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Incorporating projected climate conditions to map future riparian refugia

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Abstract

Identifying areas expected to remain buffered from climate change and maintain biodiversity and ecological function (i.e., climate refugia) is important for climate adaptation planning. As structurally diverse transitional zones between terrestrial and aquatic environments, riparian areas are often biological hotspots and provide critical corridors for species movement, particularly in arid and semi-arid regions. In our study region in the western and central USA, identifying riparian areas that could serve as climate refugia is a priority for wildlife managers. We mapped areas with connected riparian habitats that, based on landscape diversity and projected changes in summer temperatures and landscape runoff, are expected to serve as climate refugia. To incorporate uncertainty and balance the need for near- and long-term planning, we mapped potential refugia for 2 future time periods (2040–2069, 2070–2099) based on 2 climate models that represented divergent but plausible climate outcomes. The approach we developed is not constrained by physiology or behavior of target species and can be used to identify areas expected to fare comparatively well under a wide range of future climate scenarios. Our approach can also be used to identify areas where restoration could increase riparian connectedness and climate resilience.

KEYWORDS

climate change, climate refugia, connectivity, drought, landscape diversity, management, resilience, restoration, stream, warming

1 | INTRODUCTION

Identifying, restoring, and protecting areas with the greatest potential to provide refugia from climate change is critical for maintaining biodiversity, population connectivity, and ecological function (Ashcroft et al., 2012; Keppel et al., 2012). Climate refugia—areas relatively buffered from and least exposed to contemporary climate changes (Morelli et al., 2020)—are often formed by vegetation, landforms, or other structural features that create microclimates that moderate changes in temperature and precipitation (Anderson et al., 2014; Dobrowski, 2011; Rull, 2009). These refugia can allow species to persist despite changing climate conditions or can provide stepping-stone habitats that aid species in tracking suitable conditions (Ackerly et al., 2020; Beier, 2012; Keppel et al., 2012).

Riparian areas are biological hotspots that are also often recognized inherently as potential climate refugia (Capon et al., 2013; Krosby et al., 2018; Sabo et al., 2005). As transitional zones between terrestrial and aquatic environments, riparian areas are influenced by periodic flooding or saturated soils and provide ecosystem services such as filtering nutrients and sediments (Knopf et al., 1988; Naiman & Decamps, 1997). Proximity to water and structural complexity from vegetation, combined with local landscape features, create diverse environmental conditions that increase hydrologic and terrestrial connectivity, and provide important habitat for many species (Ashcroft et al., 2012; Manning et al., 2020; Patten, 1998). And by connecting river valleys with smaller tributary streams that flow from higher elevations, riparian areas can also provide dispersal corridors that span a gradient of microclimates (Naiman et al., 1993; Stromberg et al., 2017).

The importance of riparian areas for biodiversity may be especially important in semi-arid and arid environments, such as desert and prairie ecoregions common in western North America. Riparian vegetation can range from broad galleries that merge into surrounding forests to narrow ribbons along streams; these latter systems are especially common in semi-arid and arid environments (Patten, 1998; Stromberg et al., 2017). For example, in many areas of western North America, riparian areas may only cover 1%–3% of a landscape but are used by >80% of species (Knopf et al., 1988; Naiman & Decamps, 1997). Small prairie streams often lack well-defined riparian areas with trees, especially in areas with extensive agricultural development, yet they still provide important habitat for a broad range of species and shape local ecological communities (Dodds et al., 2004; Johnson, 1999). These narrow riparian areas are likely more vulnerable to changes in temperature and moisture from edge effects (e.g., Williamson et al., 2021), increasing the importance of identifying areas that are expected to maintain the capacity to support species diversity and ecological function under a changing climate (sensu Gunderson, 2000; Anderson et al., 2014).

Collectively, the features of riparian areas and their importance to many species make these areas central to many local and regional conservation efforts. Identifying riparian areas expected to be least affected by climate change can aid conservation and restoration efforts as well as broader climate adaptation planning. While some refugia mapping studies have focused on the role of streams or riparian habitats by applying fixed buffers around features or streams (e.g., Brost & Beier, 2012; Rouget et al., 2003; Williamson et al., 2021), as pointed out by Krosby et al. (2018), most studies have used stream as proxies for riparian habitat and few have accounted for variation in features of riparian areas across broad landscapes that influence regional climate adaptation planning. Further, while refugia mapping is commonly incorporated into climate adaptation planning globally (e.g., Anderson et al., 2014; Ashcroft et al., 2012; Keppel et al., 2012; Morelli et al., 2020), we are unaware of examples of broad-scale mapping of riparian refugia that incorporate both considerations of potential resilience and exposure to climate change.

Here, we map potential riparian refugia based on characteristics we expect will reflect resilience or exposure to change: connectedness of existing and potential riparian areas and landscape diversity (resilience), and projected changes in landscape moisture and summer temperatures (exposure). Our study area encompassed a large portion of the western and central USA (Figure 1), an area dominated by desert, montane forest, and prairie ecoregions with often large differences in forecasted changes in temperature and moisture. To incorporate uncertainty and balance the need for near- and long-term planning, we mapped potential refugia under 2 future time periods (mid- and late-century) based on 2 climate models that together represented a range of plausible temperature and moisture outcomes (Hostetler & Alder, 2016; Rangwala et al., 2021). Our approach allowed us to map an index of riparian refugial quality—areas expected to serve as climate refugia—to guide future prioritization for protection or restoration, a critical component for climate adapted planning.

2 | METHODS

2.1 | Study area

Our study area comprised 8 states in the western and north-central USA: Idaho, Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska, and Kansas (Figure 1). The study area is topographically diverse and includes a wide range of environmental and climatic conditions. Landscapes in southern Idaho, central Wyoming, and western Colorado are dominated by deserts with sagebrush and shrub-scrub habitats (Omernik & Griffith, 2014). Riparian areas in these systems generally do not have extensive tree cover, but it still often exceeds tree cover in dry uplands (Patten, 1998; Stromberg et al., 2017). The Rocky Mountains run along a southeast–northwest axis through our study area (Figure 1). These areas have cold, snowy winters with dry summers. Rivers flowing from the mountains tend to be constrained by

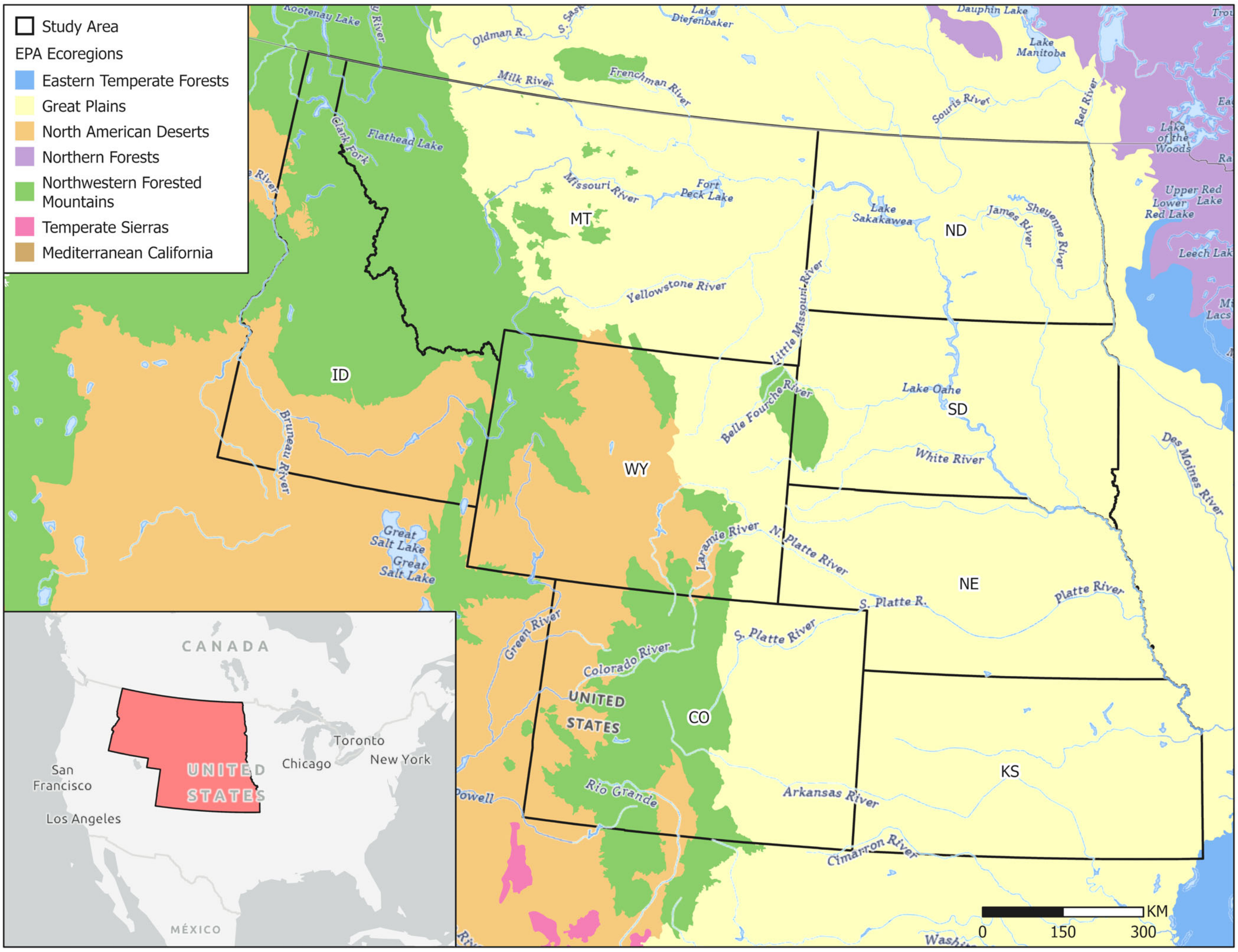

FIGURE 1 Geographic variation in dominant major biomes in the western and central USA, relative to the 8 states that comprised our study area.

landforms and riparian vegetation often merges with coniferous forests, reducing the distinction between riparian and upland zones (Patten, 1998). East of the Rockies, semi-arid sagebrush and grassland prairies of the Great Plains predominate (Omernik & Griffith, 2014). The eastern portion of the Great Plains receives more moisture than the western portion, especially in the summer (Omernik & Griffith, 2014). Rivers in the Great Plains often have extensive riparian areas, but it is common for small streams to have few trees or other forms of riparian vegetation, especially in areas with extensive agricultural development (Dodds et al., 2004; Johnson, 1999).

2.2 | Study motivation

During 2021 and 2022, we held several meetings with wildlife managers from 7 of the 8 states in our study area to learn what information was most needed to help integrate climate-informed planning into their State Wildlife Action Plans. State Wildlife Action Plans are state-led efforts to identify species and habitats most in need of conservation (AFWA, 2012). Managers in our study area unanimously identified riparian areas as the most important landscape feature for which to have information on expected vulnerabilities and resilience. Riparian areas were already featured prominently in some State Wildlife Action Plans, but applying a uniform approach to mapping riparian refugia across the region can aid with integrating climate-informed planning within and across state boundaries (Szcodronski et al., 2022).

2.3 | Overview of spatially explicit analyses

We mapped an index of potential riparian refugial quality based on abundance and connectedness of riparian

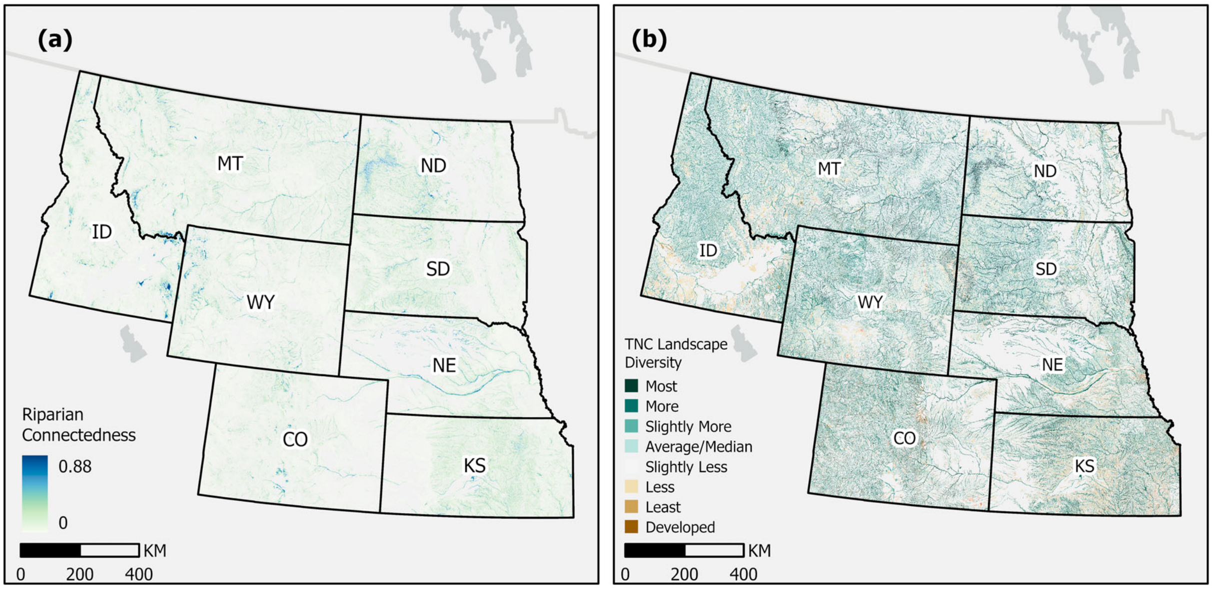

FIGURE 2 Variation in (a) riparian connectedness calculated as the mean for buffer widths of 30, 100, and 500 m and (b) landscape diversity across our study area in the western and central USA.

vegetation, landscape features that may provide microclimatic refugia and mediate exposure to impacts from climate changes, and climate projections for changes in warm summer temperatures and the amount of overland water runoff during mid-and late-century periods (Table S1). To bookend the range of plausible future conditions, we used projections from 2 climate models that represented plausible but contrasting outcomes (moderately hot and wet, hot and dry) for our study area rather than an ensemble approach that reduces variation in projected outcomes (e.g., Rangwala et al., 2021; Schloss et al., 2022).

2.4 | Riparian connectedness

We estimated the "connectedness" of gridded riparian vegetation data by calculating the average proportion of riparian cover across three extents (Figure 2a; Table S1). We assumed smaller or less connected riparian areas would provide less refuge for species from edge effects and the negative effects of high temperatures (Williamson et al., 2021) and larger or more connected riparian areas would provide more variation in vegetation structure and microclimate and increase their use as corridors (Hilty & Merenlender, 2004; Naiman et al., 1993). The riparian vegetation data were from the LANDFIRE existing vegetation type dataset, which includes cover from shrubs and trees (LANDFIRE, 2020). We calculated the proportion of cover within a moving (or sliding) window with the Focal Statistics tool in ArcGIS Pro 3.0.0 (ESRI, Redlands, CA). Moving window analysis is commonly used to calculate landscape pattern measures, particularly across the multiple scales likely of import to species and ecosystems (e.g., Riitters, 2019). For each focal raster cell, we calculated the proportional coverage of riparian vegetation within a specified window radius for both upland (lateral) and stream-associated (longitudinal) locations. To represent fine- and coarse-grain habitat needs or preferences, we calculated the proportion of riparian vegetation within windows with radii of 30, 100, and 500 m (Ellis, 2008; Wood et al., 2022). We considered this a proxy measure for connectedness by taking the average proportion of riparian vegetation across all 3 radii, representing the proximity of another cell of riparian area across multiple scales. Finally, to limit analyses to areas of current and potential riparian areas near water courses, we masked the calculated connectedness based on the U.S. Forest Service map of riparian areas (Table S1; Abood et al., 2022).

2.5 | Landscape diversity

We used The Nature Conservancy's landscape diversity data to represent structural components that could interact to shape microclimate (Anderson et al., 2014; Dobrowski, 2011) (Figure 2b; Table S1). We expected greater landscape diversity would confer greater resilience to climate change (Anderson et al., 2014). The landscape diversity data were calculated based on variation in landform variety (topographic position, slope, and aspect) and presence of wetlands and other small non-flowing waterbodies (Anderson et al. 2018a; Anderson et al., 2019; Anderson, Clark, et al., 2018; Buttrick et al., 2015). The landscape diversity data are normalized as z-scores and pre-assigned into one of 8 categories (excluding water) that range from developed areas (category 1) to the most diverse areas (category 8) (Anderson et al. 2018a; Anderson et al., 2019; Buttrick et al., 2015). Only 12% of cells in riparian areas in our study area were categorized as "most diverse" and 11% were categorized as "less diverse," "least diverse," or "developed."

2.6 | Climate change

To account for climate change in our index of riparian refugia, we used projections of changes in 2 climate variables: (1) the change in projected number of days when the maximum temperature would exceed the 90th percentile during June–August, compared to the historical period (1971–2000; hereafter, "warm days") (Abatzoglou, 2013; Abatzoglou & Brown, 2012) and (2) percent changes in landscape runoff during March–July, based on a monthly water balance model (Alder & Hostetler, 2021; Hostetler & Alder, 2016) (Table S1; Figures S1 and S2). We focused on increases in warm days because thermal maxima disproportionately influence the distribution of many species, including plants that provide riparian structure (Allen et al., 2015; Germain & Lutz, 2020). Likewise, we focused on March–July for runoff because that period reflects yield from melting snow that accumulated over the winter as well as spring rains; both of these sources influence availability of surface water, which is of critical importance to riparian areas.

The monthly water balance model incorporates projected precipitation and temperatures to predict water available for overland runoff from a given location on the landscape (Hostetler & Alder, 2016). Runoff is the final output from a monthly water balance model that accounts for direct runoff, surplus runoff, soil moisture storage and groundwater contribution, and evapotranspiration. This water balance model is an updated version of a previous model (Wolock & McCabe, 1999) that has been used widely to explain variation in stream runoff (McCabe & Wolock, 2008, 2011). The updated model was applied to output from a downscaled global circulation model (Alder & Hostetler, 2021; Hostetler & Alder, 2016), allowing higher-resolution projections of landscape runoff that have been used to explain variation in regional runoff, wetland dynamics, and water use by plants (Miller et al., 2018; Ray et al., 2016; Tercek et al., 2021).

We calculated our index of riparian refugial quality under 4 climate scenarios. We incorporated projected changes in temperature and runoff based on 2 different global circulation models that provide divergent "bookend" outcomes when comparing across a scatter of many potential models: (1) moderately hot and wet (CNRM-CM5) and (2) hot and dry (IPSL-CM5A-MR) (Sepulchre et al., 2020; Voldoire et al., 2013). We then considered these models over 2 time periods, comparing historical climate (1971–2000) to (1) mid-century (2040–2069) and (2) late century (2070–2099) projections. Thus, the 2 climate models and 2 time periods produced 4 climate scenarios used to evaluate riparian areas as climate refugia: (1) CNRM-CM5 2040–2069, (2) CNRM-CM5 2070–2099, (3) IPSL-CM5A-MR 2040–2069, and (4) IPSL-CM5A-MR 2070–2099. All model outputs were based on the RCP 8.5 atmospheric carbon emission scenario, which is considered the most likely for the mid-21st century (Schwalm et al., 2020).

2.7 | Index of riparian refugial quality

We combined the above data (riparian connectedness, landscape diversity, and projections of changes in temperature and runoff) into a single index to reflect potential riparian refugial quality under each of the 4 climate scenarios (e.g., Schile et al., 2014; Yang et al., 2011) using ArcGIS Pro 3.0.0 Suitability Modeler (Figure 3). All data layers were resampled to 100 m in ArcGIS Pro using nearest neighbor interpolation prior to combining. In Suitability Modeler, we divided each input variable into 5 categories and then assigned each category a refugial quality score from 1 (expected low refugia potential) to 5 (expected high refugia potential) (Table 1). The landscape diversity data were already divided into 8 ordinal categories ranging from developed to the most diverse lands (Anderson et al. 2018a). We binned the categories to fit the 1–5 scoring scheme for the refugial quality based on bin similarities and the relative commonness of each category (Table 1). The other input layers were numeric variables and were also binned into the 1–5 scoring scheme. Riparian connectedness values ranged from 0 to 0.88 and were strongly skewed: 79% of cells had connectedness values ≤0.10 and only 1.8% were >0.50. Therefore, we assigned a suitability score of 5 to all raster cells with a connectedness value ≥0.500 and then divided connectedness values of 0.001–0.499 equally into 4 categories (Table 1).

We used similar methods to assign changes in warm days and landscape runoff into the 5 suitability categories (Table 1). However, since the range of these scores varied by climate scenario, we first combined all outputs across the region for all climate scenarios and then divided the total range into 5 equal categories. This approach ensured changes in warm days and landscape runoff were scored based on the same potential values, rather than unique scales for each climate scenario. Next, we summed across the 4 input variables with equal weights to calculate the

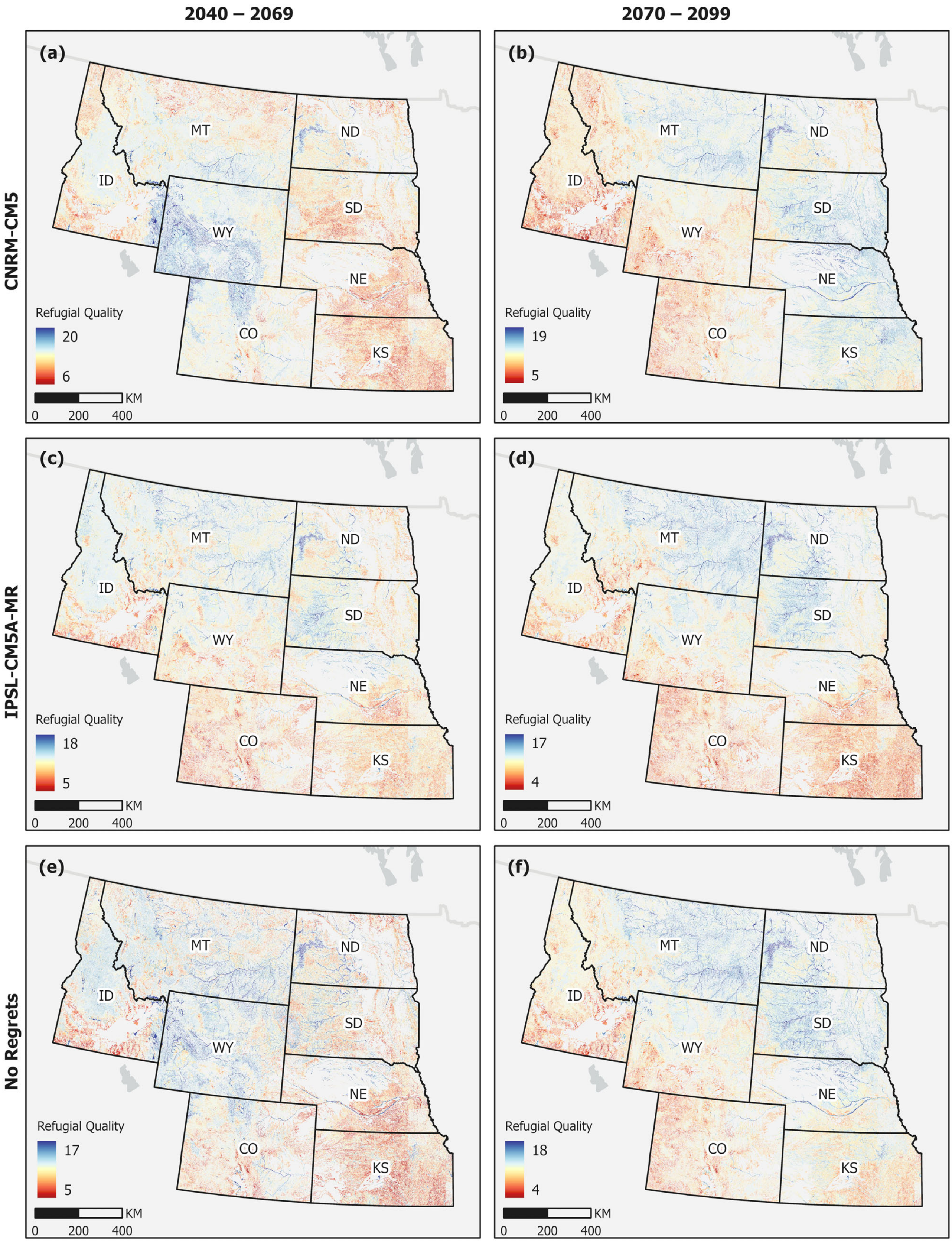

FIGURE 3 Legend on next page.

TABLE 1 Quality scores (1 is lowest) assigned to ranges of values for each of 4 input variables used to map potential riparian refugia. Riparian connectedness is based on mean proportion of riparian cover within moving windows with radii of 30, 100, and 500 m. The Nature Conservancy landscape diversity data represent increasing levels of landform complexity and were pre-assigned to 8 categories. Cases where we combined categories are indicated by the "+" sign in the landscape diversity column. Projected increase in number of days that the maximum temperature would exceed the historical 90th percentile during June–August (i.e., warm days) and percent change in landscape runoff during March–July are relative to conditions during 1971–2000. Changes in warm days and runoff represent the full range of projected changes across all 4 climate scenarios considered. Note that quality scores were assigned independently for each input variable, so, for example, a given cell could have had a quality score of 1 for riparian connectedness and 5 for increase in warm days.

Refugial value	Riparian connectedness	Landscape diversity	Increase (no.) in warm days	Change (%) in runoff
1	0.000–0.125	Developed + least landscape diversity	74.07–86.87	−90.57–−63.45
2	0.125–0.250	Less + slightly less landscape diversity	61.27–74.07	−63.45–−36.33
3	0.205–0.375	Average/median landscape diversity	48.47–61.27	−36.33–−9.22
4	0.375–0.500	Slightly more + more landscape diversity	35.67–48.47	−9.22–17.90
5	0.500–0.880	Most landscape diversity	22.87–35.67	17.90–45.02

final index of refugial quality, which served as an indication of the potential to maintain ecological function under climate change. Projected values could range from a minimum of 4, if a 1 (lowest refugial quality) were assigned to each of the 4 input variables, to a maximum of 20, if a 5 were assigned to each of the 4 input variables. Last, to provide opportunities for "no-regrets" planning (sensu Schloss et al., 2022) based on areas with high potential to serve as refugia under a wide range of potential future climate conditions, we averaged the refugial index values for the 2 climate scenarios for mid-century (2040–2069) and late-century (2070–2099) separately.

The input data and outputs are available at https://doi.org/10.5066/P96WZLMS (Szcodronski et al., 2024). And an ArcGIS dashboard that allows users explore the implications of different data combinations and scenarios is available at geonarrative.usgs.gov/RiparianClimateRefugiaDataExplorer.

3 | RESULTS

3.1 | Summary of input variables

Riparian connectedness ranged from 0.00 to 0.88 across the study area (Table 2). The overall mean for the region was only 0.07, indicating low levels of riparian connectedness. With some notable exceptions, such as much of southern Idaho and south-central Colorado, areas of high landscape diversity were distributed fairly evenly across our study area (Figure 2b). Landscape diversity tended to be greatest in areas with extensive badlands topography, such as the Missouri Breaks in central Montana and the northern Great Plains (Figure 2b).

The number of warm days during June–August exceeding the 90th percentile during the historical period (1971–2000) is projected to increase across the region and through the century, with greater increases for the hot and dry climate model than the moderately hot and wet model. Regionally, mean increase in number of warm days during June–August is projected to range from 37 to 63 days, with greater warming in the western and southern portions of our study area (Table 2, Figure 3, Figure S1). Changes in mean projected runoff during March–July ranged from −4.55% during the late-century period under the moderately hot and wet climate model to −39.68% under the hot and dry model, also during the late-century period (Table 2). While continued drying is expected from mid- to late-century under the hot and dry model, projected changes between mid- to late-century were smaller under the moderately hot and wet model, with absolute increases in moisture expected in some areas during the latter period, especially in the Great Plains (Figure S2).

FIGURE 3 Indices of riparian refugia (refugial quality) based on changes in summer warmth and landscape runoff from the CNRM-CM5 (a, b; moderately hot and wet) and IPSL-CM5A-MR (c, d; hot and dry) climate models for 2 time periods, mid-century (a, c; 2040–2069) and late century (b, d; 2070–2099), compared to historical climate conditions (1971–2000). The bottom "no-regrets" maps (e, f) show the highest-ranked riparian refugia across both climate scenarios for the mid-century and late century periods. Suitability indices could range from 4 to 20, with higher values reflecting greater expected climate resilience. Note that the range of realized index values differed among climate scenarios and thus maps.

TABLE 2 Summary statistics for input variables used to map potential riparian refugia. Summaries for runoff and warm days show different expected values under 2 climate models (CNRM-CM5, IPSL-CM5A-MR) and 2 time periods (2040–2069, 2070–2099), whereas riparian connectedness was based only on current conditions. Landscape diversity, also based on current conditions, is not shown here because it used ranked categories. The 2 climate models generally represent moderately hot and wet (CNRM-CM5) and hot and dry (IPSL-CM5A-MR) conditions for our study area.

Input variable	Mean (SD)	Minimum	Maximum
Riparian connectedness	0.07 (0.09)	0.00	0.88
Runoff CNRM-CM5 2040–2069	−6.45 (16.65)	−61.32	42.72
Runoff CNRM-CM5 2070–2099	−4.55 (20.88)	−66.19	45.02
Runoff IPSL-CM5A-MR 2040–2069	−33.70 (19.39)	−78.77	28.16
Runoff IPSL-CM5A-MR 2070–2099	−39.68 (25.21)	−90.57	31.85
Warm days CNRM-CM5 2040–2069	36.50 (7.93)	22.87	57.33
Warm days CNRM-CM5 2070–2099	49.95 (9.53)	35.00	71.27
Warm days IPSL-CM5A-MR 2040–2069	45.16 (7.48)	33.40	71.83
Warm days IPSL-CM5A-MR 2070–2099	62.80 (8.42)	47.17	86.87

TABLE 3 Mean (range) index values of riparian refugia for each state and the 3 dominant biomes in our study area under each of the 2 climate models (CNRM-CM5: moderately hot and wet; IPSL-CM5A-MR: hot and dry) conditions for our region. The potential range for the riparian refugia index was 4 (lowest quality) to 20 (highest quality).

	CNRM-CM5 2040–2069	CNRM-CM5 2070–2099	IPSL-CM5A-MR 2040–2069	IPSL-CM5A-MR 2070–2099
State				
Idaho	11.01 (7–19)	9.83 (6–17)	10.73 (7–17)	8.92 (5–15)
Montana	11.11 (6–18)	12.01 (7–19)	11.74 (7–18)	10.60 (5–17)
Wyoming	12.55 (7–20)	10.67 (6–17)	10.83 (6–16)	9.39 (4–15)
Colorado	11.45 (6–19)	10.69 (5–17)	9.90 (5–16)	8.00 (4–14)
North Dakota	10.88 (7–17)	12.01 (8–18)	11.10 (7–17)	10.78 (7–17)
South Dakota	10.33 (6–17)	12.79 (8–19)	11.40 (8–18)	10.38 (5–17)
Nebraska	9.93 (6–16)	13.00 (8–19)	10.82 (7–17)	8.90 (5–15)
Kansas	9.86 (6–17)	12.33 (8–18)	10.31 (7–16)	7.78 (5–13)
Regional mean	10.94 (6–20)	11.63 (5–19)	10.91 (5–18)	9.40 (4–17)
Biome				
Deserts	11.73 (7–20)	9.84 (5–16)	10.16 (5–17)	8.48 (4–15)
Forested mountains	11.67 (6–19)	10.65 (6–17)	11.09 (5–16)	9.28 (4–15)
Great Plains	10.49 (6–18)	12.42 (6–19)	11.06 (5–18)	9.68 (4–17)

In general, pairwise correlations among the 4 input variables were weak, indicating independent contributions from input variables. Mean correlations across climate scenarios ranged from −0.21 (runoff and warm days) to 0.21 (riparian connectedness and landscape diversity; Table S2). As might be expected, the strongest individual correlations between input variables were for increased number of warm days and decreased landscape runoff (−0.50; Table S2). These particular pairwise correlations were especially strong because they reflected large increases in warm days accompanying large reductions in runoff in the western and southern portions of our study area (Figures S1 and S2).

3.2 | Mapping potential riparian refugia

Index values for refugial quality ranged from 4 to 20 and varied geographically and across the 4 climate scenarios (Table 3, Figure 3). All pairwise correlations between the

4 input variables and mean refugial quality were positively correlated except the relationship between increased warm days and refugial quality (Table S2). The strongest mean correlations with refugial quality were for landscape diversity (0.61), followed by change in runoff (0.51), riparian connectedness (0.46), and increase in warm days (−0.22; Table S2). Correlations between riparian refugial quality and increase in warm days under different climate scenarios were highly variable (range: −0.57–0.49) compared to the other 3 input variables (Table S2).

Based on the moderately hot and wet model (CNRM-CM5), the areas with the best potential to provide riparian refugia during mid-century were clustered in the forested mountains of the central Rocky Mountains and desert systems of southwestern Wyoming and northwestern Colorado (Table 3, Figure 3a). Other concentrated areas of high refugia value under this moderate, mid-century climate scenario were in south-central Montana and the badlands of southwestern North Dakota, both areas where landscape diversity is high. By late century, the areas with the greatest riparian refugia values shifted to the east and south compared to mid-century, so that areas dominated by the Great Plains had the highest refugial quality values and montane and desert areas in the west were the lowest (Table 3, Figure 3b). These shifts were driven by increases in runoff under the moderately hot and wet model between 2040–2069 and 2070–2099, despite expectations for moderate increases in warming (Table 2, Figures S1 and S2).

Based on the hotter and drier IPSL-CM5A-MR climate model, areas with the highest riparian refugial quality during mid-century were spread sparsely and widely across the northern portion of the study area (Table 3, Figure 3c). Areas of high topographic diversity, such as the Missouri Breaks in Montana and badlands in western North Dakota and South Dakota had high concentrations of riparian areas with high quality index values (Figures 2b and 3). During the late century, areas with the greatest expected refugial quality retracted to the northern Great Plains, where projected warming and drying were less severe relative to the rest of the region (Tables 2 and 3, Figure 3d, Figures S1 and S2).

Based on the no-regrets maps for each time period, the central Rocky Mountain region in western Wyoming and northern Great Plains in eastern Wyoming and southeastern Montana were expected to provide the best refugia during 2040–2069 (Figure 3e). During 2070–2099, the riparian areas most likely to serve as climate refugia shifted to the east and north (Figure 3f). Under both no-regrets scenarios, the topographically diverse Yellowstone River watershed in southeastern Montana and areas with badlands topography in western North Dakota and South Dakota are expected to provide some of the best riparian refugia in the region.

4 | DISCUSSION

Through their structural complexity and proximity to water, riparian areas often provide diverse microclimates that are decoupled from the broader regional climate. The important habitat features they provide, their potential to serve as dispersal corridors, and their rarity in many landscapes has made riparian areas vital to local and regional conservation efforts. This importance was demonstrated by state wildlife managers in our region who identified riparian areas as the most important landscape feature for which to have information on expected vulnerabilities and resilience (see *Study Motivation*). Our results—based on data for existing riparian vegetation, landscape features that mediate climate exposure, and 4 future climate scenarios—quantified the potential refugial quality of existing riparian areas that we expect to be most resilient and least exposed to climate change.

Evaluating potential riparian refugia under 2 climate models and for 2 future time periods revealed a wide range of potential outcomes for our study area. Areas most likely to be projected to provide high quality riparian refugia in the future tended to have high measures of landscape diversity and increased March–July landscape runoff. For the mid-century time period (2040–2069), projected high quality riparian refugia based on the wetter CNRM-CM5 climate model were clustered in the central Rocky Mountains and sagebrush steppe systems of southwestern Wyoming and northwestern Colorado, with other concentrated areas in south-central Montana and the badlands of the northern Great Plains. Based on the hotter, drier IPSL-CM5A-MR climate model, riparian areas with the greatest resilience during mid-century were spread more evenly and widely across the northern portion of the study area. By late-century (2070–2099), most areas of high refugial quality shifted to the Great Plains for both climate models, but the differences were driven by contrasting climate projections. Shifts in high quality refugial areas under the moderate CNRM-CM5 model followed increased runoff in the Great Plains, which is projected under some climate scenarios (Hostetler & Alder, 2016; Voldoire et al., 2013). For example, in an assessment of projected water stress across the contiguous USA in 2040, only stream catchments in the northern Great Plains had reduced water stress (Theis et al., 2023). In contrast, continued drying and warming was expected for our entire study region under the hotter, drier IPSL-CM5A-MR climate model, but the projected changes were less severe in the northern Great

Plains, allowing maintenance of some riparian areas with high refugia index values.

The link between riparian areas and streams, which occur as branched, linear networks, often translates to riparian areas having higher structural connectedness than adjacent terrestrial areas. This is one reason, along with greater legal protection of streams than terrestrial systems, riparian areas are often promoted for climate adaptation planning (Fremier et al., 2015; Seavy et al., 2009). Although our study area is sparsely populated overall and has a high proportion of protected lands (Vincent et al., 2020), increased development of agricultural lands near riparian areas and other forms of human development could cause loss of riparian vegetation (Jones et al., 2010). Similarly, long-term drying projected for most areas under the climate scenarios we evaluated could cause death of trees and simplify riparian structure, producing negative feedbacks that further increase temperatures and aridity (Schook et al., 2022; Stromberg et al., 1996).

Maintaining or increasing riparian vegetation or connectedness is a common goal on its own (Dodds et al., 2004; Knopf et al., 1988; Patten, 1998), and of all the inputs in our analysis, vegetation is the most amenable to management actions. Riparian vegetation that extends to higher elevations or other climate refugia can aid dispersal and population connectivity and is often a focus of climate adaptation planning (Beier, 2012; Hilty & Merenlender, 2004; Naiman et al., 1993). Riparian connectedness averaged across 30, 100, and 500 m buffers in our study area was low for most streams (mean = 0.07, range: 0.00–0.88). While they used different methods and had different objectives, Krosby et al. (2018) reported a similar mean and range of values for an index of riparian climate corridors in the northwestern USA, including part of our study area. Areas with high riparian connectedness were present in each state in our study area but were especially concentrated in the Greater Yellowstone Ecosystem of southwestern Montana, northwestern Wyoming, and eastern Idaho; southwestern North Dakota; and the Platte River system in Nebraska and Colorado. The relative importance of high connectedness to future climate refugia also provides opportunities to increase resilience of existing riparian areas through restoration, changes in water management, promotion of beaver-based restoration, or other management strategies that support growth of riparian vegetation (Cooper et al., 1999; Levine & Meyer, 2019; Seavy et al., 2009).

Evaluating potential riparian refugia based on 2 divergent climate models and 2 time periods rather than using the more typical approach of averaging across climate models revealed more underlying uncertainty for decision-making (e.g., 2040–2069 vs. 2070–2099 for CNRM-CM5; Figure 3), but the wider range of potential outcomes can also help identify priority areas for planning and management (Rangwala et al., 2021; Schloss et al., 2022). One strategy to reduce uncertainty is to prioritize areas that scored highly for refugial quality under all evaluated climate scenarios. For example, in a study to identify connectivity pathways in California (USA) based on land use, topography, and 2 contrasting climate scenarios, areas with concurring predictions for high future connectivity were recommended as a means of “no-regrets” planning (Schloss et al., 2022). Notably, these pathways tended to follow riparian valleys, a tendency that grew stronger under future climate scenarios (Schloss et al., 2022).

In our study, areas with high refugial values under this no-regrets framework were frequently found around rivers with well-connected floodplains; these areas often have extensive wetland habitats within the floodplain that collectively contribute to a wide riparian zone (Figure 3a,b). These areas occurred in regions with high topographic complexity, such as the Yellowstone River in Montana, the Little Missouri River in southeastern Montana and southwestern North Dakota, and the Cheyenne River in South Dakota. Several areas were projected to have high riparian refugial values except under the single hottest, driest scenario for a particular location. These locations were common in the southern portion of our study area (e.g., North Platte River, Colorado and Nebraska; Figures 1 and 3) where riparian cover can be limited even in the absence of human development or disturbance (Dodds et al., 2004; Johnson, 1999). Areas with limited riparian cover or other priority areas to managers that are surrounded by low refugial quality might be suitable candidates for restoration to increase riparian cover, connectedness, and ultimately, future resilience (Briggs & Cornelius, 1998; Patten, 1998; Seavy et al., 2009).

Like similar studies that rely on spatial data and forecasts of future climate, the utility of the potential riparian refugia we identified is limited by the accuracy and resolution of data for existing riparian vegetation, landscape diversity, and climate projections. Our results also assume the relationships between landscape characteristics and climate will be the same in the future as they are now, a common assumption that is not always realistic (Maclean et al., 2017). The relatively coarse scale of projected temperature and runoff data (4 km) can also obscure variation, especially in areas with complex topography. This is a common limitation, yet finer resolution, downscaled climate data may produce false confidence in identifying future refugia. Incorporating vegetation and landform characteristics into analyses can also help compensate for relying on 4 km climate data (Anderson et al., 2014; Schloss et al., 2022). The scale (30 m) of riparian and landscape diversity data may also obscure the importance of fine-scale features, such as small gaps in tree coverage or geographic variation in landforms, that can form microrefugia (Ashcroft et al., 2012; Dobrowski, 2011; Rull, 2009). The importance of scale and variation in species' habitat preferences or requirements, and our lack of a priori focus on any particular group of species, is one reason we averaged proportional cover across 3 moving window sizes to represent a multi-scale "connectedness." For example, if management focus is on more mobile species, connectedness at broader extents might be emphasized compared to species that select habitats at a fine grain or are limited to specific habitat conditions. Similarly, input variables such as connectedness or landscape diversity could be weighted differently to tailor outputs for specific objectives.

Constraining connectedness to current and potential riparian areas (e.g., Krosby et al., 2018; Theobald et al., 2013) differs from most prior studies of connectedness along streams. We made this decision partly because wildlife managers emphasized the importance of riparian connectedness for current and future planning in our mostly semi-arid region, where riparian areas are especially important to biodiversity and conservation (Knopf et al., 1988; Naiman & Decamps, 1997). It will be important to consider riparian connectedness and future climate conditions in the context of the surrounding landscape and specific management priorities, perhaps especially when areas of high riparian connectedness or projected climate resilience are surrounded by highly modified or fragmented lands or lands particularly vulnerable to climate change. It will also be important to evaluate projection outcomes under constantly improving or more finely resolved climate models and time periods, especially when faced with land acquisition or other management actions for targeted areas rather than broad averages across a large region. However, our approach, using divergent, plausible climate projections supports our general no-regrets approach, and for specific locations, we encourage managers to visit the ArcGIS dashboard (geonarrative.usgs.gov/RiparianClimateRefugiaDataExplorer).

Although riparian areas are widely recognized for their importance to ecosystem function and conservation, they have not often been directly incorporated into climate adaptation planning, especially under a range of potential future climate conditions. The methods we developed can be used to identify areas that could provide refugia under divergent climate scenarios and can be used to prioritize areas that are more likely to fare well under a wide range of potential climate scenarios, or to identify areas where restoration could increase climate resilience. Further, our results are not constrained by physiology or behavior of target species, such as assuming species that currently inhabit riparian areas will track suitable conditions as climate changes. The use of similar approaches to identify resilient riparian areas and other important ecotypes can be used to protect or restore riparian areas.

AUTHOR CONTRIBUTIONS

KES, AAW, and BRH designed the research; KES, AAW, SEB and BRH performed the research and wrote or edited the paper.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts.

DATA AVAILABILITY STATEMENT

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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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