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Spatially prioritizing wetland conservation decisions for climate adaptation: An Illinois case study

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Abstract

Amid shifting federal regulations and intensifying climate extremes, wetlands across the US are increasingly at risk of degradation and conversion, especially in Illinois where 70.1–73.3% of the remaining wetland area is unprotected. However, risks to wetlands and their societal co-benefits are unevenly distributed across the state due to spatial variation in climate and land use dynamics. Thus, to identify state regions with similar wetland management needs, we synthesized existing datasets to map four wetland ecosystem services, unprotected wetland areas, wetland areas recently converted to agriculture and impervious cover, and projected changes in four climate extremes. This revealed that wetland ecosystem services are greater in counties with more conversion and climate risk. In addition to having the most unprotected wetland area, southwestern IL has the most wetland area recently converted to agriculture and projected increases in three of four evaluated climate extremes, underscoring the need to conserve the region's unique and biodiverse wetlands. Enhancing and preserving existing wetlands is also most important in northeastern IL because it has the most wetland protection yet greatest wetland area recently converted to impervious cover and projected reductions in frost days. Across northwestern and southeastern IL, restoring wetlands for climate resilience should be highest priority due to the region's low wetland services and intermediate to high future climate extremes, including excess heat and longer dry and wet spells. Because our approach relied on widely available public data, it can be readily applied beyond Illinois to strategically prioritize areas for wetland protection, enhancement, and restoration.

1 Introduction

In 1990, following a decade of elevated public concern about wetland degradation, the U.S. Army Corps of Engineers (USACE) and U.S. Environmental Protection Agency (USEPA) established a national goal to achieve "no net loss" in wetland area and function under the Clean Water Act (CWA) by requiring compensatory mitigation for adverse impacts (Hough & Robertson, 2009; USACE & USEPA, 1990). While the no-net-loss goal stemmed losses in wetland area, they accelerated between 2009 and 2019 not only because of traditional drivers, including conversion to uplands and open water, but also increasingly because of global climate change leading to sea level rise, increased evapotranspiration, and shifting rainfall patterns (Lang et al., 2024). Climate responses will vary across wetland types and geographic regions, but elevated temperatures and novel hydrologic regimes are broadly expected to alter wetland biogeochemical processes and species compositions (Junk et al., 2013). These changes will in turn reduce wetlands' ability to provide ecosystem services, including flood control, water purification, carbon sequestration, and wildlife habitat. In the Midwestern US, more frequent and intense spring rainfall could overwhelm wetland flood storage capacity, limit retention time for nutrient removal, and enhance tree mortality in forested floodplains (Wuebbles et al., 2021). Conversely, more extreme heat, longer summer droughts, and less freezing could reduce biodiversity in fens, bogs, and small depressional wetlands by increasing the abundance of invasive species (Hou et al., 2014) and the mortality of amphibians that need aquatic refugia for thermal regulation (Pottier et al., 2025). Although the net effect on radiative forcing remains difficult to predict, more prolonged spring flooding and extended dry periods should also reduce the carbon sequestration benefit of wetlands by enhancing greenhouse gas emissions and depleting soil carbon stocks (Moomaw et al., 2018).

On top of more frequent and intense climate extremes, wetland ecosystem services face elevated risk of impairment and loss without compensatory mitigation because the 2023 *Sackett v. EPA* Supreme Court decision narrowed CWA jurisdiction to only include wetlands if they have "continuous surface connection" to "waters of the United States" (WOTUS), which were limited to "relatively permanent waters" (RPWs). This ruling came after 50 years of litigation and Supreme Court decisions that gradually narrowed federal regulation of geographically isolated wetlands and nonperennial streams (Grewal & Scanlan, 2025). These decisions have subsequently motivated numerous revisions to administrative rules that expand or narrow the definition of WOTUS to include or exclude aquatic resources based on their flow permanence and connectivity with traditionally navigable waters (Walsh & Ward, 2022). After issuing a rule to conform with *Sackett* in late 2023, federal agencies proposed additional rules in 2025 and 2026 that could leave more than 33.1 million wetland hectares (81.9 million wetland acres or 91% of all nontidal wetlands) outside CWA jurisdiction (Gold, 2024; USACE & USEPA, 2023, 2025, 2026). Moreover, because federal regulation has become inextricable from surface water presence, longer dry spells due to climate change have the potential to further increase wetland vulnerability to conversion by disrupting their connectivity with downstream waters.

Thus, assessing wetland risks to inform regional conservation strategies requires evaluating interactions between climate and land use policy. Furthermore, accurately mapping wetland protection status requires integrating policy information across multiple levels of government. In direct response to *Sackett*, five states limited their wetland protections by expanding categorical exclusions

(Tennessee and Indiana) or by aligning their state waters definition with the federal standard (Louisiana, North Carolina, and Kentucky) (Table A1). However, four states enhanced wetland protections by allowing residents to file civil suits against expected polluters (Maryland) or by establishing permitting and mitigation requirements for wetland dredge and fill (Colorado, Delaware, and New Mexico). Hence, some protections have been lost or weakened, but the number of states with broad wetland protections has increased since 2023 (Kihslinger et al., 2023). Many counties, municipalities, and Tribes have also responded to *Sackett* or previous Supreme Court decisions by establishing regulations for isolated wetlands in their stormwater ordinances, municipal codes, or tribal wetland programs (Osborne & Stelk, 2024; USEPA, 2026). For example, though Illinois wetland protections are limited to state-funded activities (Kihslinger et al., 2024), eight of its counties have adopted wetland permitting and mitigation requirements (Peterson et al., 2025).

While these developments highlight nonfederal pathways to conserve wetlands, the shifting policy landscape and changing climate, alongside outdated wetland maps, make it challenging to determine which wetlands and communities face the most risk. Additionally, it remains unclear how losses in wetland area translate to losses in ecosystem services because they have not been consistently mapped or modeled at large spatial scales (Janse et al., 2019; Lang et al., 2024). To date, estimates of *Sackett* impacts on services have relied on unit-area averages, such as 2.5–3.7 million gallons of floodwater storage per wetland hectare (1–1.5 million gallons/acre; EDF, 2025) and $1,840 in avoided residential flood damage per wetland hectare ($745/acre; Woods, 2024). Similarly, many studies have developed unit estimates for the monetary value of wetland ecosystem services (de Groot et al., 2012; FSD, 2021). These estimates are a critical first step for approximating impacts of potential degradation, but wetlands have strong functional tradeoffs due to variability in hydrology, watershed position, vegetation composition, soil properties, and surrounding land uses (Zedler, 2003). For example, wetlands that are important for carbon sequestration and water quality improvement due to high primary productivity, nitrogen inputs, and soil organic matter contents are likely to have lower plant, bird, and amphibian richness (Jessop et al., 2015). Thus, more comprehensive maps of wetland services are essential for better quantifying spatial variation in the impacts of wetland degradation and benefits of wetland protection.

With a focus on Illinois, our first objective was to develop county-level maps of four wetland ecosystem services: carbon storage, floodwater storage capacity, and richness of plants and herpetofauna, including amphibians and reptiles. After creating these maps, our second objective was to evaluate the spatial relationships of wetland services to regional trends in wetland protection status, recent conversion rates, and projected increases in four climate extremes, including less cold and more heat, drought, and rainfall. We hypothesize that future climate extremes will be strongly correlated with unprotected wetland areas and services toward southern latitudes (Wuebbles et al., 2021). Conversely, more northern latitudes will have lower unprotected wetland areas and future climate extremes but higher urban development rates. By mapping climate and conversion risk across counties with different levels of wetland protection and function, this analysis provides essential information to help stakeholders prioritize areas for wetland conservation, restoration, and enhancement. Although we use Illinois as a case study, the workflow we used to synthesize data on policy, wetland services, land use trends, and downscaled climate data can be leveraged in any region to integrate wetland management into a broad portfolio of climate adaptation efforts that includes nature-based solutions.

2 Methods

2.1 Wetland protection status and conversion risk

By considering federal, county, and local policies, we quantified the total area of unprotected wetlands in each Illinois county using the National Wetlands Inventory (NWI), National Hydrography Dataset (NHD), National Levee Database (NLD), National Land Cover Dataset (NLCD), and Protected Areas Database of the United States (PAD-US) using a workflow adapted from Gold (2024) and Simmons et al. (2024). First, we quantified the area of wetlands that are not “waters of the United States” (non-WOTUS), and therefore not regulated by the CWA, due to the cumulative effects of three previous Supreme Court rulings: *Sackett v. Environmental Protection Agency* (2023), *Rapanos v. United States* (2006), and *Solid Waste Agency of Northern Cook County v. U. S. Army Corps of Engineers* (2001). Starting from NWI polygons as the base layer of potentially WOTUS wetlands, we used Cowardin modifiers to remove deepwater polygons (rivers and lakes) and polygons with long-standing categorical exclusions under the CWA (farmed, excavated, artificially flooded, or area less than 0.04 ha). Then, we used the 2024 NLCD to remove polygon inclusions with cultivated crops or medium-to-high intensity development (codes 23, 24, or 82).

Secondly, we integrated NHD flowline, waterbody, and area shapefiles to create two plausible layers of WOTUS surface water features that capture uncertainty in agency flow-permanence requirements for "relatively permanent waters" (RPWs). Given the incomplete flow-permanence attributes in the NHD flowline shapefile, we used data from Brinkerhoff et al. (2024) to update hydrologic classifications (ephemeral, intermittent, or perennial) that were based on NHD attributes and connectivity rules to fill in unknown flowlines (Peterson et al., 2025). If Brinkerhoff et al. (2024) classified the flowline as ephemeral, we updated the NHD-based hydrologic classification; otherwise, we kept the existing classification (*Appendix A.1*). After removing ephemeral flowlines, we excluded isolated waterbody features (lakes and ponds) that did not intersect perennial or intermittent flowlines. We proceeded to merge all non-ephemeral and non-isolated NHD features into one layer and filtered this layer to create one with NHD features that are strictly perennial and another with NHD features that are at least intermittent.

Since agency rules are expected to require wetlands to strictly abut RPWs (USACE & USEPA, 2025), we only evaluated two fixed-distance buffer layers (1 and 10 m) around each plausible WOTUS network to model distance thresholds for wetland spatial connectivity with RPWs. Similarly, WOTUS wetlands are likely to need surface water at least during the wet season, so we only evaluated four flood-duration thresholds based on the Cowardin water regime modifier (Seasonally Flooded, Semipermanently Flooded, Intermittently Exposed, and Permanently Flooded) to model thresholds for wetland temporal connectivity with RPWs. Although wetlands with seasonal flooding are increasingly unlikely to be included in WOTUS (USACE & USEPA, 2026), we kept this lower flood-duration threshold for comparison with previous studies. This led to 16 federal policy scenarios that represent unique combinations of RPW flow-permanence, RPW buffer-distance, and wetland flood-duration thresholds. For a given scenario, we classified a wetland polygon as "Non-WOTUS" if it did not intersect a buffer around the likely WOTUS network, if it occurred entirely within a leveed area, or its Cowardin water regime modifier fell below the minimum required flood-frequency threshold.

After identifying non-WOTUS wetlands, we intersected NWI polygons with the PAD-US and TIGER/Line shapefile of Illinois counties to create a data field that indicates each wetland's highest level of non-federal protection. We categorized a polygon as "Managed for biodiversity" if it had a GAP Status of 1 or 2, "Managed for multiple uses" if it had a GAP Status of 3, and "County permitting and mitigation" if it occurred within one of eight counties (Cook, DeKalb, DuPage, Grundy, Kane, Lake, McHenry, Will) with ordinances that require dredge-and-fill permits and compensatory mitigation. All other wetland polygons were categorized as "Locally unprotected". Finally, we combined the local protection indicator field with the non-WOTUS indicator field for each policy scenario to estimate the total wetland area lacking any form of legal protection within each Illinois county (*Appendix A.2*). Since larger counties are likely to have more wetlands, we also divided the county-level unprotected wetland area estimate by the total county wetland area to calculate the unprotected wetland percentage. Additionally, wetland protection status is not necessarily indicative of conversion risk, so we used the NLCD to estimate the total area of NWI wetlands (not deepwater, excavated, farmed, or artificially flooded) that were converted to row crops (code 82) and to medium or high intensity development (codes 23 or 24) between 1987 and 2024. This led to four county-level maps representing wetland protection status and conversion risk: (1–2) unprotected wetland areas and percentages and (3–4) wetland areas recently converted to row crops and impervious cover.

2.2 Ecosystem service estimates

By integrating biodiversity databases and geospatial data layers, we created county-level maps of four wetland ecosystem services: plant species richness, herpetofauna species richness, carbon (C) storage, and aboveground floodwater storage capacity (Table 1). To estimate the aggregate plant species richness of all wetlands in a county, we obtained county-level plant species lists from a recently compiled Midwest database based on the Biota of North America Program North American Plant Atlas (Zinnen et al., 2026). Then, we estimated the number of wetland-dependent plant species in each county (N) by subsetting the county-level lists to isolate species with wetland indicator values that are obligate (OBL) or facultative wetland (FACW) based on the U.S. Army Corps of Engineers National Wetland Plant List (USACE, 2023).

Similarly, we used Illinois Natural History Survey (INHS) lists of herpetofauna to quantify the number of wetland-dependent amphibians and reptiles, including frogs, toads, salamanders, turtles, lizards, and snakes, in each county (INHS, 2025). After using the county-level lists to identify all unique herpetofauna species in the state, we searched the IUCN Red List of Threatened Species to determine each species' habitat requirements (IUCN, 2026). If the IUCN determined that a species required inland wetlands, we used the "Habitat and Ecology" section to record which of nine inland wetland categories are used by the species (5.1–5.9). Since IUCN uses a broader definition of wetlands than our study, we determined that a species is wetland-dependent if one of four wetland categories were considered marginal or suitable habitat: (5.3) Shrub-Dominated, (5.4) Bogs, Marshes, Swamps, Fens, Peatlands, (5.7) Permanent Freshwater Marshes/Pools [< 8 ha], or (5.8) Seasonal/Intermittent Freshwater Marshes/Pools [< 8 ha].

To estimate wetland C storage, we summed together UNEP-WCMC above- and belowground biomass C stock estimates with soil organic carbon (SOC) stock estimates from gNATSGO and SoilGrids 2.0. Given its higher resolution (10 m), we used gNATSGO as the primary raster layer for SOC stocks at depths between 0 and 100 cm. However, given the incomplete areal coverage of gNATSGO, we resampled the 250-m SoilGrids 2.0 layer to fill areas with NoData or negative SOC stocks. If neither gNATSGO nor SoilGrids had an SOC value for a pixel, we conservatively assumed that it had an SOC stock equal to zero. After adding the SOC and biomass C stock rasters, we used Zonal Statistics to approximate total C storage (Mg) in each NWI wetland polygon as the pixel area (a [9 m^2]) times the sum of the C stocks (Mg/ha) over all pixels within the wetland. Finally, we summed these C storage estimates over all wetlands within each county.

To quantify aboveground floodwater storage capacity, we used a 3-m statewide LiDAR-derived digital elevation model to approximate the basin volume of each NWI polygon (ISGS, 2015). Specifically, we used the ArcPro Feature to Line tool to create a shapefile of lines representing wetland boundaries and used Add Surface Information to identify the minimum elevation of each boundary (Z_i^{min}). From these minimum elevations, we used rasterio and geopandas in Python version 3.13.9 to calculate the basin volume of wetland i (V_i) as the pixel area (a [9 m^2]) multiplied by the elevation difference between the minimum elevation of the wetland boundary and the elevation of each pixel (Z_{ij}) summed over all n pixels within the wetland provided that the pixel elevation was below the minimum boundary elevation:

$$V_i = a \sum_{j=1}^{n} 1_{Z_i^{min} > Z_{ij}}$$

where $1_{Z_i^{min} > Z_{ij}}$ is an indicator function that is 1 if $Z_i^{min} > Z_{ij}$ and 0 if $Z_i^{min} \leq Z_{ij}$. Then, we exported the results and used R version 4.5.2 to estimate county totals as the sum of basin volumes over all wetlands within each county. As with the land use conversion calculations, we only considered NWI polygons that were not deepwater, excavated, farmed, or artificially flooded when estimating carbon and floodwater storage.

Table 1
Summary of datasets used to estimate each wetland ecosystem service by county. All carbon datasets were resampled to 10-meter resolution.

Ecosystem service	Resolutions	Datasets
Wetland-dependent plant species richness	County	The Biota of North America Program North American Plant Atlas (Zinnen et al., 2026) and the National Wetland Plant List (USACE, 2023)
Wetland-dependent herpetofauna richness		Illinois Natural History Survey Herpetology Collection (INHS, 2026) and IUCN Red List of Threatened Species (IUCN, 2026)
Aboveground flood storage capacity (m^3)	3 m	Statewide LiDAR-derived digital elevation model from the Illinois Height Modernization Program (ISGS, 2015)
Carbon storage (Mg)	10–250 m	Soil organic carbon [0-100 cm] stocks in gNATSGO (Soil Survey Staff, 2026) and SoilGrids 2.0 (Poggio et al., 2021)
	300 m	Above- and belowground biomass carbon stocks (UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), 2020)

2.3 Future climate extremes

After quantifying four wetland services, we assessed how shifts in conservation policies and land use conversion could synergize with future climate change to decrease societal co-benefits from wetlands. Climate extremes rather than means are expected to drive future risk (Easterling et al., 2000), so we obtained 6-km resolution extreme event metric projections for rainfall and temperature derived from the Climate Model Intercomparison Program Phase 6 CMIP6 Localized Constructed Analogs (CMIP6-LOCA2) dataset (Alder, 2024, 2025). Although the full CMIP6-LOCA2 dataset includes 27 global climate models (GCMs), we used coefficients obtained from Bayesian Model Averaging to estimate weighted multi-model means across the smaller set of 16 GCMs used in the National Climate Assessment (Alder & Hostetler, 2013).

From the weighted raster ensembles for 1950–2100, we estimated historical averages of each climate extreme metric over the 30-year baseline period (1981–2010) and two future 30-year climatology periods (2041–2070 and 2071–2100) for two Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0), which correspond to intermediate and high greenhouse gas emission scenarios.

For each SSP and future climatology period combination, we calculated the projected increase in each climate metric by subtracting the historical average from the future average and estimated the mean change for each county with Zonal Statistics in ArcGIS Pro 3.6.0.

Finally, we reviewed scientific literature to determine which climate extremes present risks to each ecosystem service and selected one metric from the dataset for each category of climate extreme: less cold, excess heat, drought, and excess rainfall (Table 2). The respective metrics chosen were the annual number of frost days (FD), annual number of days with maximum temperature greater than 100°F [38°C] (TXge100F), annual maximum dry spell length (MDSL), and annual maximum wet spell length (MWSL).

Table 2

Summary of wetland ecosystem service vulnerabilities to changes in four climate extreme or threshold metrics calculated from a 16-model weighted ensemble (Alder, 2024, 2025). *All metrics have units of days per year.*

Climate extremes		**Wetland ecosystem services**			
		Biodiversity services		**Biophysical services**	
Category	**Metric (Abbreviation)**	Plant diversity	Herpetofauna diversity	Flood mitigation	Carbon sequestration
Less cold	Decrease in the number of frost days (-ΔFD)	Fewer days with below-freezing temperatures could allow less cold tolerant invasive species to shift northward and compete with native species[1–2].	Warmer winters could increase metabolic activity, deplete energy reserves, and reduce cold tolerance, which increases mortality and decreases reproductive success[6].		Wamer temperatures increase microbial metabolic and enzyme activity, which increase carbon dioxide and methane emissions while depleting carbon stocks[9]. Elevated temperatures also increase greenhouse gas emissions by enhancing litter carbon inputs and reducing the solubility of gas in water, which lowers dissolved oxygen concentrations and increases methane ebullition.
Excess heat	Increase in the number of days with maximum temperature greater than 100°F [38°C] (ΔTXge100F)	Extreme heat could reduce native seed production, seed germination, and seedling growth; increase native seedling mortality; and favor invasive species seed germination plus seedling survival and growth[1–3].	More extreme heat events are expected to reduce thermal safety margins and increase the number of species exposed to overheating, which increases their likelihood of mortality[7]. The absence of aquatic refugia can amplify these impacts.		
Drought	Increase in annual maximum dry spell length (ΔMDSL)	Drought could reduce native plant germination, growth, and survival[2], which could allow non-wetland species to encroach into wetlands[4] and facilitate post-drought invasion[5]. Drought could especially impact rare plants in bogs, fens, and small depressional wetlands[4].	Less wetland area and water permanence (i.e., longer dry periods) could limit amphibian breeding success and offspring survival, leading to smaller populations[4,8]. Desiccation associated with low humidity and water availability can also reduce activity[8].		More frequent non-saturated soil moisture levels could increase carbon dioxide emissions[4], but droughts could slow decomposition if heterotrophs become water limited[10]. Additionally, drier conditions should suppress methane emissions[9]. Drying risk is highest for rain-fed bogs and depressional wetlands with small contributing watersheds[4].
Excess rainfall	Increase in annual maximum wet spell length (ΔMWSL)	Increased winter and spring flood durations could increase tree mortality in forested floodplains with large contributing watersheds[4]. It may also disproportionately favor a small number of flood-tolerant species and thereby reduce diversity. However, more water		More intense and frequent rainfall events will increase likelihood that wetland flood storage capacity is overwhelmed during more intense rainfall events or more	Longer anoxic intervals may promote SOC accrual but could also increase methane emissions[9,11–12].

[1]Hou et al. (2014), [2]Orsenigo et al. (2014), [3]Tushabe et al. (2023), [4]Wuebbles et al. (2021), [5]Sanders et al. (2025), [6]Schmidt et al. (2024), [7]Pottier et al. (2025), [8]Ficetola and Maiorano (2016), [9]Guan et al. (2025), [10]Wang et al. (2024), [11]Zhang et al. (2017), [12]Li et al. (2026)

Climate extremes	Wetland ecosystem services	
	Biodiversity services	**Biophysical services**
	availability can alleviate heat wave impacts[3].	prolonged wet spells[4].

[1]Hou et al. (2014), [2]Orsenigo et al. (2014), [3]Tushabe et al. (2023), [4]Wuebbles et al. (2021), [5]Sanders et al. (2025), [6]Schmidt et al. (2024), [7]Pottier et al. (2025), [8]Ficetola and Maiorano (2016), [9]Guan et al. (2025), [10]Wang et al. (2024), [11]Zhang et al. (2017), [12]Li et al. (2026)

2.4 Data visualization and statistical analyses

Before running statistical analyses, we described spatial distributions of the 12 county-level variables estimated, including

- Four wetland ecosystem services (plant species richness, herpetofauna species richness, carbon storage, and aboveground floodwater storage capacity);
- Mean unprotected wetland area and percentages across four modeled WOTUS requirements for wetland flood duration (Seasonally Flooded, Semipermanently Flooded, Intermittently Exposed, and Permanently Flooded)
- Total wetland area converted to row crops and to medium or high intensity impervious cover between 1987 and 2024; and
- Projected changes in four climate-extreme metrics across two Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) and two future climatology periods (2041–2070 and 2071–2100)

Specifically, we interpreted these spatial patterns in the context of six Illinois regions that approximate groups of its major natural divisions, which have similar glacial histories and therefore wetland types: Wisconsin Driftless/Rock River Hill Country, Northeastern Morainal, Western Forest-Prairie, Grand Prairie, Southern Till Plain/Wabash River Border, and Shawnee Hills/Coastal Plain (Schwegman, 1997; Figure A1).

Next, we used multiple statistical approaches to quantify how wetland ecosystem services are spatially related to wetland protection status, recent conversion trends, and projected climate extremes. We also focused the statistical analyses on projected changes in climate extremes under SSP2-4.5 from 2041–2070 and mean unprotected wetland areas and percentages if all wetlands with less than semipermanent flooding are excluded from WOTUS. We chose this flood-duration threshold because it represents the least restrictive policy scenario among current proposals where wetlands could be excluded from CWA jurisdiction because they lack surface water for the entire wet season or year-round except for extreme drought events that last 30 days or less (USACE & USEPA, 2025, 2026). After scaling the 12 county-level variables by their respective means and standard deviations, we ran the K-means clustering algorithm to identify four groups of similar counties. Then, we fit Bayesian linear models without slopes to compare the 12 variables among the four clusters (*brms* package; Bürkner, 2017) and ran a Principal Component Analysis (PCA) to evaluate linear relationships among all variables (*ggfortify* package; Horikoshi et al., 2026).

We further evaluated if counties with very high risks are more likely than random chance to have very high wetland ecosystem services or very low ecosystem services. First, we ran separate PCAs on the four service variables and the eight risk metrics for the same wetland flood-duration threshold, SSP, and future climatology period as the clustering and linear model analyses. Given the high respective collinearity of the services and risks (Figure D1), we extracted the first principal component from each PCA to use as variables and used BiCopSelect() to identify the bivariate copula family that minimized the Akaike Information Criterion (AIC; *VineCopula* package; Nagler et al., 2025). Finally, we used this minimum-AIC copula to calculate the upper tail dependence coefficient, which measures the coincidence of high risks and high services, and repeated this analysis with the ecosystem service axis inverted to measure the cross tail dependence coefficient, which measures the coincidence of high risks and low services.

3 Results

3.1 Spatial distributions

3.1.1 Ecosystem services

All four wetland ecosystem services have a bimodal distribution with the greatest county totals occurring in northeastern and southwestern Illinois (IL; Fig. 1). Consequently, county-level wetland ecosystem services are generally highest in the Northeastern Morainal and Shawnee Hills/Coastal Plain natural division groups, somewhat elevated in the Western Forest-Prairie and Southern Till Plain/Wabash River Border natural division groups, and lowest in the Grand Prairie and Wisconsin Driftless/Rock River Hill Country natural division groups (Figure B1).

3.1.2 Protection status and conversion risk

Outside the Northeastern Morainal natural division, which has negligible unprotected wetland areas yet high wetland services, county-level unprotected wetland areas tend to follow the spatial distribution of wetland services (Fig. 2a). Thus, unprotected wetland areas are second least in the Wisconsin Driftless/Rock River Hill Country natural division group, intermediate in the Grand Prairie and Western Forest-Prairie natural division groups, and greatest in the Southern Till Plain/Wabash River Border and Shawnee Hills/Coastal Plain natural division groups (Figure A4).

Unprotected wetland percentages share the broad increasing trend of unprotected wetland areas from north to south but are more shifted toward east central and southeastern IL (Fig. 2b). This led to greatest unprotected percentages in the Southern Till Plain/Wabash River Border and Grand Prairie groups, intermediate percentages in the Western Forest-Prairie and Wisconsin Driftless/Rock River Hill Country groups, and least percentages in the Shawnee Hills/Coastal Plain and Northeastern Morainal groups (Figure A4). Just like unprotected areas, unprotected percentages within each group exhibit the greatest increase when the WOTUS requirement for wetland flood duration is raised from at least seasonal to at least semipermanent and thereafter plateau with increasing flood-duration requirements.

Wetland areas converted to row crops from 1987 to 2024 are more spatially variable than either protection status metric (Fig. 2c). There is a clear trend in lower recently converted areas where historical wetland drainage for agriculture and urban development was greatest and higher recently converted areas outside these regions (Suloway & Hubbell, 1994). Consequently, recent wetland conversion to agriculture is lowest in the Northeastern Morainal and Grand Prairie groups, intermediate in the Western Forest-Prairie and Wisconsin Driftless/Rock River Hill Country groups, and greatest in the Southern Till Plain/Wabash River Border and Shawnee Hills/Coastal Plain groups (Figure A5). Wetland areas recently converted to medium or high intensity impervious cover are concentrated around the state's major urban areas (Fig. 2d). However, recently converted wetland areas are greatest by two orders of magnitude in the Northeastern Morainal natural division, which includes the Chicago metropolitan area (Figure A5).

3.1.3 Projected changes in climate extremes

The projected changes in temperature-driven climate metrics (decrease in frost days and increase in days with maximum temperature greater than 100°F [38°C]) also have a north-south gradient similar to the trends in unprotected wetlands areas (Figs. 3a and 3b). Moreover, these projected changes consistently increase over time for a given Shared Socioeconomic Pathway (SSP) and with greenhouse gas emissions (GHG) for a given future climatology period across every group of state natural divisions (Figure C1).

Compared to temperature-driven climate extremes, the projected increase in maximum dry spell length is more shifted toward east central and southeastern IL and therefore more like the spatial trend in unprotected wetland percentages than areas (Fig. 3c). Of all climate metrics evaluated, the projected increase in maximum wet spell length is the most spatially variable (Fig. 3d). Although projected changes are generally lower in northern than southern IL, there is a large cluster of counties with high projected changes in central IL.

Despite this, the increase in maximum wet spell length is greater than zero for all SSP and future climatology period combinations across natural division groups, whereas the increase in maximum dry spell length is only greater than zero in the Southern Till Plain/Wabash River Border and Shawnee Hills/Coastal Plain groups (Figure C1). Similarly, the increase in maximum wet spell length tends to worsen over time for a given SSP and with GHG emissions for a given future climatology period, but the increase in the maximum dry spell length only worsens with time and GHG emissions for the natural division groups where it is consistently greater than zero.

3.2 Statistical analyses

3.2.1 K-means clustering

The K-means clustering algorithm divided Illinois counties into four groups that are mostly spatially contiguous (Fig. 4), which we chose to describe as southwest (n = 27), southeast (n = 30), northeast (n = 6), and northwest (n = 39) despite the southeast and northwest groups including parts of east central IL. These clusters broadly represent two climate risk categories split into subgroups of counties with higher versus lower wetland ecosystem service values, recently converted wetland areas, and degrees of wetland protection.

Despite having greater projected reductions in frost days, the two northern IL clusters have lower projected increases in days with maximum temperature over 100°F [38°C], maximum dry spell length, and maximum wet spell length. Compared to northwestern IL, however, northeastern IL has much greater wetland ecosystem services and areas recently converted to impervious cover, somewhat greater wetland areas recently converted to row crops, and lower unprotected wetland areas and percentages. Conversely, the two southern IL clusters are projected to have lower reductions in frost days yet more days with maximum temperatures over 100°F [38°C] and longer maximum dry and wet spells. Among these clusters, southwestern IL has greater wetland ecosystem services, wetland areas recently converted to row crops and impervious cover, and unprotected wetland areas than southeastern IL, which has greater unprotected wetland percentages. Thus, climate and conversion risk are greatest in the two regions with the most wetland services, but conversion risk to urban development is greatest in the northeast, whereas climate risk and conversion risk to agriculture are greatest in the southwest.

3.2.2 Principal component analysis

We visualized the first two PCA axes because they explain over 50% of variance (29.8% and 24.1%) and because there is a large decrease in variance from the second to third axis (24.1% to 10.8%) (Fig. 5). The first axis is primarily a climate risk, conversion type, and wetland protection gradient from counties with higher projected reductions in frost days and wetland areas recently converted to impervious cover to counties with higher projected increases in days with maximum temperature over 100°F [38°C], maximum dry and wet spell lengths, unprotected wetland areas and percentages, and wetland areas recently converted to row crops.

The second axis is primarily a wetland ecosystem service gradient from counties with lower to higher biodiversity (plant and herpetofauna species richness) and biophysical (carbon storage and floodwater storage capacity) services. Nonetheless, the first axis has a weak positive correlation with herpetofauna species richness and weak inverse correlation with all other services. Along the second axis, all four wetland services have a positive correlation with unprotected wetland area, wetland area recently converted row crops and impervious cover, and projected increases in days with maximum temperature over 100°F [38°C] and maximum wetland spell length. Hence, these services have an inverse correlation with the unprotected wetland percentage, projected reduction in frost days, and projected increase in maximum dry spell length.

These axes created strong separation among the four regional clusters identified with the K-means algorithm. The first axis effectively divided the clusters by latitude with the two southern IL clusters having more wetland climate risk, conversion risk to agriculture, and unprotected wetland area than the two northern IL clusters, which have more risk of conversion to impervious cover. This axis further illustrates how the northeastern IL cluster has less climate risk and unprotected wetland area but more area recently converted to impervious cover than the northwestern IL cluster. The second axis divides the clusters into two groups with different levels of wetland services and conversion rates, with southwestern and northeastern IL having greater services and recently converted wetland areas than southeastern and northwestern IL.

3.2.3 Bivariate copula

The bivariate copula family that minimized the AIC for the climate and conversion risk axis versus the wetland ecosystem service axis is the Student-t copula, which has symmetric upper and lower tail dependence (Fig. 6). Specifically, we found that the correlation between the two axes was weak (Kendall's tau of 0.11), but there was a modest tail dependence coefficient ($\lambda_U = \lambda_L = 0.20$). This implies that counties with greater wetland services have a non-random spatial co-occurrence with counties that have greater wetland areas recently converted to row crops, unprotected wetland areas and percentages, and projected changes in all climate metrics except the reduction in frost days. Moreover, due to the symmetry of the Student-t copula, counties with low services have a non-random spatial co-occurrence with counties that have greater wetland areas recently converted to impervious cover and projected reductions in frost days. By inverting the ecosystem service axis, we also found a weak cross tail dependence coefficient of

0.09, which indicates that counties with low services are somewhat less likely to coincide with six of the eight risk variables than counties with high services. However, counties with low wetland services are still not independent of those with high values for climate risk, unprotected wetland area, and wetland area recently converted to row crops.

4 Discussion

4.1 Current best estimates for unprotected wetland area

As the global climate continues to warm, communities across the world have experienced more intense weather-driven natural disasters, including wildfires (Jolly et al., 2015), heat waves (Russo et al., 2014), droughts (Yuan et al., 2023), and floods (Hirabayashi et al., 2013). Wetlands have the potential to reduce these climate impacts by attenuating flood peaks, providing evaporative cooling, storing water, and creating refugia from wildfire and extreme heat (Ahongshangbam et al., 2025; Endter-Wada et al., 2020; Markle et al., 2022). However, substantial historical drainage and filling of wetlands across Illinois (Suloway & Hubbell, 1994), the United States (Lang et al., 2024), and world (Fluet-Chouinard et al., 2023) has reduced the availability of this natural climate resilience. Furthermore, wetlands are facing increasing risk of degradation and destruction without compensatory mitigation after the 2023 *Sackett* decision narrowed federal Clean Water Act (CWA) permitting requirements to only those wetlands with a continuous surface connection to relatively permanent waters (Grewal & Scanlan, 2025). Thus, protecting and restoring wetlands is essential not only for helping threatened and endangered species but also for helping communities adapt to a changing climate.

Among US states, Illinois has the sixth greatest percentage of historical wetland losses, with 85% of its former 3.3 million hectares (8.2 million acres) drained between the 1780s and 1980s (Dahl, 1990). Since then, an additional 3–5% has been lost (Peterson et al., 2025; Suloway & Hubbell, 1994). Given limited agency guidance on criteria for “continuous surface connection” and “relatively permanent”, we previously estimated that up to 72.1% of remaining state wetland area could be non-federally jurisdictional under the CWA if wetlands must have at least seasonal flooding to qualify as WOTUS. However, our estimate for non-WOTUS wetland area increases to 94.6% if US agencies adopt a wet season requirement for relatively permanent, which exactly agrees with a previous national analysis (Gold, 2024; USACE & USEPA, 2025). This percentage would reach 97.5% if the WOTUS definition is further narrowed to require wetlands to have perennial surface water except for anomalous or non-anomalous events including droughts or dry spells lasting no more than 30 consecutive days per year (USACE & USEPA, 2026). If the agencies delete the definition of adjacent, our estimate reaches the highest possible value at 99.7% because few wetlands are permanently flooded and directly abutting an RPW. While this uncertainty cannot be resolved until the final rule is issued, 94.6–99.7% of state wetland area being non-WOTUS translates into 70.1–73.3% lacking any form of legal protection because the Illinois does not have broad permitting requirements beyond the federal standard except for state-funded activities (Kihslinger et al., 2024).

Although *Sackett* impacts on streams have been underemphasized relative to wetlands, our updated flow permanence categories based on Brinkerhoff et al. (2024) support that 84,600 km (52,568 mi or 43.9%) of Illinois streams are ephemeral and therefore guaranteed to be non-WOTUS under the Amended 2023 Rule and current rule proposals. An additional 49,067 km (30,489 mi or 25.5%) of Illinois streams are intermittent, so all of these stream kilometers could also be non-WOTUS if perennial flow is adopted as the relatively permanent standard (USACE & USEPA, 2026). Because nonperennial streams have an important role in flood attenuation, water supply, nutrient fluxes, and trophic dynamics, it is likely that impacts on these 133,667 vulnerable stream kilometers will synergize with impacts on unprotected wetlands (USEPA, 2015).

4.2 Regional actions for wetlands in climate adaptation

Illinois’ remaining unprotected wetlands and their ecosystem services are unevenly distributed across the state due to regional variation in wetland types, historical conversion to agriculture and urban development, and nonfederal protection measures, including parks, preserves, easements, and county ordinances. Similarly, the vulnerability of communities surrounding wetlands to future climate extremes varies spatially with factors that affect hazard exposure, including time, greenhouse gas emissions, and watershed position, and factors that affect hazard sensitivity, including socioeconomic status, resources access, and built infrastructure (Thomas et al., 2018). Given this spatial heterogeneity in wetland services and risks, together with limited financial and institutional resources for climate adaptation (Bierbaum et al., 2013), policy and management actions will be most effective when focused on vulnerable areas and tailored to local community needs. For example, the Resist-Adapt-Direct framework has been developed as a heuristic guide for conservation managers to select from policy alternatives given practical constraints, organization goals, climatic uncertainty, and ecological trajectories (Sesser et al., 2025). Although wetlands are one aspect of a broader climate adaptation

portfolio with technology- and nature-based solutions (Singh et al., 2020), here we propose a general framework for incorporating wetland protection, restoration, and enhancement into climate adaptation (Fig. 7). Then, we applied this framework to the four groups of Illinois counties that we identified based on their similar wetland services, unprotected wetland areas and percentages, wetland areas recently converted to row crops and impervious cover, and projected shifts in four climate extremes.

As expected, southwestern IL counties have the greatest average unprotected wetland areas among the four regional clusters due to their lack of county permitting requirements and lower historical wetland losses before 1987 (Suloway & Hubbell, 1994). Additionally, these large wetland areas are associated with the most wetland-dependent herpetofauna species richness among all four regional clusters and more wetland-dependent plant species richness, carbon storage, and floodwater storage capacity than all regional clusters except northeastern IL. Despite impacts from agriculture and hydrologic modification, this far southern IL region is still home to rare wetland types with unique plant and animal species, including swamps with *Taxodium distichum* (baldcypress) and *Nyssa aquatica* (water tupelo) (Duram et al., 2004; Middleton, 2023). These swamps are common throughout the Mississippi River Embayment and reach their northernmost extent in Illinois' Coastal Plain natural division. The most notable example of this community type is the Cache River and Cypress Creek wetland complex, a Ramsar Wetland of International Importance (Convention on Wetlands Secretariat, 2014). Although southwestern IL has significant areas of public and private land managed for biodiversity or multiple uses (Figure A6), wetlands outside designated parks, preserves, and easements are vulnerable to traditional direct impacts (e.g., drainage, filling, or vegetation removal). Indeed, the average county wetland areas converted to row crops from 1987 to 2024 in southwestern IL greatly exceeded those in all other regional clusters (Fig. 4). By contrast, the average county wetland areas recently converted to impervious cover in southwestern IL were much lower than those in northeastern IL but still greater than those across the rest of the state and concentrated around metropolitan areas.

Alongside conversion risk, the wetlands in southwestern IL face disproportionate risk of warmer temperatures and shifting rainfall patterns altering their hydroperiod and species composition because southwestern IL counties drive the non-random spatial coincidence between wetland ecosystem services and future climate extremes. For example, more prolonged dry periods and extreme flood-drought cycles could limit regeneration of keystone swamp species like *T. distichum* (Lei & Middleton, 2018). Alternatively, more extreme heat and late-summer water deficits could increase the mortality of state threatened or endangered amphibians that depend on aquatic refugia for body-temperature regulation (Pottier et al., 2025) and rely on the forested bottomlands or swamps of southern IL (Figure B2; Crawford et al., 2021). Hence, the top priority action in this region should be to protect the existing species-rich and culturally significant wetlands. One option for doing this is to expand the wetland area in conservation management through collaboration with private and public landowners (e.g., Cache River Joint Venture Program), which can be improved by resolving challenges associated with conflicting organizational goals, budget structures, and decision-making strategies (Behnken et al., 2016). Another option is to establish baseline permitting requirements that go beyond the current federal CWA standard and that are robust to future rulemaking changes. While reducing carbon emissions is critical for limiting climate impacts, local management actions could alleviate local stressors, such as hydromodification, nutrient enrichment, and invasive species, to increase the resilience of these wetlands to more intense seasonal weather variation (Erwin, 2009).

Despite having lower unprotected wetland areas, recent conversion rates, and ecosystem services than southwestern IL counties, southeastern and northwestern IL counties have marginally greater average unprotected wetland percentages of their remaining wetland areas. Although geographic distance (i.e., lack of direct abutment) can disqualify a wetland as WOTUS, this spatial trend is mostly due to wetlands in southeastern and northwestern IL not meeting the federal standard for having flooding at least during the wet season, which could be associated with higher elevation watershed positions (Figure A7). Ultimately, the combination of temporal and spatial federal requirements for wetland connectivity to relatively permanent surface water implies that an average of more than 70% of wetland areas across nearly 70 state counties are vulnerable to traditional direct impacts. Furthermore, all Illinois communities will experience more intense climate extremes, but the southeastern IL county group has low wetland services due to significant historical wetland losses yet has the second highest or highest projected changes in extreme heat, maximum wet spell length, and maximum dry spell length. Hence, these counties have less resilience to future climate-driven natural disasters, including more intense rainfall, because of their limited floodwater storage capacity (Gourevitch et al., 2026). It follows that restoration should be the highest priority wetland action strategy for climate adaptation in this agricultural region. As with southwestern IL, expanding legal protections through permitting requirements or public conservation areas can help prevent net loss in wetland area and function, especially around major cities. However, stakeholders can also explore voluntary restoration through programs like the USDA Agricultural Conservation Easement Program, which have improved water quality throughout the Mississippi River Basin (Karwowski & Skidmore, 2025).

Surprisingly, northeastern IL has a juxtaposition of high wetland services and recent conversion to impervious cover yet low unprotected wetland areas and projected changes in all climate extremes except the reduction in frost days. The high wetland biodiversity of this region, which intersects the Northeastern Morainal natural division, is consistent with the heterogenous geology and unique flora associated with repeated glaciation and proximity to Lake Michigan (Zinnen et al., 2026). Additionally, the elevated wetland carbon stocks are due to the region's abundant histosols (Lilleskov et al., 2025). The near-zero unprotected wetland areas were also expected due to eight county ordinances having some degree of wetland permitting and mitigation requirements. Despite offering weaker safeguards from conversion than parks, preserves, or easements, we considered these ordinances an important form of local wetland protection because they maintain the baseline mitigation policy that has been lost due to Supreme Court decisions and offer policy stability across rulemaking changes with each administration. Since most of these eight ordinances define their jurisdictional waters as everything that is non-federal, wetland impacts in these counties should continue to be mitigated elsewhere, although policy enforcement may vary. However, this does not imply that wetland area and function in this region is not at risk of impairment, which is evident from the high wetland conversion to impervious cover between 1987 and 2024. While the growth of the mitigation banking industry has improved restoration outcomes relative to permittee-responsible mitigation, neither are guaranteed to replace services lost after these permitted impacts to wetlands, especially those with more carbon-dense soils or native plant community richness (Ballantine and Schneider, 2009; NRC, 2001; Tillman and Matthews, 2023).

As with traditional impacts, these carbon- and species-rich wetlands are likely to be the most vulnerable to future climate change. Specifically, the greater reduction in frost days northern IL could lower native wetland plant diversity by promoting the spread of invasive species (Hou et al., 2014) and lower native herpetofauna diversity by reducing cold tolerance and increasing wintertime metabolic activity (Bukaita, 2026; Schmidt et al., 2024). By enhancing microbial decomposition, altered hydrology and warmer soils could further accelerate the degradation of peatlands, which represent a disproportionate share of global wetland carbon storage (Page & Baird, 2016). When considering the other three of four climate metrics, northeastern IL is expected to have the least absolute change in exposure to climate extremes. However, net climate impacts depend on local variables, such as built infrastructure, land cover, population density, and community sensitivity (Hunt & Watkiss, 2011). Namely, the dense impervious surfaces typical of urban infrastructure are likely to synergize with future extreme heat (Zhao et al., 2018) and rainfall (Skougaard Kaspersen et al., 2015), thereby exacerbating negative impacts on the surrounding population beyond those suggested by raw climate projections. Aging combined sewer systems are also increasingly susceptible to overflow during rainfall events, which is exacerbated by lack of open space for infiltration (Zou et al., 2026). Thus, many additional nature-based adaptation efforts, such as tree planting, rain gardens, and green roofs, will be essential for improving community resilience to more frequent and intense climate hazards. With respect to wetlands, the priority action we recommend is to enhance and preserve existing wetland services by limiting the need for compensatory mitigation. This can be achieved by emphasizing impact avoidance and minimization as permit conditions and increasing the area of wetlands managed for biodiversity (e.g., through parks, preserves, or easements). To prevent gradual declines in wetland area and function, it could also be beneficial to reduce categorical exclusions for smaller and lower quality wetlands, which are still important for water purification and flood mitigation. In fact, nutrient enrichment reduces species diversity, so lower floristic quality could be indicative of a wetland serving as a nutrient sink (Jessop et al., 2015).

In summary, we recommend that stakeholders prioritize enhancing wetlands in northeastern IL, protecting them in southwestern IL, and restoring them elsewhere to conserve valuable ecosystem services and promote community resilience to future climate change. Nonetheless, it is important to emphasize that these three actions are not mutually exclusive and can be applied in any region. Despite being highest priority in watersheds with the most historical losses, wetland restoration should be undertaken in all IL counties with sufficient resources and landowner interest. Similarly, those restoration efforts have the most potential for leading to net gains in state wetland services and therefore climate adaptation if wetlands are protected by legal mechanisms such as conversation easements or basic permitting requirements formerly offered by Section 404 of the CWA. Wetlands across Illinois (Price, 2019) and the world (Zedler & Kercher, 2005) have also undergone long-term declines in quality because of non-native species invasion, woody encroachment, nutrient enrichment, and hydromodification associated with urban and agricultural intensification. Thus, all wetlands have the potential to benefit from enhancement, which could involve direct management interventions like removing invasive species or reducing external stressors like pollutant inputs by establishing wetland buffer strips (McElfish et al., 2008), which are also important for many amphibians and reptiles that require access to uplands and water (Semlitsch & Bodie, 2003). As narrow buffers alone can be insufficient to prevent wetland impairment, an even more holistic approach should consider reducing downstream impacts at the watershed scale by protecting and restoring terrestrial ecosystems, including forests and grasslands (Houlahan & Findlay, 2004).

4.3 Method limitations and generalizability

The goal of this analysis was to synthesize accessible public data on wetland services, risks, and protection status to guide the prioritization of wetland management actions at the regional scale. However, there are necessarily limitations of aggregating disparate information sources into spatial zones, like watersheds, counties, or natural divisions, that are larger than the scale of ecological processes and climate impacts. For example, wetland plant and herpetofauna species are not uniformly distributed across wetlands in a county due to variation in wetland impairment, soil, and hydrology. Thus, a certain percentage of county wetland area being unprotected does not translate into the same percentage of county wetland species being unprotected. Moreover, recent impacts of land use change may not be reflected in natural history databases, which could imply that we overestimated current wetland biodiversity levels, especially in urban northeastern IL (Chu & Molano-Flores, 2013). Similarly, using aboveground floodwater storage capacity derived from a digital elevation model as a proxy for wetland flood control benefits could be biased toward depressional wetlands with a discrete boundary. Hence, our approach is likely to have underestimated the storage capacity of linear floodplain wetlands and flood attenuation benefits due to surface roughness (Gourevitch et al., 2026). Beyond persistent uncertainty in wetlands' net GHG fluxes, both our floodwater storage capacity and carbon storage estimates cannot resolve legacy omission and commission errors in the National Wetland Inventory (Matthews et al., 2016). Lastly, we relied on average projected changes in climate extremes derived from LOCA statistical downscaling of output from Earth System Models, both of which have difficulty capturing fine-scale extreme precipitation events despite improvements from CMIP6 to CMIP5 (Pierce et al., 2023).

Another recent study demonstrated how empirical modeling with literature-based parameterization can be used to estimate wetland floristic quality and functions (Pang & Deal, 2026). However, the comparative simplicity of our data-driven approach readily lends itself to generalization and upscaling. Zonal estimates of wetland-dependent species richness could be made for any region with historical species distribution maps if integrated with criteria for wetland dependence, such as the IUCN habitat requirements or wetland indicator status values. For example, the data in Zinnen et al. (2026) used to make county-level maps of floral conservatism could be used to make county-level wetland-dependent plant species richness maps for six states in the midwestern US. Given the wide availability of digital elevation models and their increasing resolution (e.g., USGS 3D Elevation Program), maps of wetland aboveground floodwater storage capacity could be developed for the entire US. Similarly, rasters of soil organic carbon stocks from US databases like gNATSGO and global databases like SoilGrids 2.0 can be overlayed with wetland areal maps to estimate wetland carbon storage.

While there are resolution mismatches between wetland polygons and regional or global raster datasets, they still represent a starting point for mapping heterogeneous wetland services on a scale meaningful to policy and management and therefore offer an improvement over unit-area estimates (Costanza et al., 2014). Just like the initial effort for mapping wetland types and extent across the US had errors associated with the methods and imagery available at the time (Tiner, 1990), so too will initial efforts to map wetland values and services. Nonetheless, ongoing policy rollbacks (Gold, 2024), accelerating wetland losses (Lang et al., 2024), and persistent climate change (Xi et al., 2021) demand that we integrate the data available to inform the conservation and wise use of wetlands in the 21st century.

5 Conclusion

Nonstationary climate extremes and the evolving policy landscape are posing novel challenges to the remaining wetlands in Illinois and their essential societal co-benefits, including biodiversity, carbon storage, and flood control. Because of wetlands' important role in climate resilience, identifying where these conversion and climate risks intersect with low versus high wetland services is essential to help stakeholders spatially prioritize conservation actions and resources. By synthesizing available datasets and considering likely policy scenarios, we estimated that 94.6–99.7% of the remaining state wetland area is not federally regulated and 70.1–73.3% is unprotected. Moreover, county-level unprotected wetland areas are greatest in southwestern IL where abundant wetland services coincide with the most risk of conversion to agriculture and worsening extreme heat, drought, and rainfall. Due to county permitting requirements, unprotected wetland areas are negligible in northeastern IL, yet this region has the most risk of conversion to urban development and loss of freezing days. Although unprotected wetland areas and conversion risks are lower outside these two regions, counties in southeastern and central IL have limited wetland services to buffer against relatively high exposure to future climate extremes. Thus, preserving wetlands where services are high at the northern and southern ends of the state but restoring wetlands where services are low elsewhere will help to maintain and increase the nature-based climate resilience of Illinois' communities.

Declarations

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

C. P. wrote the original manuscript draft, conducted statistical analyses, and prepared the figures and tables. J. W. reviewed the manuscript and provided research supervision. All authors helped acquire funding and conceptualize the research objectives and methods.

Data availability

All code and county summaries used to run statistical analyses are available at https://github.com/chelseamarpeterson/dual-climate-policy-wetland-risks. All input datasets used are publicly available: National Wetland Inventory (https://www.fws.gov/program/national-wetlands-inventory/download-state-wetlands-data), National Hydrography Dataset Plus High Resolution (https://doi.org/10.5066/P13V7GVY), Brinkerhoff et al. (2024) ephemeral stream data (https://doi.org/10.5281/zenodo.10658663), National Land Cover Dataset (https://www.mrlc.gov/data), National Levee Database (https://levees.sec.usace.army.mil/data-services/services/), Protected Areas Database of the United States (https://doi.org/10.5066/P96WBCHS), CMIP6-LOCA2 temperature (https://doi.org/10.5066/P13OV6GY) and precipitation (https://doi.org/10.5066/P13FGPRM) extreme metrics, gNATSGO (https://nrcs.app.box.com/v/soils/folder/364782695230) and SoilGrids 2.0 (https://docs.isric.org/globaldata/soilgrids/access_on_gee.html) soil organic carbon stocks, UNEP-WCMC above- and belowground biomass carbon stocks (https://doi.org/10.34892/QDB8-BH36), statewide digital elevation model (https://data.isgs.illinois.edu/arcgis/rest/services/Elevation/IL_Statewide_Lidar_DEM_WGS/ImageServer), vascular plant species by county (https://bonap.net/fieldmaps), and herpetofauna species by county (https://herpetology.inhs.illinois.edu/resources/species-lists/illinois-herpetology-species-by-county/).

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Figures

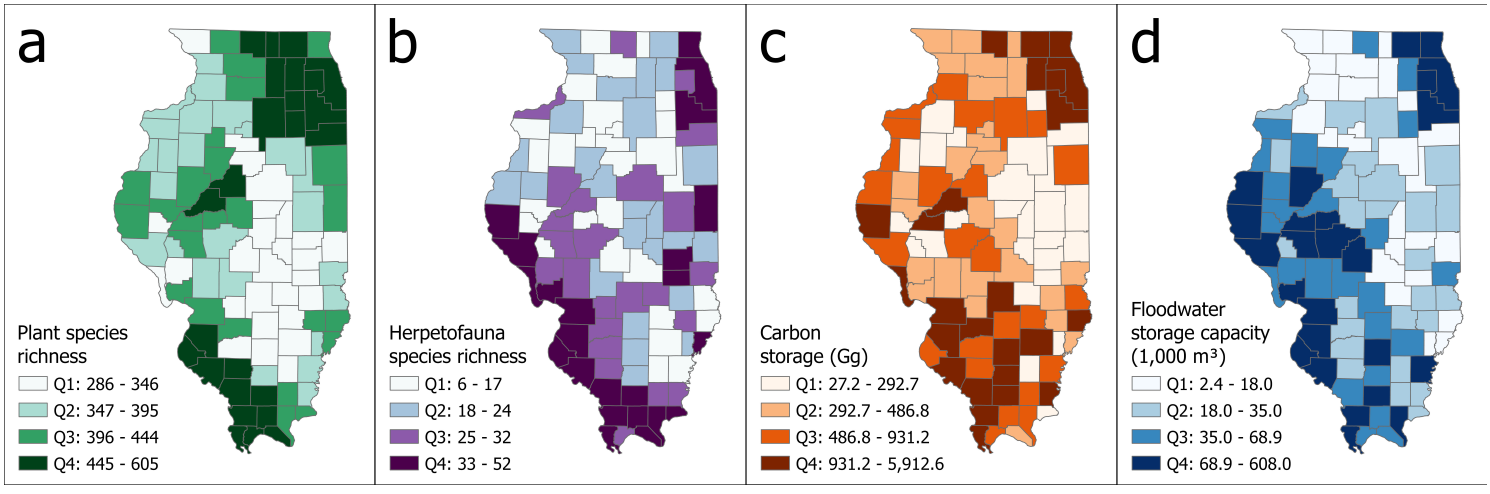


Figure 1

Spatial distribution of county-level estimates for wetland (a) plant species richness, (b) herpetofauna species richness, (c) carbon storage, and (d) aboveground floodwater storage capacity. The map legends provide the four county quantiles for each variable: Q1 (0-25%), Q2 (25-50%), Q3 (50-75%), Q4 (75-100%).

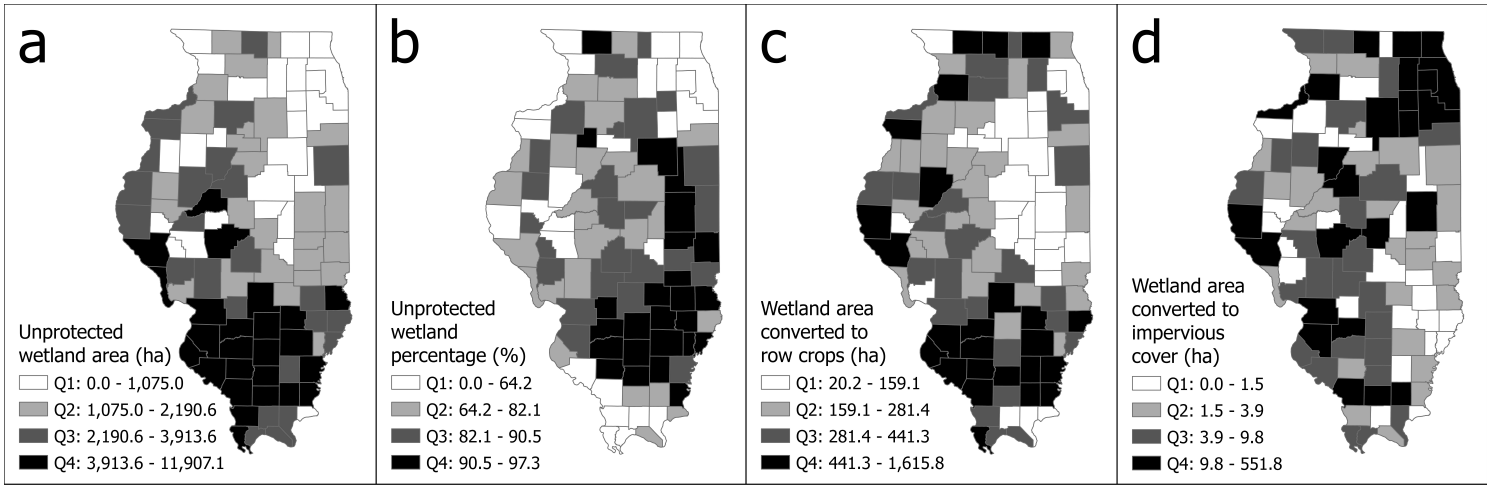


Figure 2

Spatial distribution of county-level estimates for average unprotected wetland (a) areas and (b) percentages if all wetlands without at least semipermanent flooding are excluded from WOTUS and total wetland areas converted to (c) row crops and (d) medium or high intensity impervious cover between 1987 and 2024. Averages for unprotected areas and percentages were calculated over four buffer-distance and flow-permanence policy scenarios. The map legends provide the four county quantiles for each variable: Q1 (0-25%), Q2 (25-50%), Q3 (50-75%), Q4 (75-100%).

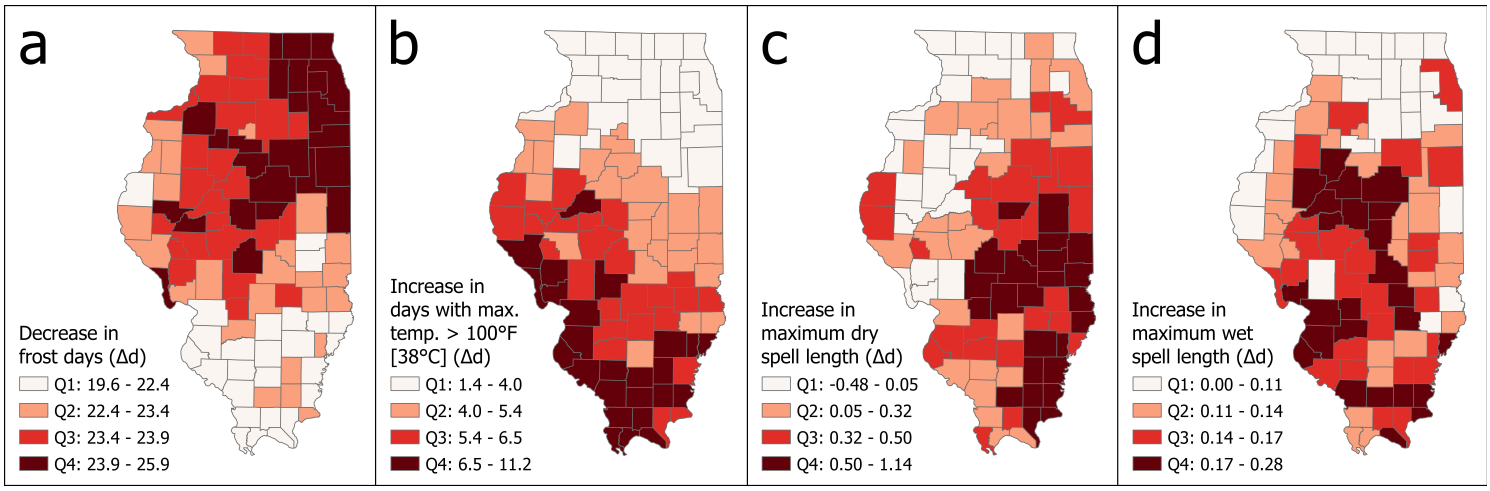


Figure 3

Spatial distribution of county-level averages for the projected (a) reduction in frost days and increase in (b) days with maximum temperature over 100°F [38°C], (c) maximum dry spell length, and (d) maximum wet spell length for SSP2-4.5 over the 2041-2070 future climatology period. The map legends provide the four county quantiles for each variable: Q1 (0-25%), Q2 (25-50%), Q3 (50-75%), Q4 (75-100%).

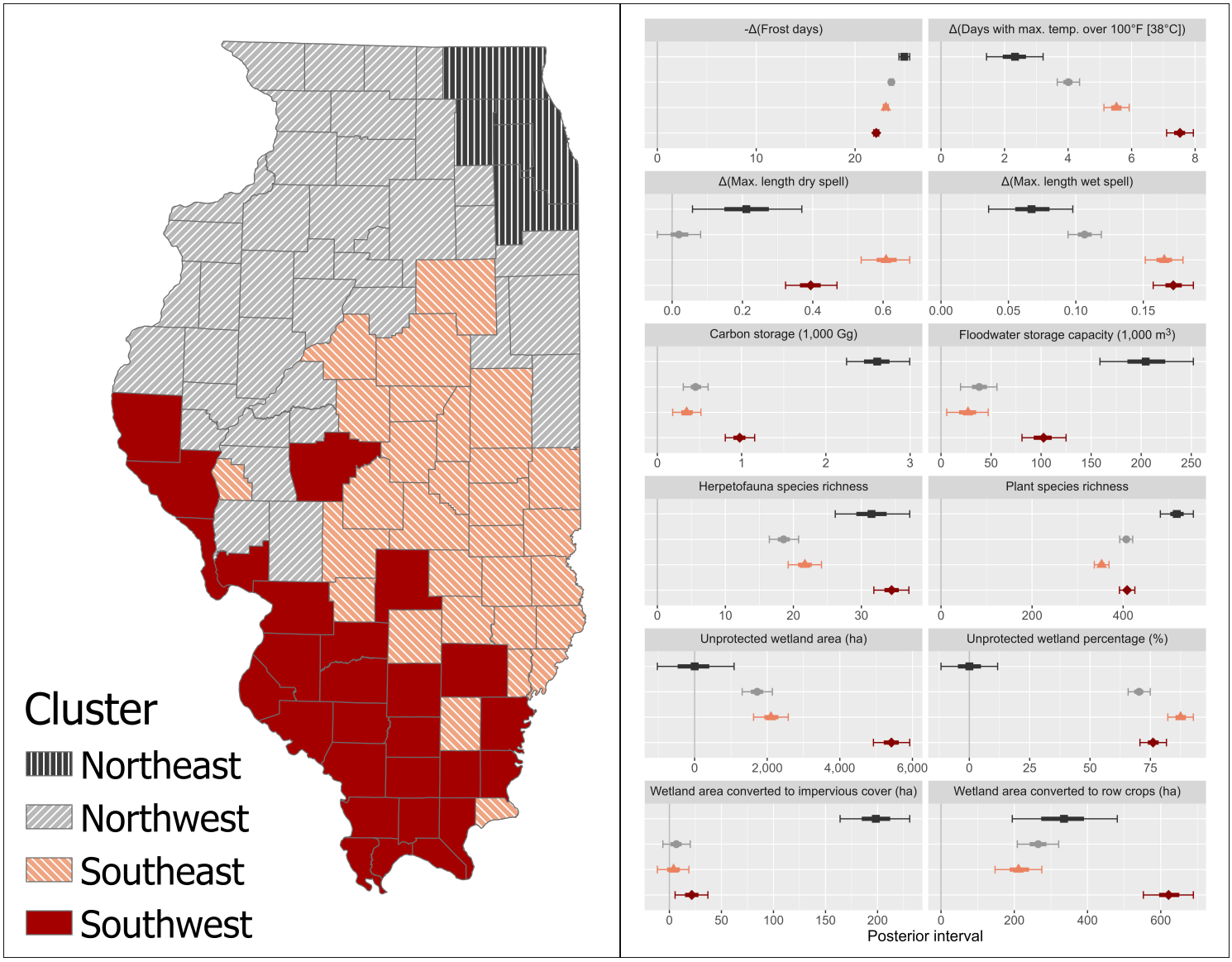


Figure 4

K-means clustering with four groups on twelve scaled county variables: projected changes in four climate extremes under SSP2-4.5 from 2041-2070, four wetland ecosystem services, average unprotected wetland areas and percentages if all wetlands without at least semipermanent flooding are excluded from WOTUS, and wetland areas converted to impervious cover and row crops between 1987 and 2024. Points indicate the posterior mean of each county-level variable within a cluster; the thicker and thinner bands around the points respectively indicate the 50% and 90% highest posterior density intervals.

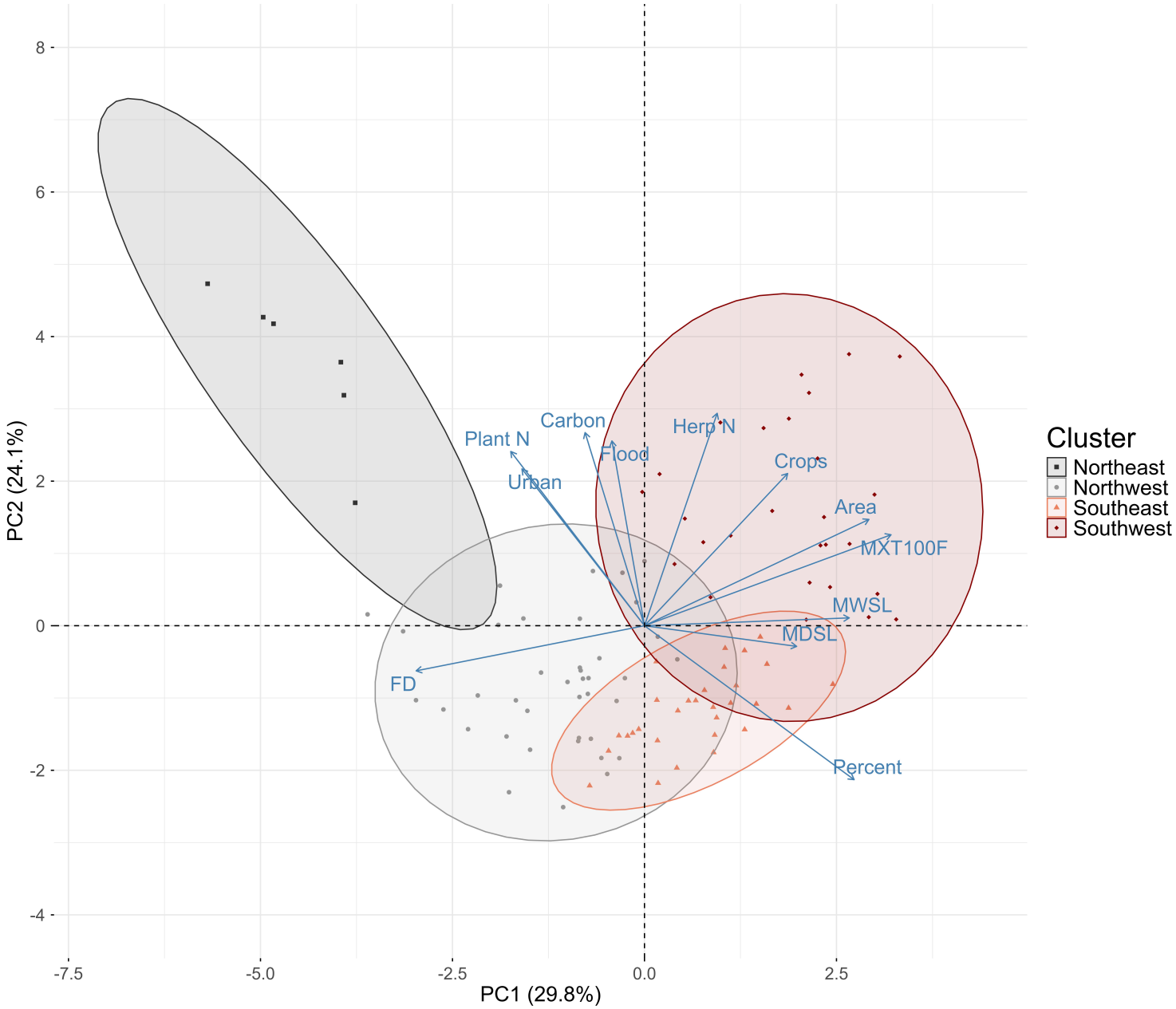


Figure 5

First two axes of principal component analysis on scaled estimates of twelve county-level wetland service and risk variables. The abbreviations for the variables are reduction in frost days (FD), increase in days with maximum temperature over 100°F [38°C] (MXT100F), increase in maximum dry spell length (MDSL), and increase in maximum wet spell length (MWSL), plant species richness (Plant N), herpetofauna species richness (Herp N), carbon storage (Carbon), floodwater storage capacity (Flood), unprotected wetland area (Area) and percentage (Percent), and wetland area converted to row crops (Crops) and impervious cover (Urban) between 1987 and 2024.

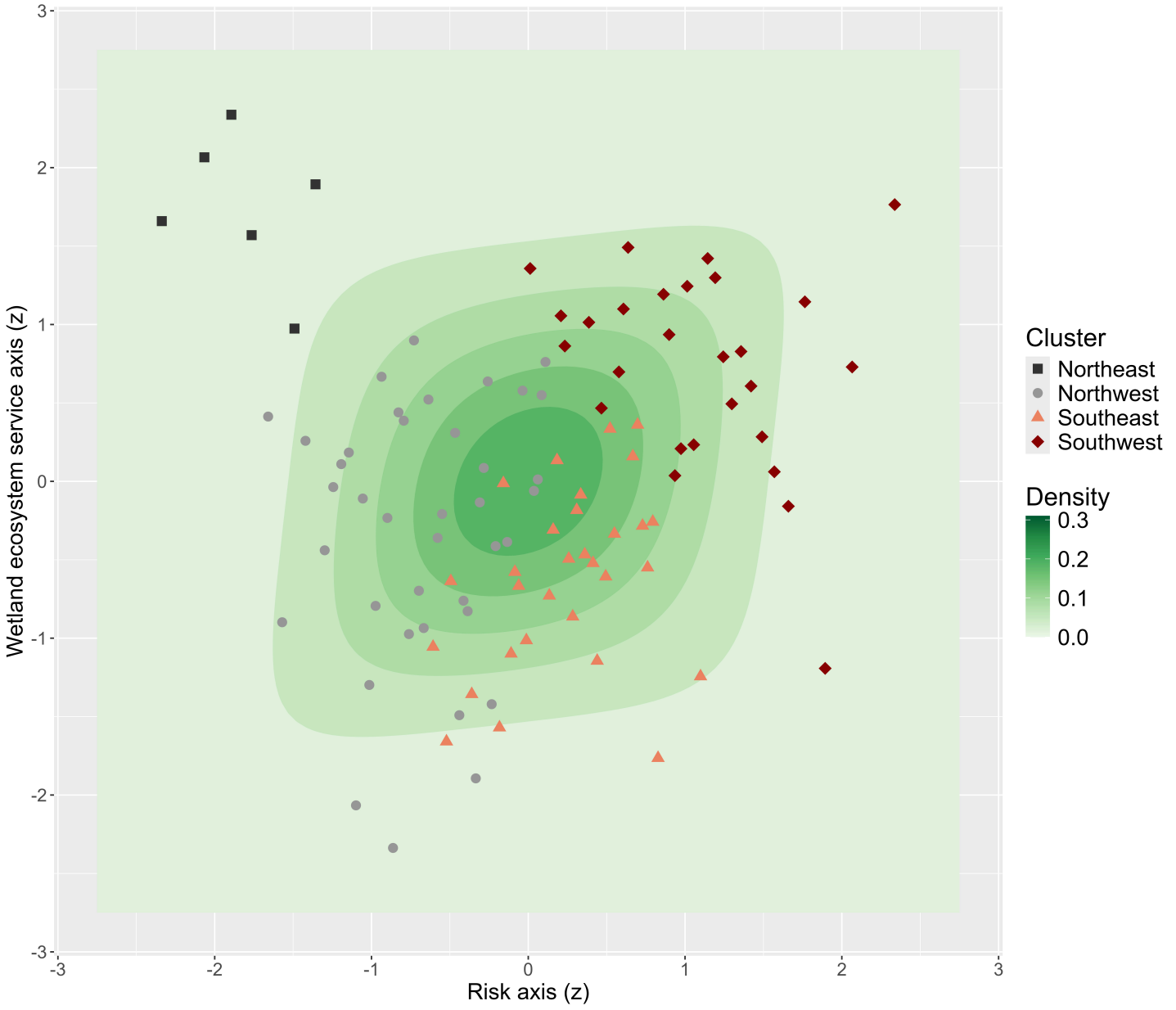


Figure 6

Student-t copula of wetland ecosystem service versus risk axis. These axes were created by extracting the first principal component from separate principal component analyses on the four scaled wetland services variables and the eight scaled risk variables, including four projected climate extremes, unprotected wetland areas and percentages, and wetland areas converted to row crops and impervious cover between 1987 and 2024 (Figure D1).

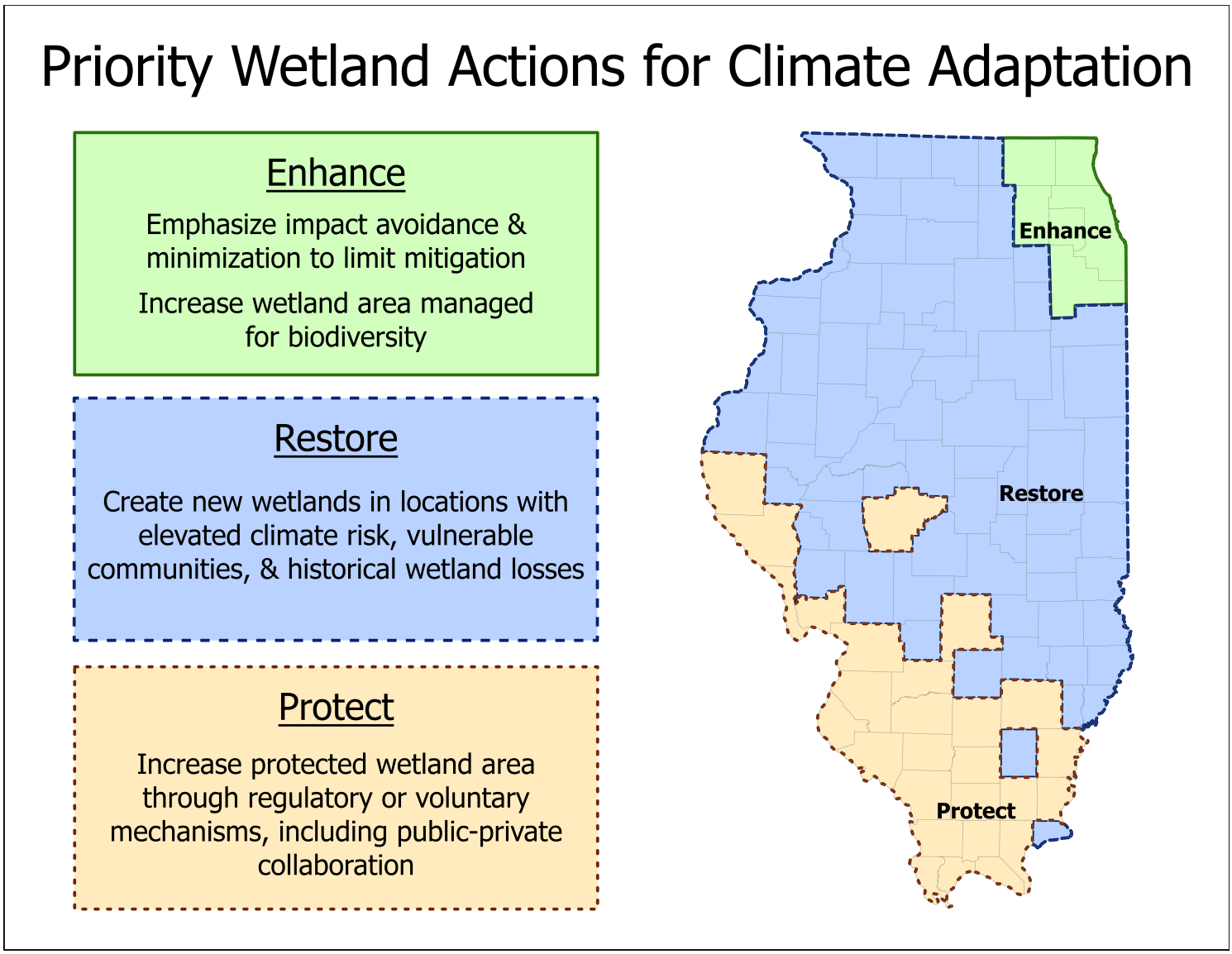


Figure 7

Recommended priority actions for integrating wetlands into climate adaptation by Illinois region based on clustering counties with similar wetland services, unprotected wetland areas and percentages, recently converted wetland areas, and projected climate extremes.

Supplementary Files

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- SuppInfoPolicyClimateImpacts.docx