch between our climate and biodiversity indices were evident, particularly when considering specific landscapes to prioritize for conservation (Figure 3). In CONUS, high-value lands were identified by all three indices in the Pacific coastal ranges, the mountains of Arizona and New Mexico, the Ozark and Ouachita Mountains, and the Appalachian region (Figure 1). Our climate index additionally identified high-value lands in the Pacific Northwest, southern Texas, and the Southeastern plains, largely driven by high climate stability in these three regions and high carbon storage in the Pacific Northwest (Figure 1b; Appendix S3: Figure S1). Conservation value of landscapes in southern California, southern Utah, and the forests of the upper Midwest was largely driven by their importance for biodiversity, exhibiting high richness of imperiled species and/or high ecological connectivity (Figure 1c; Appendix S3: Figure S1).

In Alaska (Figure 2), all three indices identified high conservation value lands in the Copper River watershed and the Alaska Range. The climate index highlighted the importance of Southeastern Alaska (the Alexander Archipelago and neighboring mainland areas) in mitigating and adapting to climate change through high carbon storage and climate stability, as well as the Arctic Foothills, with relatively high total carbon and high climate accessibility (Figure 2b; Appendix S3: Figure S2). Alaska's interior lowland forests (north of the Alaska Range) scored highly on the biodiversity index, driven by high vertebrate species richness and ecological connectivity (Figure 2c; Appendix S3: Figure S2). Major Alaskan highways, particularly those running north–south between Anchorage, Fairbanks, and Prudhoe Bay, were noticeably discernible in the biodiversity and combined indices (Figure 2a,c). This was driven by the influence of highways on the ecological integrity and ecological connectivity indicators and highlights the relatively low impact of human modification throughout the rest of the state (Appendix S3: Figure S2b,d).

Approximately 8.3% of the total land area of CONUS (64.5 million ha) currently falls within GAP 1 or 2 PAs, with these PAs capturing between 11% and 13% of high-value lands (i.e., lands in the top quartile of index values) identified by each of the three indices (Table 2). In Alaska, PAs cover approximately 39.6% of the land area (60.1 million ha) and provide greater coverage of high-value lands identified by each index (between 27% and 34%) (Table 2).

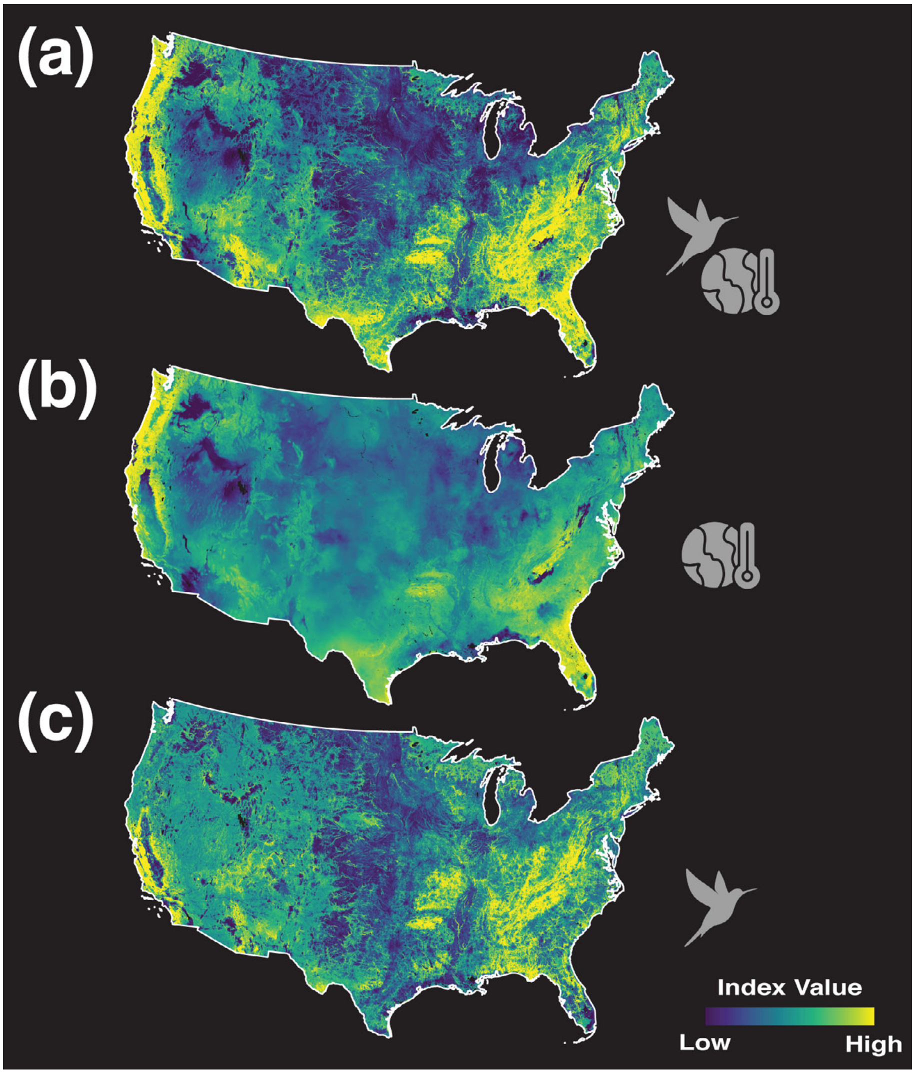

FIGURE 1 Maps of composite indices of conservation value for the conterminous United States (CONUS), showing the (a) combined index, (b) climate index, and (c) biodiversity index.

Focusing on high-value unprotected lands identified by each index, we found relatively limited overlap at the local (i.e., pixel) level between areas identified as high-value by the climate and biodiversity indices in CONUS (Appendix S3: Figure S3), highlighting the trade-offs between these two sets of conservation objectives when identifying specific landscapes for increased protection. Approximately 37.9% of high-value unprotected lands identified by the climate index were also identified by the biodiversity index, while 37.6% of high-value unprotected lands for biodiversity were also identified by the climate index. By design, the CONUS combined index largely reconciled this trade-off between conservation objectives, with 71.7% and 66.9% of high-value unprotected lands identified by the climate and biodiversity indices, respectively, overlapping with those identified by the combined index. These patterns were evident in regions of otherwise high correspondence between the climate and biodiversity indices, such as the Ozark and Ouachita Mountains (Figure 3a,b) and Appalachia (Figure 3c,d). Substantial proportions of unprotected land in each region were identified as high value by one of the two indices but not both, while the combined index largely captured all high-value unprotected lands identified by the other two indices. Overlap between high-value unprotected lands identified by the climate and biodiversity indices was even lower in Alaska (Appendix S3: Figure S3): 23.7% of high-value unprotected lands identified by the climate index were also identified by the biodiversity index, and 22.1% of high-value unprotected lands for biodiversity were identified by the climate index. Again, the combined index for Alaska resulted in substantially higher overlap, by design, with top unprotected areas identified by the combined index overlapping with 67.7% of high-value unprotected lands identified by the climate index and 66.3% identified

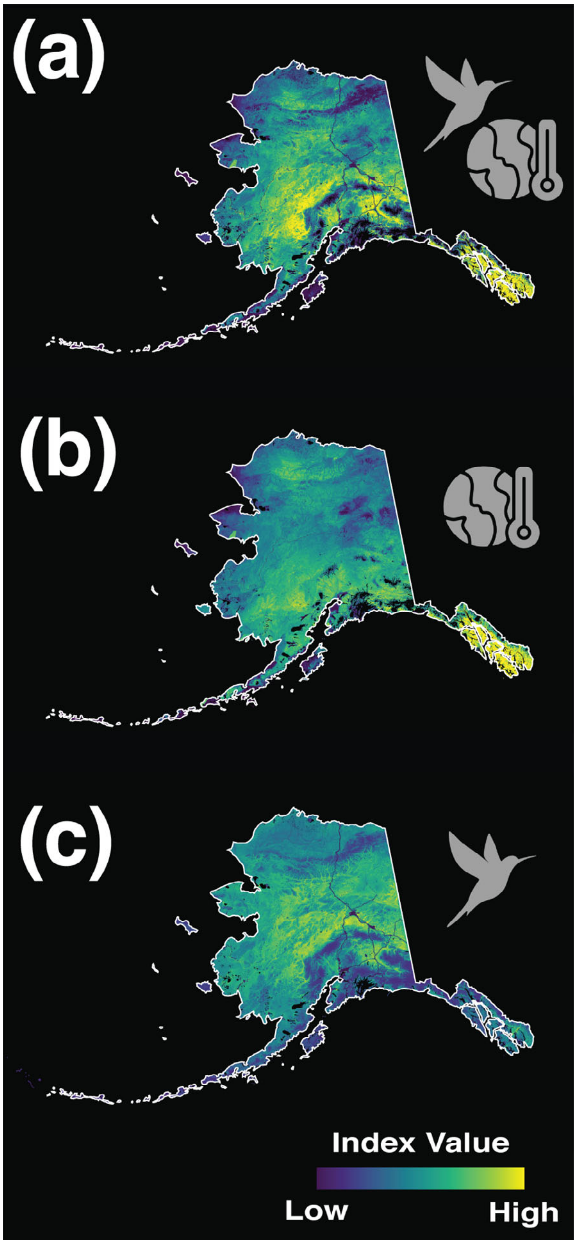

FIGURE 2 Maps of composite indices of conservation value for Alaska, showing the (a) combined index, (b) climate index, and (c) biodiversity index.

by the biodiversity index. These patterns were evident in the Alaska Range (Figure 3e,f), where the combined index captured the most high-value unprotected lands identified both jointly and separately by the climate and biodiversity indices.

We quantified the contribution of each land management category to supporting high-value unprotected lands in two ways. We first estimated the proportion of total high-value unprotected lands identified by each index that fell within a given land management category, an estimate that inherently reflects the total land area under each management type. In CONUS, 72.7% of unprotected landscapes (i.e., those falling outside of GAP 1 or 2 PAs) are privately managed (Table 3), and thus the majority of high-value unprotected lands identified by each of the three indices also fell on private land (>70% for each index). Federal lands accounted for the next largest proportion of unprotected top pixels for each index in CONUS, followed by other public lands and tribal lands (Table 3). In Alaska, the largest proportion of unprotected top pixels for each index fell on lands categorized as other public lands (consisting largely of state-managed lands), followed by federal lands, private lands, and tribal lands (Table 3). We next considered the proportion of unprotected lands in each land management category that was identified as high value by each index (Figure 4), providing an estimate of the importance of each land management category to conservation that was corrected for total land area in that category. We found that other public lands tended to have relatively high proportions (27.3%–41.6%) of high-value unprotected lands across indices and geographic extents. Tribal lands in Alaska (Figure 4b) also contained high proportions of high-value lands, particularly as identified by the combined (29.1%) and climate (45.5%) indices.

DISCUSSION

Addressing climate change and limiting further biodiversity loss are two of the most important conservation challenges facing humanity today (Pörtner et al., 2021; Ripple et al., 2021) and should be key priorities in systematically determining future targets for land conservation and formal protection. We developed composite indices to identify the highest conservation value lands across CONUS and Alaska for addressing climate change and biodiversity separately, revealing considerable correspondence between indices at large scales (i.e., regions of the United States containing high-value landscapes) but substantial mismatch at the more local scales relevant to conservation planning (Figure 3). We also developed a combined index that simultaneously addresses climate impacts and biodiversity loss, allowing us to identify places that are predicted to experience relatively small departures in climatic conditions between now and mid-century (Williams et al., 2007) and that may therefore support adaptation to climate change by facilitating species movement and range shifts (Littlefield et al., 2019). Our combined index answers calls to explicitly consider climatic conditions, climate refugia, and connectivity when prioritizing landscapes for new conservation actions (Lawler et al., 2020; Stralberg et al., 2020), identifying places with the potential to provide long-term, stable conservation value.

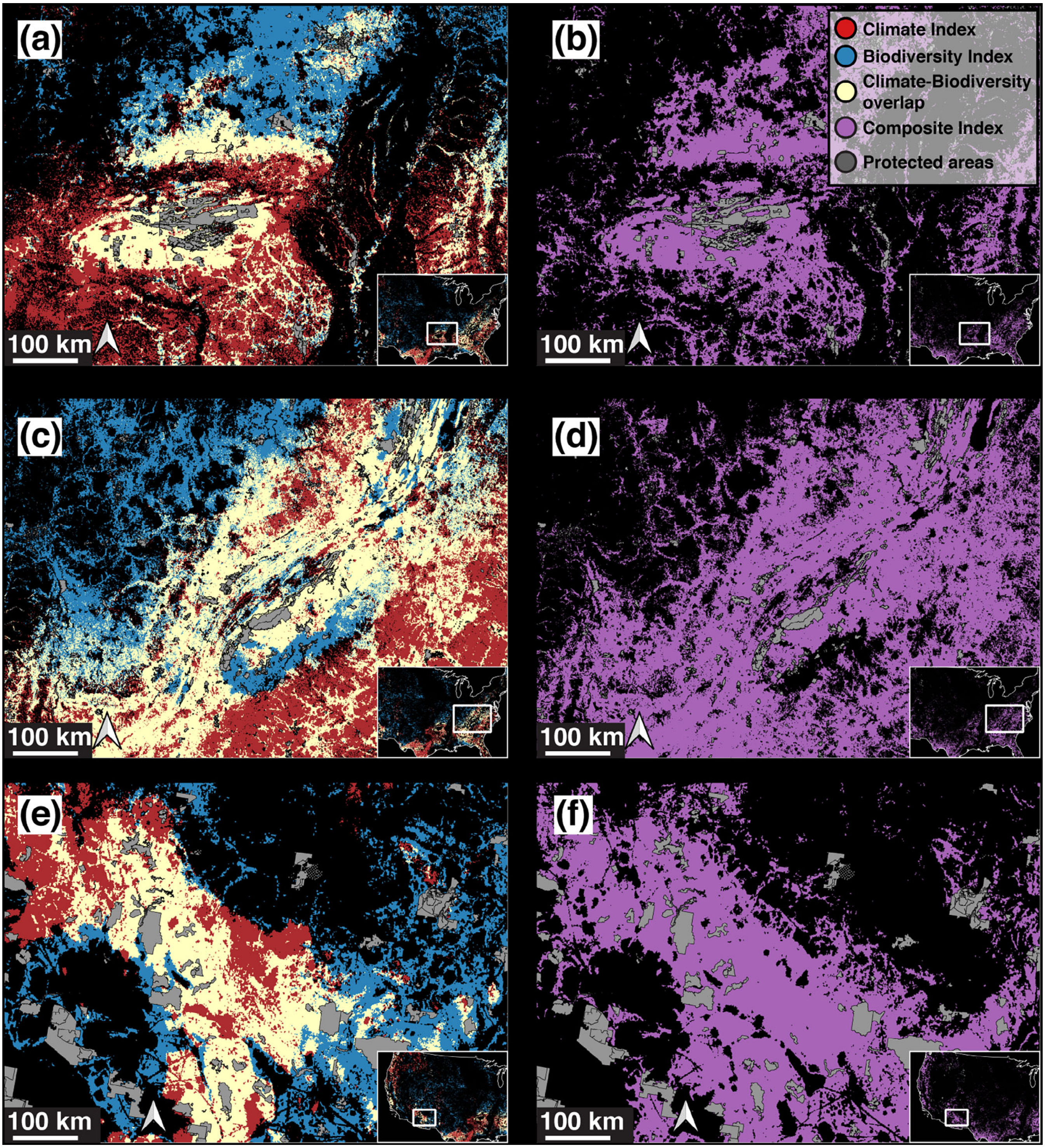

FIGURE 3 Overlap between high-value lands (i.e., those with pixel values in the top quartile) identified by each index. Each map highlights a region of the United States with substantial amounts of high conservation value lands in the conterminous United States (a–d) and Alaska (e, f). (a, c, e) High-value lands identified by the climate (red) and biodiversity (blue) indices, as well as lands identified as high value by both indices (yellow). (b, d, f) High-value lands identified by the composite index (purple), corresponding to the same regions shown in (a, c, e). Existing protected areas are shown as gray polygons.

Balancing climate change mitigation and biodiversity conservation remains a challenge given spatial trade-offs between these two objectives (Soto-Navarro et al., 2020). While focusing conservation efforts on carbon-dense forests, for instance, will ostensibly achieve both goals by protecting the carbon and ecological communities that

TABLE 2 Protected lands and their overlap with high conservation value areas in the conterminous United States (CONUS) and Alaska.

	All lands		High-value lands: Combined index		High-value lands: Climate index		High-value lands: Biodiversity index	
Region	Area protected	% total area	Area protected	% total area	Area protected	% total area	Area protected	% total area
CONUS	64.5	8.3	23.0	11.7	20.8	10.3	25.0	13.2
Alaska	60.1	39.6	11.6	27.6	11.9	32.0	13.3	33.8

Note: The "All lands" columns present the area of protected lands in CONUS and Alaska in millions of hectares (million ha) and as a proportion of the total land area in the corresponding region. The "high-value lands" columns present the area (in million ha) and percentage of high-value lands (i.e., pixels in the top quartile of each index) falling within existing protected areas.

TABLE 3 Area and percentage of unprotected lands in the conterminous United States (CONUS) and Alaska by management category (see text for management category definitions).

	All unprotected lands		High-value unprotected lands: Combined index		High-value unprotected lands: Climate index		High-value unprotected lands: Biodiversity index	
Management	Area	% total	Area	% total	Area	% total	Area	% total
CONUS								
Private	519.5	72.7	124.6	71.9	132.7	73.5	116.0	70.2
Federal	117.5	16.5	29.8	17.2	30.9	17.1	30.0	18.2
Other public	33.0	4.6	10.6	6.1	9.0	5.0	10.6	6.4
Tribal	44.2	6.2	8.4	4.8	7.8	4.3	8.6	5.2
Alaska								
Private	24.7	26.5	6.3	20.7	4.0	15.9	7.0	26.6
Federal	31.1	33.3	9.1	30.2	7.9	31.4	7.7	29.3
Other public	32.0	34.3	13.3	43.8	10.8	42.8	10.8	41.2
Tribal	5.5	5.9	1.6	5.2	2.5	10.0	0.7	2.8

Note: The "All unprotected lands" columns show the amount of unprotected land (i.e., not categorized as GAP 1 or 2) falling into each management category, expressed as area (in millions of hectares) and percentage of total unprotected land area. For instance, there is 519.5 million ha of unprotected private land in CONUS, which constitutes 72.7% of all unprotected land in CONUS. The "High-value unprotected lands" columns show the area (in millions of hectares) and percentage of high-value unprotected lands (i.e., currently unprotected pixels falling in the top quartile of each index) in each management category. For instance, 124.6 million ha of high-value unprotected lands identified by the combined index occur on private land in CONUS, which constitutes 71.9% of all high-value unprotected lands in CONUS identified by the combined index.

those forests contain (Strassburg et al., 2010), several studies have highlighted the often weak spatial correlation between carbon and biodiversity, suggesting that, in many cases, co-benefits may be limited (Anderson et al., 2009; Beaudrot et al., 2016; Di Marco et al., 2018; Paoli et al., 2010) (but see Brandt et al., 2014). This correlation can be highly scale dependent (Di Marco et al., 2018), ranging from a relatively strong positive association between carbon and biodiversity at large spatial scales to progressively weaker, and in some cases negative, correlations at smaller scales. Our analysis—which addressed changes in climatic conditions in addition to carbon storage—found similar patterns, with the correspondence between climate and biodiversity benefits being evident at large regional scales but less apparent at the local scales relevant to conservation planning. As noted above, some regions of the United States were identified as high-value by both the climate and biodiversity indices (Figures 1 and 2), particularly mountainous regions with substantial forest cover (e.g., Pacific coastal ranges, Appalachia, and the Alaska Range), which tended to have relatively high climate accessibility and high ecological integrity (Appendix S3: Figures S1 and S2). However, when considering individual locations (i.e., pixels), we found relatively limited correspondence between the high-value unprotected lands identified by these two indices (Figure 3). This is particularly true in Alaska, where the overlap between climate and biodiversity indices was less than 24%. Thus, while

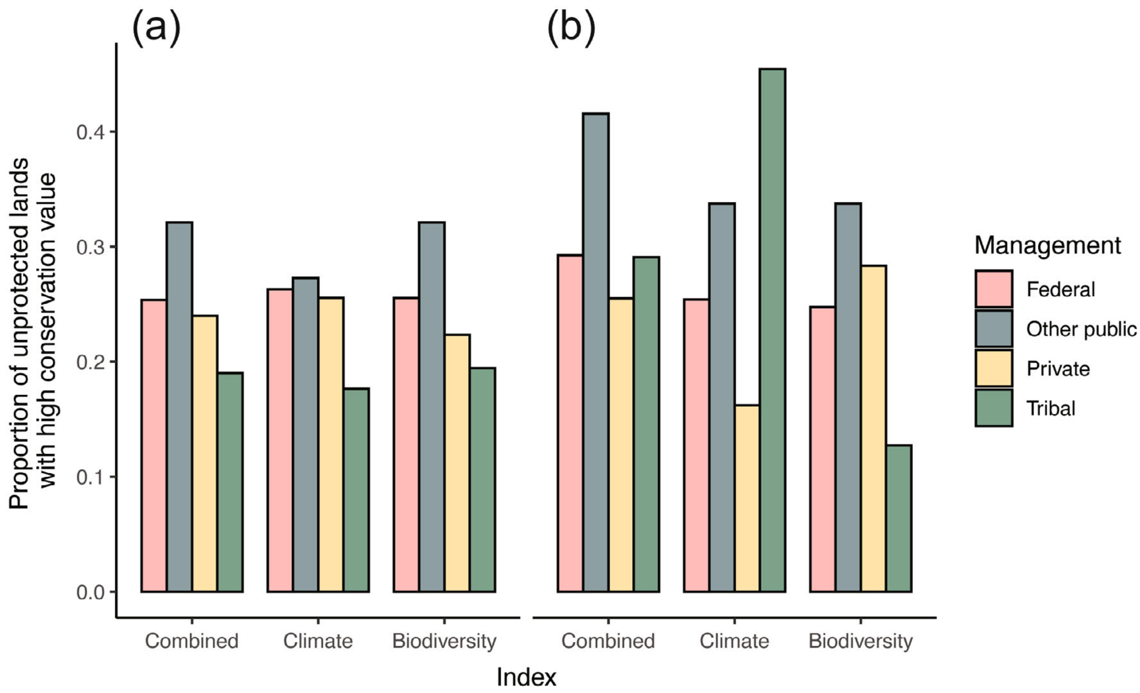

FIGURE 4 Proportion of unprotected lands within each land management category that were classified as high conservation value (i.e., pixel values falling in the top quartile for each index) for both (a) the conterminous United States and (b) Alaska.

these two indices can be used to inform conservation planning that prioritizes either climate change or biodiversity, our analysis of overlap between indices suggests we cannot assume that decision-making based on one set of objectives will address both conservation challenges (Beaudrot et al., 2016). Our composite indices largely reconciled these spatial trade-offs between climate and biodiversity objectives, identifying high-value unprotected lands that overlapped by 66.3%–71.7% (depending on the index and geographic extent) with those identified by the climate and biodiversity indices.

In CONUS, less than 15% of the high-value lands identified by each index were currently protected (34% or less in Alaska; Table 2). Our findings are thus consistent with previous assessments, which suggest that current PAs have limited effectiveness in protecting the most important areas for conservation, both in the United States (Belote et al., 2017; DellaSala et al., 2001; Dietz et al., 2020; Jenkins et al., 2015) and globally (Buchanan et al., 2020; Maxwell et al., 2020). However, our analysis of currently unprotected lands in the United States suggests considerable opportunity for new conservation actions to target high-value landscapes, particularly on privately managed lands. We found that, across all three indices, >70% of high-value unprotected lands in CONUS occurred on privately managed lands, which make up the large majority of currently unprotected landscapes in CONUS (Table 3). Per unit area, other land management categories tended to have greater amounts of high-value unprotected land (Figure 4). However, the fact that, in absolute terms, the large majority of unprotected high-value lands in CONUS are privately managed highlights the critical importance of private lands conservation in reaching area-based conservation targets (Chapman et al., 2021). The percentage of high-value unprotected lands under private management was lower in Alaska—approximately 16%–27%, depending on the index—where a large proportion of the land area is managed by the state and federal governments (Table 3). The "other public lands" category (i.e., lands managed at the state or local level) also stood out as important targets for conservation in both CONUS and Alaska, with relatively high proportions of unprotected other public lands being identified as high value by each index (Figure 4). These findings highlight the importance of engaging private landowners and state and local governments in federally led efforts to dramatically expand the total footprint of protections in the United States (e.g., the Biden administration's 30 × 30 initiative). This will be particularly critical in regions of the country (e.g., the Northeast) with little federal land and where small, private parcels predominate (Loeb & D'Amato, 2020). It is important to note, however, that federally managed lands still have a crucial role to play in reaching area-based conservation targets in the United States, particularly in western states where a substantial proportion of land area is managed by the U.S. Forest Service (USFS) and the Bureau of Land Management (BLM). Currently, unprotected federal lands account for almost 150 million ha across CONUS and Alaska (Table 3), and in some cases, the preservation of large tracts of federal land through a single act of congress or executive order (e.g., wilderness or national monument designations) may provide a more efficient pathway toward the conservation of large contiguous landscapes than the piecemeal establishment of conservation easements on multiple private land holdings.

The federal government has recently articulated a commitment to engage with Tribal Nations in advancing conservation efforts in the United States (Department of Interior, 2021). Our analysis suggests that supporting Indigenous-led land management will be critical to comprehensive and long-term conservation of some of the most important landscapes, particularly in Alaska, where large proportions of tribal lands were identified as having high conservation value (Figure 4). Tribal lands additionally contain millions of hectares of high-value lands in CONUS (Table 3), reflecting the crucial contributions that Indigenous communities have made to addressing climate change and to conserving biodiversity (Ricketts et al., 2010; Schmidt & Peterson, 2009; Schuster et al., 2019). This finding emphasizes the importance of federal engagement with Tribal Nations to provide communities with the resources necessary to continue their land stewardship work (Fletcher et al., 2021).

It is worth noting that, as with any model-based index, the results of our composite indices depended on the exact indicators used and the relative weights they were assigned. We have endeavored to (1) choose a comprehensive set of indicators that reflects both biodiversity and climate-related conservation objectives, and (2) ensure that all indicators had equal influence in determining the value of the resulting indices. It was beyond the scope of this work to examine model sensitivity to a range of different indicator weighting schemes (i.e., treating some indicators as more influential than others). However, we acknowledge that the decision to equalize influence across indicators may not reflect the goals and values of all users and note that a low score on our composite indices does not necessarily imply that a landscape is unimportant for conservation. For instance, combined index values were relatively low in the coastal plain of Alaska due to low values of climate stability and species richness (as compared to central or southeastern Alaska), despite this region's critical importance for mitigating climate change (through limits on oil and gas development) and protecting critical habitat for particular threatened species (e.g., polar bears; Durner et al., 2006). We also acknowledge that there is inherent uncertainty in our model estimates derived from measurement error and spatial resolution of the underlying indicator datasets that we are unable to directly address given the deterministic nature of our composite index modeling approach. The models developed here focus specifically on the ecological and environmental values of landscapes and do not explicitly incorporate the many social dimensions that are critical to consider in developing new protections, for example, cultural and spiritual values of landscapes or accessibility of PAs by communities traditionally excluded from natural spaces (Verschuuren et al., 2018; Weber & Sultana, 2013). Finally, it is important to note that, due to differences in indicator datasets available for CONUS and Alaska, these two domains were treated separately when identifying high-value lands (i.e., lands in the top quartile for a given index). The development of U.S.-wide datasets (e.g., for connectivity and species richness) that would allow the simultaneous prioritization of landscapes across the entire United States is an important next step for achieving large-scale conservation goals.

By identifying high-value landscapes across CONUS and Alaska, our analysis provides a critical starting point for efforts to substantially increase the footprint of protected lands across the United States while simultaneously addressing climate change and biodiversity loss, as outlined in the Biden administration's 30 × 30 commitment (Executive Order No. 14008, 2021) and "America the Beautiful" initiative (DOI, 2021). The results presented above—along with the interactive web-based tool we developed to allow users to explore our indices, data layers, and current management regimes (https://csp-inc.github.io/ClimateAtlas/)—can be used to prioritize the siting of new protections within contiguous areas of high conservation value across a range of management types. For instance, we identified 125 million ha of high-value unprotected lands under private management, providing valuable targets for local or regional land trusts and/or USDA Farm Bill programs (e.g., the Agricultural Conservation Easements Program and the Conservation Reserve Program). Substantial conservation opportunities also exist on federal lands, which constitute 86% of lands currently classified as GAP 3 (Dreiss & Malcom, 2022) and contain 30 million ha of high-value, unprotected lands. Our web-based tool identifies the tracts of unprotected BLM and USFS lands with the highest conservation value, thus facilitating siting of new PAs, such as wilderness areas, national monuments, or Areas of Critical Environmental Concern. Additionally, our indices can be used to identify key areas where the federal government can partner with tribal, state, and local governments to increase conservation on lands with the greatest potential to protect biodiversity and facilitate climate change mitigation and adaptation. We anticipate that our composite indices will be useful in guiding conservation decisions across multiple scales, from local protections to nationwide planning efforts, and hope that these results can serve as a starting point for inclusive discussions on ways to increase conservation investments across the United States.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data required to replicate the analyses are either publicly available (with sources provided in the *Methods* section) or are available from Figshare (Suraci, 2023): https://doi.org/10.6084/m9.figshare.22197592.v1.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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