Targeting current species ranges and carbon stocks fails to conserve biodiversity in a changing climate: opportunities to support climate adaptation under 30 $\times$ 30

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Keywords: climate refugia, climate corridors, protected areas, biodiversity conservation, carbon mitigation

Supplementary material for this article is available online

Abstract
Protecting areas for climate adaptation will be essential to ensuring greater opportunity for species conservation well into the future. However, many proposals for protected areas expansion focus on our understanding of current spatial patterns, which may be ineffective surrogates for future needs. A science-driven call to address the biodiversity and climate crises by conserving at least 30% of lands and waters by 2030, 30 $\times$ 30, presents new opportunities to inform the siting of new protections globally and in the US. Here we identify climate refugia and corridors based on a weighted combination of currently available models; compare them to current biodiversity hotspots and carbon-rich areas to understand how 30 $\times$ 30 protections siting may be biased by data omission; and compare identified refugia and corridors to the protected areas database to assess current levels of protection. Available data indicate that 20.5% and 27.5% of identified climate adaptation areas (refugia and/or corridor) coincides with current imperiled species hotspots and carbon-rich areas, respectively. With only 12.5% of climate refugia and corridors protected, a continued focus on current spatial patterns in species and carbon richness will not inherently conserve places critical for climate adaptation. However, there is ample opportunity for establishing future-minded protections: 52% of the contiguous US falls into the top quartile of values for at least one class of climate refugia. Nearly 27% is already part of the protected areas network but managed for multiple uses that may limit their ability to contribute to the goals of 30 $\times$ 30. Additionally, nearly two-thirds of nationally identified refugia coincide with ecoregion-specific refugia suggesting representation of nearly all ecoregions in national efforts focused on conserving climate refugia. Based on these results, we recommend that land planners and managers make more explicit policy priorities and strategic decisions for future-minded protections and climate adaptation.

1. Introduction
The spatial heterogeneity of shifting climatic conditions presents challenges and opportunities for large-scale biodiversity conservation, as impacts to habitat and species can vary significantly across the landscape (Baldwin et al 2018). In North America, nearly half of species are already undergoing local extinctions (Wiens 2016), which are partially due to spatially variable changes in temperature and precipitation (Román-Palacios and Wiens 2020). In the contiguous US (CONUS), the average annual temperature has risen 1.2 °C–1.8 °C since the beginning of the 20th century (Vose et al 2017) and precipitation patterns have shifted with large reductions in the Southeast and West (Fei et al 2017, Wuebbles et al 2017). As the effects of climate change accelerate, local biodiversity will either need to find locations that serve
as refugia from extreme or rapid climatic changes or shift their ranges to better-suited habitat (Neilson et al 2005, Franks and Hoffman 2012, Keppel and Wardell-Johnson 2012, Román-Palacios and Wiens 2020). Identifying and conserving important refugia habitats and dispersal routes will be one critical step in jointly addressing the biodiversity and climate crises (Pörtner et al 2021). While expansion of the US protected areas network has been identified as an important solution to lowering extinction risk and overall ecosystem degradation (Stolton et al 2015, Gray et al 2016, Dinerstein et al 2017, 2019), efforts generally focus on current species distributions and may not effectively reflect future needs (Elsen et al 2020, Maxwell et al 2020).

Calls to address the joint biodiversity and climate crises by protecting at least 30% of Earth by 2030, known as ’30 × 30’ (Dinerstein et al 2019), have been endorsed by government and conservation leaders at global (United Nations 2020), national (Biden 2021, US DOI et al 2021), and state levels (e.g. Newsom 2020). While the specifics have yet to be established (Büsch er et al 2017, Rights and Resources Initiative 2020, Simmons et al 2021), efforts would hypothetically conserve areas needed to sustain essential ecological services and reverse extinction trends (Locke 2013, Dinerstein et al 2017). Translating these commitments into national policy may prove challenging since the current distribution of protected areas excludes many areas important for biodiversity conservation (Scott et al 2001, Jenkins et al 2015, Venter et al 2018, Dreiss and Malcom 2022) and carbon storage (Melillo et al 2016, Buotte et al 2020). While not all areas storing large amounts of carbon are also biodiversity hotspots, there are many instances of overlap; for instance, carbon-rich forests can provide important habitat and climate change buffers (Berkessy and Wintle 2008, Strassburg et al 2010). However, it is unclear how well the current network and 30 × 30 goals can ensure the conservation of climate-resilient habitat in the coming decades as climate change continues to accelerate.

Climate-resilient habitat can largely be delineated into refugia and corridors. Refugia are areas where species, natural communities, or ecosystems can persist within a larger area that has been rendered inhospitable. Such areas are relatively buffered from changes in regional environmental conditions, and allow organisms to persist as long as local conditions remain tolerable (Keppel and Wardell-Johnson 2012, Morelli et al 2016). Climate-change refugia may only be temporary for a given species (Morelli et al 2020), but can delay ecosystem transitions for decades or longer (Krawchuk et al 2020). They can serve as a ‘slow lane’, protecting native species and ecosystems from negative effects of climate change in the short term, providing longer-term havens for overall biodiversity and ecosystem function, and reducing the risk of extinction (Morelli et al 2020). Although refugia can be examined over a continuum of spatial scales, they are usually classified as either macrorefugia or microrefugia (Ashcroft 2010). Macrorefugia are identified at coarse scales, using global climate data or models, and are large enough to maintain viable animal or plant populations. Microrefugia are identified at local scales. For example, steep canyons and north-facing slopes are relatively sheltered from solar radiation and heat accumulation (Stralberg et al 2020a) and hydric or mesic microenvironments (e.g. with a perched or shallow groundwater table, or fed by seeps or springs) can remain moist during droughts (Morelli et al 2016, McLaughlin et al 2017, Stralberg et al 2020a).

At broad scales, refugia can be identified by various approaches, such as modeling topodiversity, climate exposure, and climate tracking (Michalak et al 2020). Topodiversity models are based on physical habitat data and highlight regions with varied land cover, climate, soil, and topographic conditions (Acke rly et al 2010, Groves et al 2012, Carroll et al 2018). Topographically varying areas can contain features like deep valley bottoms or shaded slopes that serve as microrefugia (Ashcroft 2010). Climatic exposure models are based on projected climatic changes and represent the degree of climate change likely to be experienced by a species or locale (Saxon 2008, Groves et al 2012). Lastly, models of future habitat suitability are informed by representative climate models and attempt to predict the proximity and accessibility of future suitable climatic conditions (Hamann et al 2015, Michalak et al 2018).

However, to survive in the face of ongoing and worsening climate change impacts, some species may need to relocate (Román-Palacios and Wiens 2020). Climate corridors can facilitate long-distance movement to more suitable habitat if rising temperatures and other changing conditions exceed an organism’s tolerance (Stralberg et al 2020b). Depending on model inputs, corridors may emphasize movement toward cooler latitudes and topographies, along rivers and streams, and/or through areas providing better habitat and less stress from disturbances (McGuire et al 2016, Littlefield et al 2017, Carroll et al 2018, Stralberg et al 2020b). For example, Parks et al (2020) found that human land modifications decrease climate connectivity.

Given the urgency of the biodiversity and climate crises, there is a pressing need to include potential climate refugia and corridors in the conservation planning process. However, some challenges exist. First, a growing body of available spatial data for identifying areas important for climate adaptation means that planners must reconcile a diversity of data that represent different mechanisms and priorities (Michalak et al 2020, Carroll and Ray 2021). Second, most conservation prioritization frameworks focus on the current state of species and environments (Cushman et al 2009, Lookingbill et al 2010,
Dickson et al 2013, Belote et al 2016, McClure et al 2016) which may result in critical oversights in protected areas siting for longer-term persistence of some target species (Monzón et al 2011, Elsen et al 2020). If this is the case, consideration of future conditions may complement efforts to preserve current biodiversity and ecosystem service hotspots, thereby reducing the threat of mass extinctions and accompanying biosphere degradation. Last, a failure to include some important local refugia may occur if areas for climate resilience are identified and prioritized at a national scale (e.g. Kraus and Hebb 2020). While this may identify the most important nationwide climate refugia, it could favor some regions (e.g. mountain ranges) and omit others entirely. Evaluating at smaller scales (e.g. stratifying by ecoregion) could include more locally important refugia. Taking additional steps to identify refugia at multiple scales may help increase ecosystem representation and protection for the unique species assemblages and services they harbor.

Proper identification, protection, and management of climate-informed refugia and corridors are essential to ensuring greater opportunity for species conservation via migration and adaptation. While previous research and policy discussion surrounding the extent and distribution of protected land and water has identified areas important to conserving the current state of biodiversity and natural carbon storage (Myers et al 2000, Scott et al 2001, Gray et al 2016, Buotte et al 2020), less attention has been paid to areas important for wildlife and plant climate adaptation. To help close this knowledge gap, we:

(a) identify areas in the contiguous US critical to climate adaptation based on coincidence and complementarity among refugia (national and ecoregion-specific) and corridors models;
(b) compare the spatial distribution of identified climate refugia and corridors with current biodiversity and carbon-rich areas; and
(c) quantify the extent to which climate refugia and corridors are considered protected.

Given the opportunity to focus land conservation using a science-driven, ecologically-meaningful (rather than opportunistic) approach, step #2 guides our understanding of how protections siting under the 30 x 30 framework may be biased by data omission, and step #3 helps to assess the current level of protection for identified climate refugia and distinguish where stronger management might be needed. Our research contributes to a growing literature demonstrating the importance of incorporating climate-informed data in place-based land protection policy and practices and helping to identify specific areas for conservation. While these analyses are not meant to serve as a map of priority lands for conservation, they help guide discussion on operationalizing 30 x 30 for strategic, future-minded conservation decisions.

2. Methods

We focus on spatial datasets based on climate models or topography to identify areas that could serve as important refugia or migration routes for the CONUS (table 1). All datasets using climate models are informed by an ensemble of three to seven general circulation models (GCMs) for emission scenario representative concentration pathway (RCP) 4.5 and projected for the time period 2071–2100 based on the Coupled Model Intercomparison Project phase 5 (CMIP5) models. All datasets have been resampled and aligned at 1 km resolution. We combined datasets for refugia (n = 8) and corridors (n = 2) separately, accounting for differences in underlying mechanisms in modeling method and landscape conservation principles.

2.1. Climate refugia

We initially analyzed relationships between datasets through a principal components analysis (PCA) where each component helps define a refugia class. The principal components spatial analyst tool in ArcPro transforms the data in the input raster bands to compress data and eliminate redundancy. The result is a multiband raster and text output containing a covariance matrix, correlation matrix, eigenvalues and eigenvectors. The number of principal components selected was based on scree plot and broken stick model. All datasets were normalized to a scale of 0 and 1 by calculating z-scores for all eight refugia datasets representing climate-, landscape-, and species-based metrics (table 1), which were then used as inputs for the PCA.

As with principal components, datasets were assigned to a class based on the sign and size of the eigenvector. However, to avoid a tradeoff in refugia identification within a single class, all datasets within the class were required to load together and in the same direction on a principal component. In addition to presenting three separate classes that represented topodiversity, climatic stability, and tree macrorefugia, we weighted and combined all eight normalized datasets. Because classes are not equivalent to principal components, they were weighted equally rather than by a measure of explained variation. As such, each dataset contributed equally to its class and each class contributed equally to the final pixel value. Unlike existing studies in this area (e.g. Michalak et al 2020), this approach groups datasets together by relationship and reduces the chances of over-emphasizing any one variable in identifying refugia. Based on the relationships between refugia datasets, the weighted combination was calculated as follows, where each variable in the equation represents the normalized spatial dataset:
Table 1. Description of refugia datasets. All datasets are currently based on the CMIP5 models. Classes are based on results from a PCA where component 1 (topodiversity) explained 33.8%, component 2 (climatic stability) explained 15.9% and component 3 (tree macrorefugia) explained nearly 13.8% of variation. See SI for additional details.

| Refugia class | Dataset | Description | Source |
|---------------|---------|-------------|--------|
| Topodiversity | Current climate diversity | Climate-based. Based on 11 bioclimatic variables using climate data for a 30 year climate normal period (1981–2010). | Carroll et al 2017 |
| Ecotypic diversity | Landscape-based and climate-based. Derived from edaphic, climatic, and landcover data. | Carroll et al 2017 |
| Land facet diversity | Landscape-based. Incorporated elevation, latitude-adjusted elevation, topographic position index, slope, modified heat load index, and soil. | Carroll et al 2017 |
| Landscape diversity | Landscape-based. Described the diversity of microhabitats and climatic gradients. Microclimates were measured by quantifying elevation range, the variety of small-scale landforms, and the density and configuration of wetlands in a 100-acre neighborhood. | The Nature Conservancy 2020 |
| Bird macrorefugia | Climate-based and species-based. Biotic velocity metric driven by overlap in current and projected future species ranges. Input derived from current species niches for 268 songbird species (Distler et al 2015); climate velocity based on 4 representative GCMs, RCP 4.5, 2080s. | Stralberg et al 2018 |
| Climatic stability | Climatic dissimilarity | Climate-based. Described how different the future climate at a location will be from its current climate. Measured in terms of multivariate climate characteristics, via a PCA of 11 biologically-relevant temperature and precipitation variables, RCP 4.5, 2080s. | Belote et al 2018 |
| | Climate velocity | Climate-based. Velocity was calculated by dividing the rate of climate change by the rate of spatial climate variability to focus on regions where climatic conditions move more slowly across the landscape. Input based on A2 emissions scenarios implemented by seven GCMs of the CMIP3 multimodel dataset, RCP 4.5, 2080s. | AdaptWest Project 2015 |
| Tree macrorefugia | Tree macrorefugia | Climate-based and species-based. Biotic velocity metric driven by overlap in current and projected future species ranges. Input derived from current species niches for 324 tree species (McKenney et al 2011); climate velocity based on four representative GCMs, RCP 4.5, 2080s. | Stralberg et al 2018 |

Combined Refugia

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Z_{\text{Combined}} = Z_{\text{Bird Macrorefugia}} + Z_{\text{Current Climate Diversity}} + Z_{\text{Ecotypic Diversity}} + Z_{\text{Land Facet Diversity}} + Z_{\text{Landscape Diversity}} + (Z_{\text{Climatic Dissimilarity}} \times 2.5) + (Z_{\text{Climatic Velocity}} \times 2.5) + (Z_{\text{Tree Macrorefugia}} \times 5).
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We analyzed locations in the 80th percentile (i.e. the top 20% of values) of the distribution of values for the combined data and for each refugia class separately. Additionally, we quantified the degree of overlap in refugia classes.

In addition to CONUS-level analyses, we extracted refugia values for each ecoregion separately (EPA level II; EPA 2006), classifying the locations that fell into the top 20% of the distribution as areas of interest. The result was a map of ecoregion-specific refugia, ensuring equal representation of all ecoregions relative to size. Results from the national- and ecosystem-scale analyses were compared and contrasted using spatial overlays.

2.2. Climate corridors

We extracted raw data values on connectivity and climate flow (The Nature Conservancy 2020) for areas that were identified as ‘climate-informed’ corridors by using the categorical connectivity and climate flow dataset as a mask (The Nature Conservancy 2020). The remaining values were rescaled to fall between 0 and 1. A 2nd climate corridor dataset on current flow centrality (Carroll et al 2018) was similarly rescaled. We then combined these two datasets and analyzed locations in the 80th percentile of the distribution of combined values.

Combined Climate Corridors

\[
Z_{\text{Combined}} = Z_{\text{Climate Informed Connectivity and Flow}} + Z_{\text{Current Flow Centrality}}.
\]
2.3. Analyses
We used spatial overlay analysis to describe the extent to which the current protected areas network covers identified climate refugia (based on national- and ecoregion-scales) and corridors in CONUS. We quantified the extent to which identified refugia would be protected by the $30 \times 30$ framework if it were to solely focus on current areas of high imperiled species biodiversity and ecosystem carbon. Data on protected areas are from the protected areas database of the US (PADUS) 2.1 database (USGS 2020). We use US Geological Survey’s Gap Analysis Program (GAP) codes, which are specific to the management intent to conserve biodiversity. GAP 1 and 2 areas are managed in ways typically consistent with conservation. Areas assigned a GAP 3 code are governed under multiple-use mandates that may include biodiversity priorities but may also include incompatible activities such as forestry and mining, and GAP 4 areas lack any conservation mandates or such information is unknown as of 2020. Imperiled species richness was assessed from publicly available range data (USGS GAP, International Union of Conservation of Nature—IUCN, and US Fish and Wildlife Service) for species defined as ‘imperiled’ (1923 species). These include species that are listed or under consideration for listing under the ESA, have a NatureServe G1-3 status and/or are critically endangered, endangered or vulnerable IUCN categories. All species ranges fitting these criteria were converted to rasters (for US FWS and IUCN ranges, USGS rasters were resampled to 1 km resolution to match the others), reclassified ($1 = $within species range, $0 = $outside of range), aligned and summed together. Modeled current total ecosystem carbon is based on a high-resolution map of global above- and below-ground carbon stored in biomass and soil (Soto-Navarro et al 2020). We define hotspots for biodiversity and carbon as the top 20% of values in the raw distribution of each dataset. We selected the top 20% as a threshold to balance selectivity and breadth of coverage, but recognize that other thresholds could be chosen. We used ArcPro v2.5 (ESRI, USA) to produce maps and run analyses, with maps using the Albers Equal Area Conic projection.

3. Results

3.1. Identifying refugia and corridors
Climate refugia datasets generally correlated well with others of similar methodology or concept; three resulting classes generally represent topodiversity, climatic stability, and tree macrorefugia (tables 1 and S1 available online at stacks.iop.org/ERL/17/024033/mmedia). The main exception was for climate-based datasets with species information, where bird macrorefugia correlated with datasets based on topodiversity, but tree macrorefugia was the sole dataset in its class (table S2). The three refugia classes exhibited very little overlap with one another at the national scale: while 52% of CONUS falls into at least one of the refugia classes, 7.5% falls into refugia identified by two or more classes (approx $568 \ 000 \ km^2$ and figure S1). Locations in the combined refugia layer that were within the top 20% of the distribution of values represent these overlaps and are used for reporting the remainder of statistics here.

Thirty-four percentage of CONUS is identified as a climate refugia or corridor under one or more datasets (approx $2652 \ 000 \ km^2$ and figure 1). Climate refugia generally follow the Appalachian, Rocky, and Cascade Mountain Ranges with additional refugia in the Ozarks and parts of California. Climate corridors are somewhat complementary to national-scale refugia, with 28.9% of their area ($444 \ 501 \ km^2$) overlapping identified refugia locations. Overlaps occur in the central Appalachians, Pacific Northwest, and portions of the Rockies, Sierra Nevadas and Ozarks. Corridors that do not overlap with refugia are key in connecting parts of the Great Plains and Mexico borderlands to refugia and in connecting refugia to northern locales.

Refugia identified in a stratified ecoregion approach were highly coincident with the national scale analysis, with 63% of all national refugia overlapping with ecoregion refugia (figure 2). Overlaps between the two cover 12% of CONUS total land area (approx 949 000 km$^2$). All refugia combined (both from national and ecoregion-specific analyses) equal 26% of the total CONUS land area (approx 2.1 million km$^2$). Locations that were emphasized in the ecoregion-specific approach include temperate and semi-arid prairies and places along the eastern coast.

3.2. Comparison to $30 \times 30$ objectives: biodiversity and carbon
Refugia and corridors are generally complementary on the landscape to areas of current high biodiversity and carbon storage values (figures 3(A) and (B)). There is some overlap between current biodiversity hotspots (i.e. top quartile of imperiled species richness values) and identified national-scale refugia (36.8%) and corridors (9.3%; table 2). Overlaps are generally concentrated in western California and Appalachia/Ozarks regions. Overlap between carbon-rich areas is greater in extent overall (refugia overlap = 32.5% and corridor overlap = 27.2%) and similar in spatial pattern with greater overlap in northern areas: northern Appalachians, Crown of the Continent and Pacific Northwest. When combining the two objectives (biodiversity and/or carbon), 45.0% (approx 1000 000 km$^2$) of the land area representing at least one of these objectives is also identified as part of a climate refuge or corridor.

Taking an ecoregion-specific approach to comparing refugia, corridors, biodiversity, and carbon results in less coincidence: 22.0% and 21.7% of stratified refugia overlap with ecoregion-specific
biodiversity hotspots and carbon-rich areas, and 17.5% and 26.1% of corridors overlap with ecoregion-specific biodiversity hotspots and carbon-rich areas, respectively (figures 3(C), (D) and table 3).

3.3. Current protections for refugia and corridors
Overall, 12.5% of the combined network of refugia and corridors is managed with the intent to conserve biodiversity (i.e. GAP 1 or 2; 4.2% of CONUS or approx 325 000 km²; figure 4). The rest of this network falls on GAP 3 (26.5%) or GAP 4 (61.0%) lands, which represents 29.2% of CONUS (approx 2280 000 km²). Proportions are similar when analyzing protection of national-scale climate refugia and corridors separately (table 2). Ecoregion-specific refugia fall more heavily in GAP 4 categories with 12.2% of area on lands managed for biodiversity conservation and 19.6% on those managed for multiple uses (figure 4 and table 3). Finally, the entire set of CONUS lands representing either biodiversity conservation (GAP 1 or 2) or 30 × 30 objectives (biodiversity hotspots and/or carbon-rich areas) coincides with 44.5% of the national climate refugia and corridor network.

4. Discussion
Currently, the US protected areas network and emerging conservation policy objectives largely fail to represent valuable climate refugia and corridors. While there is some overlap, solely using recent imperiled species ranges and carbon stores as conservation criteria will not inherently protect climate-resilient lands. In the most protective situation—if all biodiversity hotspots and carbon-rich areas were to be considered for strong conservation mandates (e.g.
Figure 2. Coincidence between national-scale and ecoregion-specific refugia. The full raster datasets were used to identify refugia in national analyses. Ecoregion-specific analyses employ a stratified approach, where refugia are identified for each ecoregion separately before combining them together. Ecoregions are outlined in black.

Figure 3. Overlap between national-scale (A), (B) and ecoregion-scale (C), (D) refugia and corridors with carbon stocks (B), (D) and biodiversity hotspots (A), (C). The full raster datasets were used to identify refugia in national analyses. Ecoregion-specific analyses employ a stratified approach, where refugia are identified for each ecoregion separately before combining them together. Ecoregions outlined in black in maps (C) and (D).
Table 2. Overlays of national-level datasets representing protected areas, carbon stores, biodiversity, climate refugia, and climate corridors. Values represent the percent of each top line item (column) that falls within each row. Values in parentheses are the percent of total CONUS area represented by the overlay.

| % of top line items that fall into each of the following: | GAP 1 and 2 | GAP 3 | Top 20% carbon | Top 20% biodiversity | Top 20% refugia | Top 20% climate-informed corridors |
|----------------------------------------------------------|-------------|-------|----------------|----------------------|----------------|----------------------------------|
| GAP 1 and 2                                              | 100 (7.5)   | 0.0 (0.0) | 12.7 (2.4)    | 3.7 (0.7)             | 13.3 (2.6)     | 13.8 (2.7)                      |
| GAP 3                                                    | 0.0 (0.0)   | 100 (16.6) | 20.2 (3.9)    | 5.1 (1.0)             | 25.0 (4.8)     | 30.4 (6.0)                      |
| Top 20% carbon                                           | 32.8 (2.4)  | 23.3 (3.9) | 100 (20.0)    | 28.8 (5.6)            | 32.5 (6.2)     | 27.2 (5.4)                      |
| Top 20% biodiversity                                     | 12.3 (0.7)  | 8.7 (1.0)   | 32.0 (5.6)    | 100 (20.0)            | 30.8 (5.9)     | 11.2 (1.8)                      |
| Top 20% refugia                                          | 34.2 (2.6)  | 29.0 (4.8)  | 32.8 (6.2)    | 36.8 (5.9)            | 100 (20.0)     | 28.7 (5.7)                      |
| Top 20% climate-informed corridors                       | 36.5 (2.7)  | 36.3 (6.0)  | 25.8 (5.4)    | 9.3 (1.8)             | 29.6 (5.7)     | 100 (20.0)                      |

GAP 1 or 2 protections)—a majority (55.5%) of identified climate refugia or corridors would still be left unprotected. Failure to include landscapes relevant to climate adaptation in planning initiatives could inhibit the potential for longer-term conservation successes. While simply protecting currently biodiverse or carbon-rich areas may not ensure the preservation of climate corridors and refugia, conserving corridors and refugia will benefit imperiled species in biodiversity-rich hotspots and promote carbon sequestration. This is particularly true in parts of the country (e.g. Appalachia and western California) where hotspots are not directly covered by climate corridors, but adjacent to them, providing opportunities for migration to refugia or future climate analogs.

With over half of the contiguous US identified as at least one type of climate refugia (topodiversity, climatic stability, or tree macrorefugia), many opportunities exist for decision makers interested in future-minded conservation. Like previous work, we demonstrate trade-offs in using one refugia dataset over others: topodiversity data favor environmentally complex regions like mountain ranges, whereas climatic exposure and tree macrorefugia highlight other lands (Michalak et al. 2020). Through our ensemble approach to refugia identification we both highlight the complementary information provided by these approaches (Belote et al. 2018) and simplify varied complex datasets for greater interpretability. A weighted combination of the datasets puts less pressure on the user to choose between mechanisms and on the decision maker to have a deep understanding of the methodology when interpreting maps. However, clarification of a specific refugia type may help states or local municipalities working to set priorities for contributing to national refugia protections based on local environments and community needs. In addition, taking a combined approach results in high overlap with an ecoregion-stratified approach, suggesting representation of nearly all ecoregions in national efforts focused on conserving climate refugia.

Currently unprotected areas among the top 20% of climate refugia and corridors represent 29.2% of CONUS, of which 38% is federally managed. Given the extent and distribution of land managers, protecting valuable climate adaptation areas can help contribute to the 30% target numerically and meaningfully. However, there will need to be a concerted effort by land managers in all jurisdictions and leadership across jurisdictional boundaries.

4.1. Lands administered by government and tribal entities

Public lands can make significant contributions to achieving 30 × 30. The federal lands estate is particularly expansive (20% of CONUS, 86% of
Figure 4. Overlap between national-scale refugia (A), climate corridors (B), and either refugia or corridors (C) with the PADUS. GAP codes are specific to the management intent to conserve biodiversity; GAP 1 and 2 areas are managed in ways typically consistent with conservation goals and GAP 3 areas are governed under multiple-use mandates that may include incompatible activities.

PADUS; CRS 2021, Dreiss and Malcom 2022) and federal land management agencies are required to varying degrees to prioritize wildlife and habitat conservation. Currently, the majority (86%, representing 18.4% of CONUS) of GAP 3 lands are managed by federal agencies, suggesting that substantial gains can be made in focusing on existing statutory authorities to advance climate-smart conservation on these lands. Of GAP 3 lands, over half are managed by the Bureau of Land Management (BLM) and another 3rd by the US Forest Service (Dreiss and Malcom 2022). Both agencies are guided by multiple use management mandates that empower them to designate and manage lands to enhance protection of areas recognized as having important conservation values (respectively, the Federal Land Policy and Management Act of 1976, National Forest Management Act of 1976). The agencies can capitalize on existing land and water designation authorities—like wilderness designation and BLM ‘areas of critical environmental concern’—to increase protection for climate refugia and corridors. Additionally, implementation of certain best management practices on federal lands, regardless of GAP status, may help ensure that these areas continue to support secure and thriving biodiversity, contribute to climate adaptation, and provide ecosystem services, such that intrinsic value, natural character, resources, and functions are maintained or enhanced now and into the future, both individually and as part of an interconnected network of lands and waters.

Expansion of GAP 1 and 2 lands to cover more refugia and corridors can also ensure greater conservation for climate adaptation. The US Fish and Wildlife Service manages the National Wildlife Refuge System (NWRS) expressly to conserve species and habitat, providing a high level of federal land protection. Pursuing the acquisition of lands fundamental to species’ survival and sustainability, including climate refugia and climate corridors, to establish new refuges would be consistent with the purview of NWRS. However, since federal land acquisition and management decisions are often politically contentious, this may be a less feasible option for conserving the additional 440 million acres of land needed to reach the 30% target.

State governments also manage significant acreage (approximately 4% of the US), including state forests, wildlife management areas, game lands, and natural area preserves. State parks, or portions thereof, may also contribute to conservation refugia and corridors, but are often categorized as GAP 4 (i.e. absent or unknown mandates for conservation). States can contribute to $30 \times 30$ by upgrading GAP status and management of undeveloped state lands that can further climate adaptation. The State Wildlife Action Planning (SWAP) process also requires each state to describe ‘locations and relative condition of key habitats and community types essential to conservation of species (USFWS and AFWA 2017)’. Results from this and other studies can help inform this process and help states increasingly update their SWAPs to include climate changes (NFWPCAN 2021).

Tribal nations hold over 56 million acres in trust by the Bureau of Indian Affairs and may manage their lands in ways that afford more substantive protections for lands and species given their lower rates of habitat modification (Lee-Ashley et al 2019). A long history of managing and observing their lands has provided many indigenous communities with valuable knowledge and experience to inform
land management and planning for climate adaptation and resilience (BIA 2018). Respectful inclusion of indigenous systems of knowledge and perspectives 'can inform our understanding of how the climate is changing and strategies to adapt to climate change impacts (National Fish, Wildlife, and Plants Climate Adaptation Network (NFWPCAN) 2021)'. As such, government-to-government relationships will be important in addressing climate adaptation needs for species and peoples and may include cross-landscape management, tribal involvement in federal and state planning, and more. The Landscape Conservation Cooperative program developed by interior offers one such mechanism to advance landscape-scale protections and coordinate climate-related land conservation activities among Tribal Nations, federal agencies, state, local, and tribal governments, and other stakeholders (NASEM 2016).

4.2. Private and non-governmental organization lands
As most land in the US is privately owned, conservation efforts on private lands will be critical to expanding protected areas. Sixty-two percent of the refugia and 56% of corridors fall outside of the protected areas network (GAP 4), but this only represents 20% of CONUS. This suggests that well-targeted, voluntary acquisitions and easements could translate to large gains in private lands conservation. Land trusts are uniquely positioned to scale-up conservation on private lands to achieve the 30 × 30 target.

In addition to the role of land trusts, private working lands and associated conservation programs can be important to achieving 30 × 30 (American Farmland Trust 2021, Garibaldi et al 2021). For instance, Farm Bill programs administered by the US Department of Agriculture such as the Agriculture Conservation Easement Program could be targeted to lands identified as climate refugia or connectivity areas and specify sensitive wetland habitats and riparian areas as eligible lands for wetland easements, as these will be increasingly valuable for supporting wildlife and ecosystem services as the climate changes (Theoharides 2014, Lewis et al 2019). Longer-term (30 year) contracts that offer a commitment to re-enrollment should be encouraged to ensure enduring conservation measures. Additionally, Environmental Quality Incentives Program and the Conservation Stewardship Program can better reflect climate adaptation needs by assigning higher ranking to practices designed to build resilient landscapes (Theoharides 2014).

4.3. Limitations
To enhance species’ resilience in the face of growing climate and biodiversity crises, corridors and refugia must be preserved across both lands and waters. Due to some limitations of data and our analyses, we recommend against siting protections based on the coincidence of current biodiversity/carbon hotspots and climate refugia/corridors alone. For one, complementarity of species assemblages is not accounted for and there may be biases toward conserving certain taxa. Additionally, while we include aquatic species in our biodiversity metric, and wetland/riparian areas in some topographic measures of refugia, we did not explicitly include aquatic refugia. Currently, there is no complete national dataset to represent aquatic refugia. Because cold-water aquatic organisms are among the most vulnerable taxa to climate change, future analyses should focus on identifying freshwater refugia and corridors where sufficient data exists. Given the international scope of 30 × 30 and the benefits of larger-scale connectivity, future work on climate adaptation in 30 × 30 implementation should look beyond terrestrial habitats and political boundaries to cover all ecosystems of North America.

Our analysis demonstrates the need to make climate adaptation a more explicit objective in conservation planning for addressing the biodiversity crisis. Without direct consideration for climate refugia and corridors, a 30 × 30 implementation focused on current species ranges and carbon stocks may be ineffective for the longer-term persistence of species. The key to operationalizing 30 × 30 and subsequent efforts will be growing a protected areas network that ensures a long-term commitment to biodiversity and climate. By incorporating climate refugia and corridors, the US can work to protect places that will continue to serve wildlife and human populations now and in the future.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://osf.io/jksyx/.

Acknowledgments

We thank M Anderson, J Grand, J Lawler, R List, J Michalak, S Saunders, and R Wynn-Grant for their thoughtful review of the project and engaging discussion over key concepts. Additional gratitude goes to those organizations that make these datasets publicly available to enable this and other research.

Recent work in the field of conservation science and STEM at large has identified a bias in citation practices such that papers from women and minorities are relatively under-cited (see Larivière et al 2013, Rudd et al 2021 and others). While we did not proactively choose references that reflect the diversity of the field in thought, form or contribution, gender, and other factors for this work, we recognize the biases that may have been unintentionally introduced. We look forward to future work that can help us to better understand how to support equitable practices in conservation science.
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