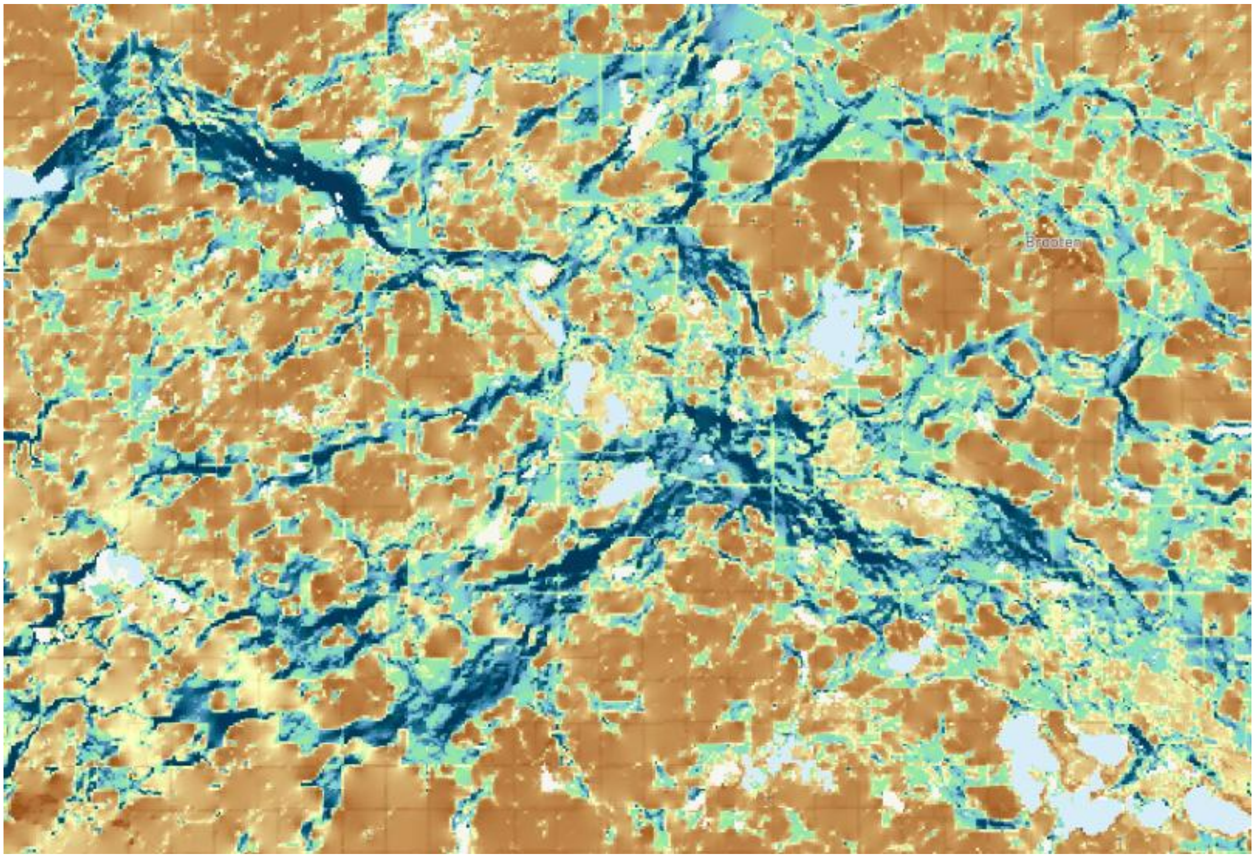

Mapping climate-informed habitat restoration priorities with multi-sector benefits for 3 Upper Midwest ecoregions

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SECTION 1. ADMINISTRATIVE INFORMATION

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SECTION 2. PUBLIC SUMMARY

Wildlife and plant species are adapted to specific environmental conditions, but climate change is shifting those conditions, prompting many species to move to more suitable habitats. This movement is a key climate adaptation strategy, yet it is limited by both species' dispersal abilities and the condition of the surrounding landscape. In the upper Midwest, large areas of row-crop agriculture, roads, and urban development reduce habitat connectivity, constraining species movement. Restoring prairie and forest habitats is essential to rebuild connectivity and support species adaptation.

Beyond ecological benefits, land restoration provides important societal co-benefits, including improved water quality through the reduction of nitrogen, phosphorus, and sediment runoff; increased carbon storage; and enhanced pollination services. However, restoration is costly, making it critical for practitioners to prioritize locations where benefits are maximized. This project aimed to identify areas where restoration would most effectively enhance habitat connectivity for climate adaptation while also delivering water quality, carbon, and pollination benefits. We used a collaborative process involving Tribal, state, federal, university, and non-governmental partners to model connectivity and ecosystem services for prioritization.

Results identified both prairie and forest restoration opportunities. While ecosystem service benefits are broadly similar between ecosystems, their spatial distribution varies: sediment and nitrogen retention are highest in the south, phosphorus retention in the northwest, and carbon storage and pollination benefits are dispersed. At the regional scale, priority restoration areas were identified by overlapping restorable land with zones of constrained connectivity. At the local scale, analysis in the Root River watershed indicated that prairie connectivity benefits were positively associated with wild bee habitat but negatively correlated with water quality and carbon outcomes. By applying different weighting approaches, specific parcels were identified that deliver multiple benefits. Integrating ecological and social outcomes enables better coordination among organizations and can increase landowner engagement in restoration efforts.

SECTION 3. PROJECT SUMMARY

Climate change driven range shifts pose a significant challenge for conservation management in the upper Midwest. One of the most common recommendations for supporting biodiversity under climate change is improving habitat connectivity, a goal that can be implemented through coordinated work to restore habitats that could act as movement corridors. However, facing the need to plan for many species with different traits, limited budgets, and the need to consider interactions with climate and land use change, planners need data and tools that help them more effectively consider different scenarios, and develop prioritizations that maximize conservation investment impacts. Our main objective was **to work collaboratively with agency land managers, Tribes, and other partners to identify high priority locations in the upper Midwest for habitat restoration to enhance connectivity that will support species' range shifts and contribute valuable ecosystem services**.

To achieve this objective, we assembled an Advisory Council (AC) of resource managers, scientists, planners, and other decision-makers representing U.S. federal, state, non-profit, academic and tribal entities in the region. Our first products identified current patterns of structural landscape connectivity for prairie and forest systems for an upper Midwest region that includes all of Minnesota, most of Wisconsin and Iowa, as well as eastern North Dakota and South Dakota. From these regional-scale, system-specific maps, we worked with our AC to select locations with high biodiversity value, where restoration actions were likely to be implemented by members of the AC and partners. For two sites within the larger geography, we conducted farm-field scale simulations in which agricultural lands were restored to prairie or forest, and we evaluated indicators of change in connectivity associated with these changes in landcover. One site was in a predominantly prairie location, and we focused on identifying prairie restoration locations that could most strongly enhance connectivity between existing grassland. The second case study site was in a prairie-forest transitional area, and we conducted simulations to explore both prairie and forest connectivity benefits and identified locations with potential for interference across the two system types. The specific rule sets used to simulate restoration actions were developed based on input from the AC. In the local-scale focal areas where we conducted these simulations, we leveraged region-wide estimates of ecosystem services, including nitrogen and phosphorus retention, carbon storage, and habitat availability for bees, a key group of pollinators. By aligning benefits for connectivity and this set of ecosystem services to the same units (representations of farm fields), we were able to develop a prioritization analysis that integrates these multiple benefits.

In response to the interests of our AC, we also developed approaches for evaluating restoration opportunity areas at the regional scale. While simulations of changes at the farm-field level were too computationally intensive to pursue for the entire region, we leveraged insights from the site-scale work to highlight restoration opportunity "zones" that can be readily evaluated with outputs from the ecosystem service modeling, and data representing climate change exposure information. We present these in our data viewer using simple rule sets that can be modified when products are downloaded. Our final products include a final report with a set of maps depicting restoration connectivity and co-benefit priorities for the two case study focal areas, a recorded webinar to describe the multiple benefits maps and their use in decision making, an online web tool and downloadable data publication through TNC's Conservation Gateway, and a peer reviewed publication detailing methods and outcomes (in progress).

Results identified both prairie and forest restoration opportunities. While ecosystem service benefits are broadly similar between ecosystems, their spatial distribution varies: sediment and nitrogen retention are highest in the south, phosphorus retention in the northwest, and carbon storage and pollination benefits are dispersed. At the regional scale, priority restoration areas were identified by overlapping restorable land with zones of constrained connectivity. At the local scale, analysis in the Root River watershed indicated that prairie connectivity benefits were positively associated with wild bee habitat but negatively correlated with water quality and carbon outcomes. By applying different weighting approaches, specific parcels were identified that deliver multiple benefits. Integrating ecological and social outcomes enables better coordination among organizations and increased landowner engagement in restoration efforts.

SECTION 4. REPORT BODY

Purpose and Objectives

Climate change driven range shifts pose a significant challenge for conservation management in the upper Midwest. The major ecoregions, which support diverse and distinct biodiversity and provide valuable benefits to society, are largely delimited by climate (Toot et al. 2020). Consequently, their distributions are expected to shift under climate change (Galatowitsch et al. 2009, Toot et al. 2020), requiring species to disperse and establish in new sites, in many cases through highly fragmented landscapes (Chaplin 2018). Improving habitat connectivity is one of the most common recommendations for supporting biodiversity under climate change (Heller and Zavaleta 2009, Prober et al. 2019), a goal that can be implemented through coordinated work to restore movement corridors, and investments in habitat protection to sustain existing networks (McGuire et al. 2016, Keeley et al. 2022). Here we use the term restoration to mean the reestablishment of prairie or forest plant communities to places that are currently in row crop agriculture. However, facing the need to plan for many species with different traits, limited budgets, and the need to consider interactions with climate and land use change (Costanza and Terando 2019), planners need data and tools that help them consider different scenarios and develop prioritizations that maximize benefits from connectivity restoration investments (Baldwin et al. 2012, Clark et al. 2023).

Taking action to sustain and improve connectivity at scales relevant for supporting species range shifts, is challenging because the connectivity value of any given place depends on its location in a complex and dynamic network (Dickson et al. 2017, Jennings et al. 2020). Across the upper Midwest, the amount of habitat loss, the type of habitats to reconnect, and the degree of climate change exposure varies, as does the support for and capacity to carry out restoration and protection work, making prioritization both possible and necessary. Yet, from a modeling perspective, evaluating the role of individual locations in supporting the broader network is a complex and computationally-intensive undertaking. A collaborative workflow that leverages products developed at different extents and scales can help us develop an understanding of how to restrict our most intensive assessments to sites with high benefits (Clark et al. 2023). Site-specific simulations of benefits from restoration provide a “search image” of where connectivity could be effectively strengthened, while consideration of large scale patterns in factors like exposure to climate change and locations relative to key thresholds or ecological boundaries may shift our priorities on which areas to emphasize as we work to bolster movement networks. For example, we might focus on areas where climate is changing the fastest to help support range shifts of sensitive species, or conversely, we might focus on places most likely to act as refugia, where improved connectivity can enhance access and gene flow. Engagement with practitioners to consider where actions align with focal adaptation strategies, and are likely and feasible (e.g., based on existing capacity, overlap with priorities, funding, and partnerships) represent an important step to further limit where to invest time on highly detailed restoration assessments. Here, we demonstrate a multi-scale, collaborative approach for informing the siting of restoration actions across the prairie to forest transition zone that was informed by connectivity and climate science, and the interests and capacity of engaged practitioners.

Even when connectivity science and practitioner goals and capacity align in a given section of habitat network, going from maps to successful implementation of restoration actions is a complex and expensive process. In recent reviews, Keeley et al. (2018a, 2018b) found that primary success factors for connectivity-focused conservation programs include corridor prioritization, engagement of broad coalitions of interested parties, and identification of co-benefits of the focal actions. Evaluating co-benefits of connectivity restoration such as carbon storage, water quality, and pollination services provides additional information for choosing among alternatives (Mooney et al. 2009, Pecl et al. 2017). The ability to share information on a range of benefits also can help broaden the coalition of support and expand access to funding for restoration actions. Our objective was to work collaboratively with land managers, Tribes, and other interested parties to identify locations where habitat restoration both enhances connectivity to support species' capacity to adapt to climate change, as well as contributes valuable ecosystem services. These data will provide restoration practitioners with information to improve the effectiveness and diversity of conservation outcomes from their restoration investments.

To achieve the objective of providing a "multi-benefit" data toolkit for evaluating restoration investments, we first identified a focal region. We chose to work in a key ecological transition zone, the prairie-forest border ecoregion of Minnesota that cross diagonally from northwest to southeast across the state. Ecotones represent a challenge for practitioners using existing structural connectivity models based on degree of naturalness (e.g., Anderson et al. 2023), as they fail to capture movement barriers associated with shift in dominant vegetation type. To ensure we produced products that were of interest to multiple partners, we expanded this region to include the extent of all TNC ecoregions that overlap Minnesota, resulting in a study area that includes all of Minnesota, most of Wisconsin and Iowa, as well as eastern North Dakota and South Dakota. By limiting the region, we were able to leverage our existing professional network of planners, resource managers, and other practitioners to build a team to help us co-develop focal questions and evaluate implementation capacity.

To ensure the project produced actionable science, we formalized our engagement by creating an Advisory Committee (AC) which included representation from six Tribal entities, four states, two state agencies, two federal agencies, one Joint Venture, three universities, and one non-profit organization. Through discussions with representatives of these interested parties, we identified decision-relevant analyses and products. Our process involved an iterative workflow in which our team discussed options with the AC and then parameterized and ran models for landscape connectivity and ecosystem service values that aligned with typical project sizes and practices applied by practitioners in our focal region. We convened the AC at the beginning to inform the initial direction for exploring the benefits of restoration actions on landscape connectivity, and six more times during the project to provide feedback and input on intermediate results and final products. We also met one-on-one with many of the AC members as relevant to frame focal area analyses or other specific products. To enhance product usability, we then explored several different ways to visualize the application and integration of data products. These included sharing products in a visualization platform, demonstrating ways to compare trade-offs between different connectivity and ecosystem service benefits, and presentation of a simple bivariate tool in which we applied thresholds to the regional-scale connectivity results and relevant additional variables that let us choose high opportunity areas across the full region. Our data viewer also includes several climate change exposure datasets of interest to the AC, facilitating consideration of climate drivers in key decisions.

We met the original objectives listed above, but one of the originally anticipated deliverables was adjusted along the way as we responded to input from the AC. We originally proposed the production of a final report depicting restoration connectivity and co-benefit priorities for four focal areas, a recorded webinar to describe the multiple benefits maps and their use in decision making, an online web tool and downloadable data publication through TNC's Center for Resilient Conservation Science, and a peer reviewed publication detailing methods and outcomes. The main adjustment to this list of objectives is instead of simulating how restoration actions could influence landscape connectivity in four smaller focal areas, we modeled connectivity and co-benefits for two small focal areas (one focal area included assessments for both forests and prairie connectivity, and interactions between options for those two system types). To further explore decisions related to restoration and connectivity, we created two regional-extent (a box that encompassed the extent of all TNC ecoregions that include Minnesota) connectivity restoration opportunity maps (one for prairie, one for forests) and expanded the co-benefit outputs to the project-wide area instead of just Minnesota. The AC provided direction for the focal area analyses.

In both large-group and one-on-one discussions with the AC, we identified many questions about restoration for connectivity in the region (Table 1). For the focal area geographies, where we planned to engage in detailed simulations of the connectivity benefits of different local actions, we were looking for both an interesting and feasible question, and clear interest and capacity for applying results. As we discussed possible focal areas geographies and connectivity restoration questions, it became clear that many AC members were interested in an analysis to identify restoration opportunity areas at a larger scale across the region. Therefore, instead of doing more small focal areas, we carried out parcel-scale connectivity modelling for four questions within two focal area geographies, and then we developed an analysis to identify the greatest opportunity regions for connectivity restoration across the project area for both prairie and forest. Through our engagement (and good luck related to project timing), one important outcome of this project was that the regional ecosystem connectivity results were included in Minnesota's State Wildlife Action Plan update, imbedding assessment products into a plan that drives many resource allocation decisions for the Minnesota Department of Natural Resources. Our remaining objective, to submit a paper to a peer-reviewed journal, is underway, and we expect to be able to submit something within the year that documents both the development and use of our analysis products.

Table 1. Subset of questions identified through Advisory Committee calls and one-on-one outreach calls to individual Advisory Committee members and their scale of analysis.

Questions	Scale of Analysis	Selected	Feasibility Comments
Where are the best places in the project area for prairie restoration?	Project area	Yes	Accomplished – products illustrate how criteria for "best" can be varied
Where are the best places in the project area for forest restoration?	Project area	Yes	Accomplished – products illustrate alignment with climate criteria
Where would you want to target restoration for refugia purposes versus movement and transition purposes?	Project area	Yes	Completed an example of how this could be done for species
As emerald ash borer moves through the region, where would the loss of black ash be most problematic to forest connectivity?	Project area	No	Challenge with obtaining high resolution maps of black ash such that gaps could be modeled

Where would loss of current prairie be most detrimental to current connectivity?	Project area	No	Feasible, but a protection priorities question rather than restoration question
What parcels should be prioritized for prairie restoration in the Glacial Lakes landscape?	Focal area	Yes	Accomplished
Where should high diversity prairie restoration occur to provide connectivity of high-quality habitats in prairie core areas?	Focal area	No	This question focused on where to pursue highest quality restoration, but our model treated movement potential as similar in different tiers of prairie quality, so not testable with this approach
Where should high diversity forest restoration occur to provide connectivity of high-quality habitat in forested landscapes?	Focal area	No	See above – this would require differentiating movement potential across different forest quality groups, so not testable without additional assumptions/data
Can forest restoration improve connectivity for snowshoe hare? Other species were also mentioned.	Focal area	No	Forest model products are highly relevant, but this specific question would benefit from use of a species-specific functional connectivity model that includes understanding of current hare distribution, habitat requirements, and behavior
What parcels if reforested contribute most to forest connectivity in the Root River watershed?	Focal area	Yes	Accomplished
What parcels if restored to prairie contribute most to prairie connectivity in the Root River watershed?	Focal area	Yes	Accomplished
Do the best parcels for improving connectivity for forests or prairie conflict in the Root River landscape?	Focal area	Yes	Accomplished

Organization and Approach

The project involved several bodies of work, including structural connectivity modeling, ecosystem service modeling, and several approaches for data visualization and integration, all guided by the input and direction of the AC. Our first products **1)** identified current patterns of structural landscape connectivity for prairie and forest systems for our focal region, a 75.9 million ha region including all of

Minnesota, Wisconsin and Iowa, as well as eastern North Dakota and South Dakota. We discussed and evaluated these products on their own, and with several additional datasets representing observed or projected climate change exposure patterns. To demonstrate an approach for multi-criteria prioritization of where to invest in restoration, we used these regional scale map products as inputs to inform a two-factor thresholding tool for highlighting "opportunity areas" which could then be visually overlayed on climate and ecosystem service data layers. **2)** From these regional-scale, system-specific structural maps, we worked with our AC to select locations with high biodiversity value, where AC members and partners were likely to be implementing restoration actions in the near future. For two sites within the larger geography, we conducted farm-field (parcel) scale simulations of restoration. For these sites, we ran structural connectivity models with hundreds of different input surfaces, with each surface representing a restoration action (agriculture to prairie or forest) on one parcel. We then evaluated "current flow" based indicators of change in connectivity associated with these changes in landcover to identify locations associated with the largest potential benefit in movement potential. At one site, Glacial Lakes, we focused on identifying prairie restoration locations that could most strongly enhance connectivity between existing prairie. The second case study site, the Root River Watershed, is a prairie-forest transitional area. For this watershed, we conducted simulations to explore both prairie and forest connectivity benefits and identified locations with potential for overlap/interference in priority sites across the two system types. The specific model parameters used to simulate restoration actions were developed based on input from the AC. In the local-scale focal areas where we conducted these simulations, we leveraged **3)** region-wide estimates of ecosystem services associated with parcel restoration, including nitrogen and phosphorus retention, carbon storage, and habitat availability for bees, a key group of pollinators. By aligning benefits for connectivity and this set of ecosystem services to the same units (representations of farm fields/parcels), we were able to **4)** develop prioritization analyses that integrate these multiple benefits.

Through these coordinated bodies of work, in this report and the associated data viewer, we demonstrate several different approaches to facilitate the integration of multiple benefits (connectivity and the ecosystem services listed below) to support the evaluation and prioritization of potential restoration sites. These range from simple (making connectivity and ecosystem service products easy to view) to more complex (demonstration of prioritization scenarios and trade-offs). As noted above, our intent was to help practitioners more effectively use our connectivity modeling products by presenting them with key climate change exposure variables that could influence the specific connectivity strategies they might choose to implement, and by enabling evaluation of key ecosystem services for restoration actions that can help broaden support and funding for implementation. Below we describe the methods and decision processes for each component.

Regional-scale Structural Connectivity, Opportunity Areas, and Climate Exposure

Our first tasks focused on developing regional-scale connectivity maps with structural connectivity models for the two dominant vegetation types, forests and prairie. To support use of these maps to inform climate change adaptation strategies, we also worked with our AC to identify a limited set of highly relevant spatial datasets representing observed and projected changes in climate. Our intent was to enable foundational conversations about different options for where to prioritize investments to meet different adaptation goals by helping practitioners understand regional patterns through interacting with connectivity and climate data in the same platform. To further facilitate data exploration and use, we also developed several regional-scale scenarios that model a workflow for prioritizing "opportunity areas" for investing in restoration to benefit connectivity. With associated methods described in later sections, these scenarios were designed to allow evaluation of ecosystem services, and changes in ecosystem service due to restoration, for the same units.

Structural Connectivity for Forest and Prairie

While there are many variations, landscape connectivity modeling approaches can be broadly classified into two general groups: structural connectivity models that describe a continuous surface of movement potential based on naturalness/degree of human modification, and functional connectivity models that emphasize species traits and identification of pathways between focal habitat patches (Baldwin et al. 2012, Hilty et al. 2019). While it is possible to parameterize a structural model to align with species-specific habitat associations, the real strength of this type of model is in providing a relative metric of how the amount and configuration of permeable (e.g., habitats that support movement) land cover types interact across space, and are influenced by the amount, proximity, and type of barriers in other parts of the landscape. The choice to use a gradient of human impact or naturalness as the basis for a connectivity analysis allows the modeler to explore hypothesis about how the location of habitat conversion, roads, and other barriers interact to constrain movement potential, with the goal of targeting land protection or barrier-crossing strategies (Cameron et al. 2022). Naturalness-based maps can help modelers identify broad pathways where ecological processes and movement potential are most likely to be buffered from human impacts and can bring attention to “pinch points” where urgent action may be required to prevent loss of the last remaining links between natural areas (Pelletier et al. 2014, McRae et al. 2016). These generalized maps have also been integrated with climate exposure data and factors like topography that indicate microclimate diversity (e.g., McGuire et al. 2016, Schloss et al. 2021, Anderson et al. 2023). However, lumping forests and prairie together as “natural” pixels suggests that transitions between these vegetation types do not represent a change in permeability for moving organisms. This assumption reduces the usefulness of naturalness-based models for some decisions, especially in regions like the upper Midwest where forested-dominated and prairie-dominated biomes meet. To inform habitat restoration decisions in this region, much of which (especially in prairie) is highly fragmented by conversion to agriculture, our first step was to develop connectivity models separately for forested and prairie ecosystems.

To quantify current connectivity of these two different ecosystems, we used a wall-to-wall Circuitscape model developed by co-PI Clark (Pelletier et al. 2014), which estimates the density of “current flow” across a resistance grid composed of landscape features that create resistance to movement (Shah and McRae 2008). Circuitscape models use the mathematics of electrical circuit theory to describe how heterogeneity in land use and other factors can influence where movement is most likely, and where movement is constrained (McRae and Beier 2007). The model is applied to a gridded resistance surface comprised of landscape features, with each feature weighted by its relative resistance to movement (Shah and McRae 2008, Dickson et al. 2016). Rather than describing the behavior of electrons, the model tracks paths of “random walkers” traveling across this resistance surface, producing a cumulative “current flow” output that describes how many times each pixel was part of a movement pathway. In a uniform landscape (all resistances are the same), current flow spreads out evenly, but in heterogeneous landscapes this even flow pattern is disrupted as the walkers avoid areas of higher resistance and concentrate in nearby areas with lower resistances. The patterns of variation in amount of current flow in each pixel, which we categorize in terms of degree of diffusion, concentration, or constraint of current flow, can then be used to describe how conditions across diverse and complex landscapes may impact species movement and the flow of ecological processes.

To produce structural connectivity maps for forests and prairie, we first created resistance grids for each ecosystem based on known movement barriers for (ecosystem-generalized) species in each ecosystem. We began with resistance surface components and weighting schemes that were developed for a previous project, described in Anderson et al. (2023). We first updated the landcover that is translated to resistances using the most recent version of the [National Land Cover Database (NLCD)](#) (USGS 2023; Fig. 1). We then refined this landcover surface by classifying developed and natural barrens through visual interpretation, and adding barriers related to solar development created by digitizing the footprint from EPA solar energy points (EPA 2024). The same landcover map underlies both models, with differences in movement potential for forest and prairie-associated species reflected in the resistance weights that are applied to various land cover classes.

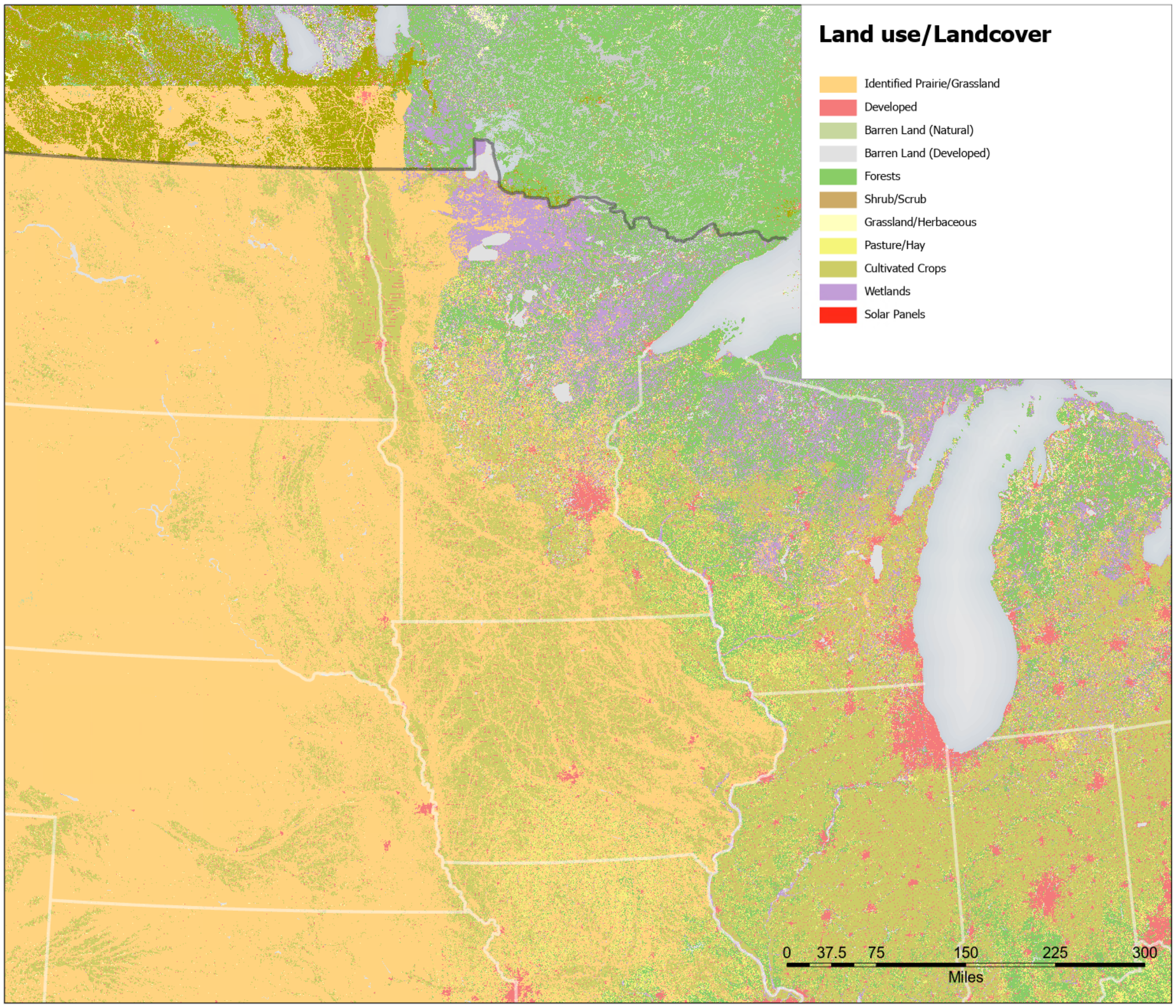

Figure 1. Land use/landcover map developed for the project region, based on the National Landcover Database (USGS 2023) and augmented with renewable energy data. This raster layer provides the basis for the resistance surface used in all of our structural connectivity models.

The weighting scheme for the prairie- and forest-focused resistance surfaces retained the same resistance weight for roads and development as our baseline "naturalness" version from Anderson et al. (2023) but assigned either prairie or forest to the lowest resistance weight and raised the resistance weight of the non-focal system type (Tables 2 and 3). Through an iterative process, the AC provided input into parameterizing the other components of the weighting scheme such as other natural vegetation types, water features, and agricultural lands (Tables 2 and 3). For prairie systems, the AC stressed the importance of including all data sources for undisturbed prairie so that the model could indicate higher movement value (lower resistance) of these areas relative to other grass-dominated land cover types (e.g., prairies that were not documented as undisturbed, and pasture/hay). With their help, we identified three data sources that we used to augment the NLCD landcover layer: the Minnesota Department of Natural Resources native prairie layer (Minnesota Department of Natural Resources (MNDNR) 2014), the Potentially Undisturbed Lands (PUDL) data (Barnes et al. 2025), and the World Wildlife Fund's Plowprint (Gage et al. 2016, accessed 2023). Our original weighting scheme for the prairie product assigned herbaceous wetlands to the lowest resistance (1), however through collaborative review of preliminary maps, we found this promoted strong current flow along linear networks of wetlands in riparian habitats, which tended to de-emphasize many prairie connectivity pathways that occurred in prairie systems with fewer rivers and wetlands. To counteract this pattern but still indicate high connectivity value for herbaceous wetlands, we increased the resistance of these systems to 2 (Table 2).

Table 2. Resistance weight values used to parameterize the resistance surface for prairie connectivity runs using Circuitscape. Lower values correspond to lower resistance (higher movement potential).

Land use / Landcover Class	Resistance Value
Undisturbed prairie/grasslands	1
Grassland/Herbaceous	2
Herbaceous wetlands	2
Pasture/Hay	2
Natural Barrens	3
Shrub/Scrub	5
Woody wetlands	5
Cultivated Crop	7
Low and Medium Density Development	10
Residential Roads	10
High Density Development	20
Primary and Secondary Roads	20

Table 3. Resistance weight values used to parameterize the resistance surface for forest connectivity runs using Circuitscape. Lower values correspond to lower resistance (higher movement potential).

Land use / Landcover class	Resistance Value
Forests	1
Woody wetlands	1.5
Natural Barrens	3
Herbaceous wetlands	6
Shrub/Scrub	5
Grassland/Herbaceous	6
Pasture/Hay	8
Cultivated Crop	9
Low and Medium Density Development	10
Residential Roads	10
High Density Development	20
Primary and Secondary Roads	20

The prairie and forest parameterized resistance grids were the primary inputs for our Circuitscape modeling runs. When the Circuitscape algorithm is applied in a “wall-to-wall" method, simulated electrical current is released from a set of pixels along the edge of the study area (these are the “source” pixels) and flows across the resistance surface to a set of pixels on the opposite edge that act as “grounds” for the circuit. As current flows across the resistance surface, the algorithm tracks which pixels are included in movement paths, and each cell receives a quantitative score that varies as a function of its resistance weight, the overall pattern of resistances that influence flow into its neighborhood, and the direction of flow. To allow the final map to represent flow potential in all directions, we run the model four times, with each edge of the focal area acting as a source for one run (grounds are at the opposite edge). The final cumulative current map is a sum of these four single-direction cumulative current maps. The cumulative current products for prairie and forest connectivity are a continuous surface, where the highest values indicate a concentration of current from higher resistance areas into lower resistance areas, such as locations where natural habitat occurs between agricultural fields. Cumulative current values will be especially high when several sources of constraint act together to funnel current into small regions; we refer to these patterns as “pinch-points.” Pinch points and other concentrated flow areas are important indicators of locations where restoration could improve connectivity (Baldwin et al. 2012, Clark et al. 2023). Areas with the lowest cumulative current values are typically broad regions with moderate to high resistance (e.g., intensive agriculture), or high resistance pixels representing roads or urban areas. Moderate values of current flow arise in low resistance areas where barriers are uncommon (the “random walkers” spread out, or “diffuse” due to homogeneity in the resistance values of neighboring pixels). Diffuse areas are critically important for sustaining movement and ecological processes across large areas, but in a restoration context, gaps in a diffuse zone are typically lower priority, as there are other options for movement nearby (Clark et al. 2023).

To facilitate interpretation and integration of our connectivity maps with other datasets, we classified the continuous cumulative current patterns into categorical current flow maps. To create categories that reflect the amount and spatial variation of cumulative current on the landscape, we applied a neighborhood analysis using 3 km radius, and grouped pixels based on current magnitudes (7 quantiles) and the standard deviation of values in the neighborhood (Anderson et al. 2019). The resulting maps include three broad categories that are shown with a consistent color scheme in all products. High diffuse flow, mapped in dark blue, occurs in the most homogeneous, intact sections of the landscape, and these areas are characterized by moderately high cumulative current flow values with low variation in the neighborhood. This pattern of high flow in the neighborhood, but a lack of disruption in flow patterns, suggests many options for movement. High levels of concentrated flow (dark orange-brown) occur in neighborhoods where current is flowing in, but high resistance pixels (i.e., intensive agriculture, urban areas, energy development) limit options for movement, and promote an accumulation of current in channels and pinch points in the remaining natural lands. These areas have the highest overall current flow values, and high standard deviations across values in the same neighborhood. Constrained flow (gray) areas can be thought of as lower classes of concentrated flow (lower amount of current entering the neighborhood, but paths are still influenced by variations in resistance, while the palest blues are lower classes of diffuse flow (these have more even patterns/low standard deviations, but very low current flow values). Areas shown in white are dominated by large expanses of non-natural land cover (high resistance), which can promote large, homogeneous areas with low current flow magnitudes.

Regional Connectivity Restoration Opportunity Areas

CONCEPTUAL APPROACH

In the context of informing restoration decisions, we see concentrated flow areas in structural landscape connectivity maps as an indicator of restoration opportunity. This is because these current flow patterns, which again are characterized by high flow magnitude and high spatial variation in flow within the spatial neighborhood, are indicators of movement constraint that could be improved by filling key gaps in the spatial network, or by expanding the width of movement pathways. In the focal area assessments, we simulated restoration (changes in landcover) by changing the resistance of individual parcels. We then evaluated the degree of change in flow magnitudes and the standard deviation of current flow in spatial neighborhoods (see the "Focal Area Restoration Connectivity Opportunity Areas" section below). As we pursued the focal area assessment simulations, we also heard from our AC that it would be helpful to have methods for identifying larger opportunity areas across the full assessment region. Our discussions with the AC indicated that restoration actions tended to be sited in locations that supported or expanded existing high biodiversity value locations, and the two focal areas described in the next section (Glacial Lakes, and the Root River Watershed) fit this model. However, elevating connectivity values as a key target for restoration might point us to some different locations, especially if the approach facilitated integration with climate change exposure and ecosystem service values. With this idea in mind, we developed a relatively simple approach for identifying opportunity areas at roughly the size of a Minnesota township (36 square miles). Top "township" units in our scenarios represent places that our models suggest will contain many high value connectivity restoration opportunities that can be considered with other key variables included here (e.g,, climate change exposure, ecosystem service benefits), and not captured here (practitioner capacity, rightsholder values, land ownership & interest in restoration, incentive programs, etc.).

In our engagement with the AC, we illustrated this process for identifying opportunities using five scenarios, two that build from the prairie structural connectivity model, two related to the forest model, and one that considers overlap in opportunities for the two ecosystem types. Our goal with these scenarios was to illustrate how the same data products could be used in different ways, depending on practitioner goals, focal strategies, and interest in integrating ecosystem service values. For each scenario, we chose two criteria for selecting locations – one based on the categorized connectivity values, and one based on area of land with specific conditions or biodiversity values. Given strong interest in protecting and supporting networks of undisturbed prairie remnants, we created a "prairie refugia" scenario, which we describe in detail here; the other scenarios follow similar logic and are described in brief below.

To emphasize connectivity values in our restoration opportunity assessments, we ranked township-scale units based on the amount of "restorable" land in one or both of the flow categories that indicate an accumulation of current flow in response to barriers (concentrated flow and constrained flow). As illustrated in the far left column of Figure 2, the largest proportion of high concentrated flow occurs in grassland land cover, but roughly 18% of the pixels in this category are associated with cultivated crops. As a general rule, we expect restoring agriculture to prairie in these locations (agricultural fields with high concentrated flow) would be most likely to strengthen connectivity by spreading out current flow and potentially increasing the number of movement pathways. As the magnitude of concentrated flow decreases (i.e., as we move to the right in Fig. 2, toward low concentrated flow, and then toward high & low constrained flow), the proportion that occurs over agriculture increases, while diffuse flow (which is rare in this map product, see results section) is very rarely found over agriculture. As noted above, while diffuse flow zones are critically important for protection and management, we do not treat them as restoration targets for connectivity, because the pattern of flow in those regions suggests many redundant options for movement.

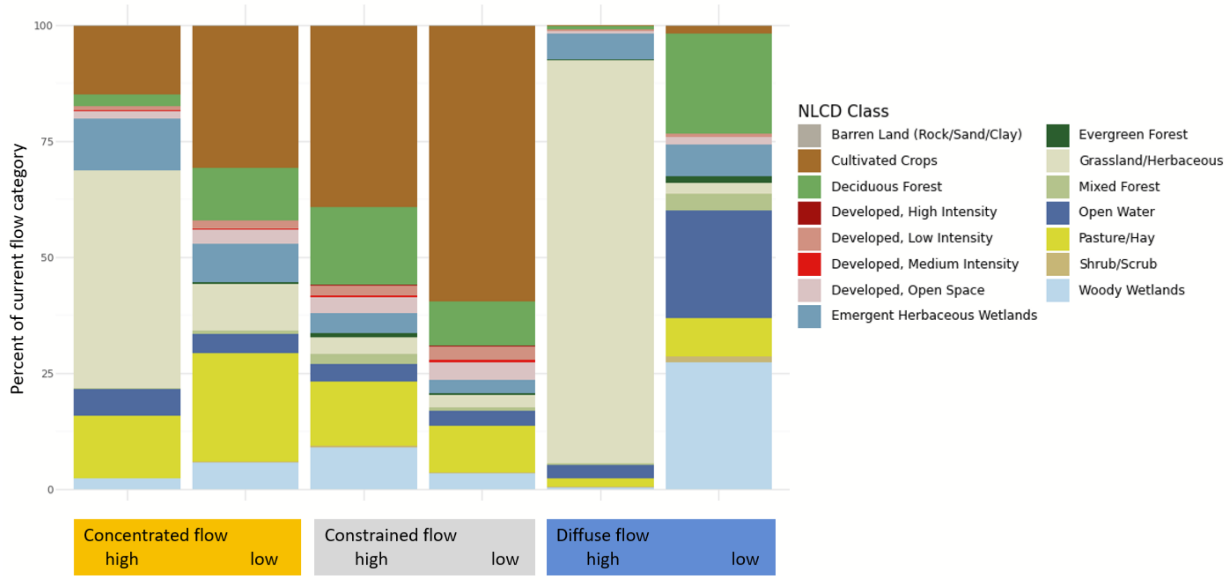

Figure 2. Composition of landcover within each of the categorized current flow categories for the prairie structural connectivity model. Cultivated crops, our target landcover type for restoration to prairie, occurs in locations that exhibit concentrated and constrained current flow, but agricultural fields in locations with high concentrated flow are expected to provide the most connectivity benefit if restored.

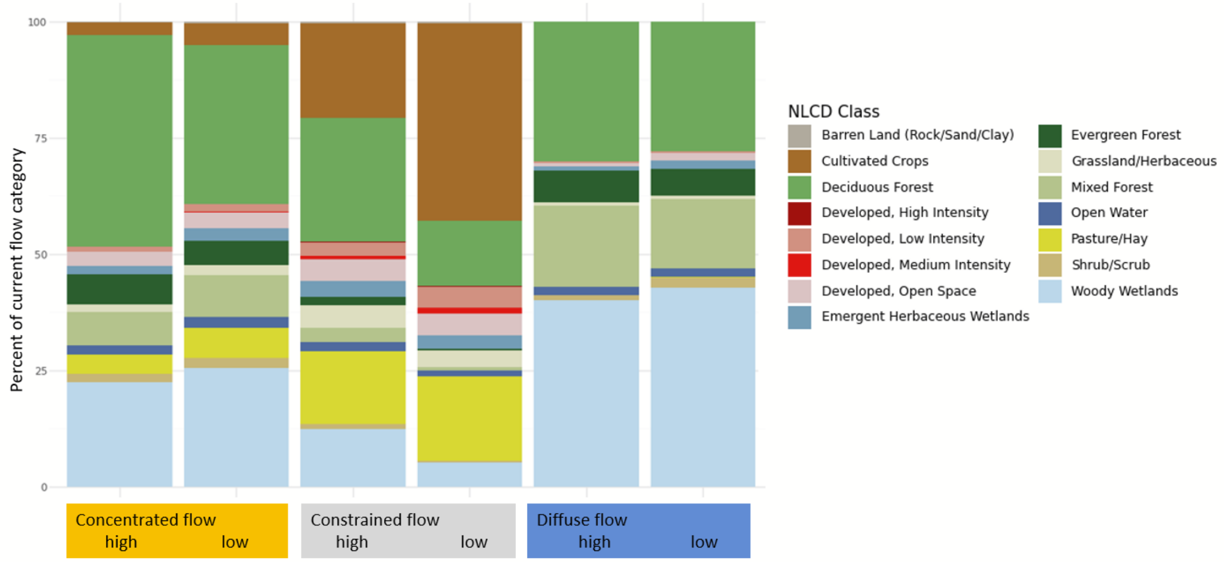

Figure 3. Composition of landcover within each of the categorized current flow categories for the forest structural connectivity model. Cultivated crops, our target landcover type for restoration to forest, occurs in locations that exhibit concentrated and constrained current flow, but agricultural fields in locations with high concentrated flow are expected to provide the most connectivity benefit if restored.

For the “prairie refugia” scenario, our rule set was quite restrictive in terms of thresholds for current flow and prairie condition. The intent here was to highlight places for long-term investment as might be warranted in locations that were expected to experience relatively stable climate conditions (“climate refugia”). To pick these highest tier sites, we scored the amount of area within each township unit with concentrated flow over agricultural landcover (rather than both concentrated and constrained). Especially in Minnesota, Wisconsin, and Iowa, these locations are rare in the landscape. In addition to this rule, we also ranked the township-like units based on acres of prairie in the "undisturbed" category within the PUDL dataset (Barnes et al. 2025). This second rule was intended to elevate township units that have more undisturbed prairie occurrences that could benefit from improved connectivity. We then grouped each township into terciles (low, medium, or high) based on area of land in these two categories and mapped the township units as a bivariate surface with nine color-coded combinations. We also produced a map of just the boundaries of the top (high-high) pixels to facilitate overlays with climate exposure data that could indicate relative likelihood of climate refugia characteristics. Our goal with this two-variable approach was to find "goldilocks" opportunities – places where connectivity was restricted but had high potential for improvement, and where the target habitat was relatively abundant, but still fragmented. Note that the first condition can be true in places without much prairie habitat, as suggested by the diversity of landcover types supporting concentrated flow for prairies in Fig. 2. While using total amount of prairie in the township as the second criterion tends to orient the opportunity area results toward existing prairie strongholds, the most intact areas tend to drop down in the prioritization because they have fewer acres of concentrated flow that occur over agriculture (the restoration opportunity). While more testing with the AC is needed, our approach provides a simple, modifiable tool for operationalizing the connectivity results to inform restoration.

For the purposes of illustration, when we described implementation of the prairie refugia strategy to the AC, we suggested that these narrow criteria (concentrated connectivity category, most restrictive definition of prairie) were our decision priorities, and additional variables like ecosystem service values would not be considered as factors for siting restoration efforts. We contrasted this restoration strategy scenario with a broad "prairie opportunity" approach. For this scenario, we again defined "restorable" units as agriculture but expanded the connectivity category cut-off to include both concentrated and constrained flow that occurred over agriculture. We also broadened the definition of prairie to include all grasslands and pasture/hay. For this scenario, which had many more units in the highest categories, we described overlaying the data layer indicating the outlines of the townships that scored high in both dimensions with the ecosystem service benefits and climate exposure gradients in the viewer. We illustrate this approach for integrating additional datasets to narrow the range of options in the results section.

For forests, we developed two scenarios. Scenario 3 is a general "forest opportunity" version that emphasizes concentrated flow for forests over agriculture as our opportunity areas (Fig. 3), and Scenario 4 demonstrates integration of climate-relevant data by restricting the outputs to forests with highest snow duration (number of days with snow). Unlike the prairie opportunity scenario (scenario 1) we did not use constrained flow for these products, as just concentrated flow alone provided a large range of options for the general opportunities map, and the snow map was intended as a subset. Our last scenario highlights township units with high restoration value opportunities for both prairie and forests. In our experience, there is potential for prairie and forest restoration projects to be considered in isolation, and this assessment can highlight places where a step of considering how work to benefit one system might negatively impact the other is most warranted.

METHODS

The scenarios described above were enabled by a conservation opportunity dataset, which can be downloaded from our data viewer. As described above, opportunity is defined by the amount of restorable land in different connectivity classifications, and by existing prairie or forest that can benefit from strengthened connectivity. To mirror real world scenarios, we created summary zones that were roughly the size of townships (36 mi^2). These zones are comprised of 144 (12 x 12) 64-hectare spatial domain units as used for the ecosystem services portion of this project, representing approximately 22,773 acres.

We assessed the amount of conservation opportunity within each zone by tabulating the total areas of constrained, concentrated, and diffuse connectivity for each of the forest and prairie connectivity models, as well as various land cover types, as described below. We used these results to develop five scenarios of restoration opportunity that are illustrated in the data viewer, but many additional scenarios are possible using the same dataset, and additional extractions can be readily added to the dataset for use in different scenarios by GIS users.

SCENARIO 1: PRAIRIE OPPORTUNITY

This scenario identifies areas where restoring row crop agriculture to prairie may help improve prairie connectivity. Here, we defined key restorable areas as existing agriculture that coincides with constrained or concentrated flow, as identified by our model of prairie connectivity. To represent prairie that can benefit from strengthened connectivity, we used the potentially undisturbed grassland layer (Barnes et al. 2025) and the grassland / pasture land cover type within the 2024 National Land Cover Dataset (NLCD). We defined high prairie restoration opportunity zones as those with greater than 5,000 acres of pixels with high flow, and pixels that could benefit from this flow.

SCENARIO 2: PRAIRIE REFUGIA

As described in detail above, this scenario is a more restrictive alternative to the prairie opportunity scenario and is intended to represent an approach for identifying top opportunities for increasing movement potential near high biodiversity value (as suggested by “undisturbed” status) prairies. Restorable areas are defined as existing row crop agriculture that coincides with concentrated flow. Existing refugia are locations with potentially undisturbed grassland (Barnes et al. 2025). Similar to scenario one, high prairie refugia zones are those with greater than 5,000 acres in each category.

SCENARIO 3: FOREST CONNECTIVITY BENEFITS

This scenario identifies areas where restoring row crop agriculture to forest may help improve forest connectivity. We identified these areas as those with over 300 acres of concentrated flow occurring over agriculture (as estimated by the forest connectivity model) and over 3,000 acres of forest, as identified by the 2023 NLCD.

SCENARIO 4: FOREST CONNECTIVITY BENEFITS FOR SNOW-DEPENDENT SPECIES

This scenario represents a narrowing of opportunities from the scenario above to focus on forest connectivity in regions with persistent snow cover that can be of particular value to snow-dependent species. This scenario is the same as scenario 3, except we only tabulate forest area which occurs in locations with greater than 120 days per year of snow cover (on average), based on the Silvis lab snow season length dataset for the years 2003-2020 (Gudex-Cross et al. 2021).

SCENARIO 5: COMBINED PRAIRIE AND FOREST BENEFITS

To identify areas with combined benefits for both prairie and forest connectivity, we identified zones which occur in both the forest connectivity high benefit areas and the high prairie opportunity areas scenarios. As noted above, for prairies this cut-off includes both concentrated and constrained flow, but for forests it only includes concentrated flow pixels.

Supporting Assessment of Climate Exposure and Climate Adaptation

A key component of our engagement with the AC focused on providing opportunities to and mechanisms for considering climate change exposure in restoration decisions. To keep the viewer interface from becoming prohibitively complex, we chose to limit the total number of variables we present, and to limit projections to near term (2050s) based on input from the AC. Our intent is to provide examples of how to integrate climate change exposure factors and connectivity opportunity areas (see Scenarios above) in ways that build interest and capacity for more comprehensive assessments with additional data. We also wanted to identify areas where restoration will be important to facilitate climate adaptation through movement by using climate data to evaluate variability in exposure across the project area.

We worked with our AC to understand what climate variables are most relevant to their primary species of concern. Example questions that we discussed included: (1) Where could we invest to strengthen movement networks for species experiencing the highest rates of change in key variables like drought stress (e.g., climate moisture index)? (2) Where might we prioritize investments to enhance movement potential and gene flow near places that seem to be changing more slowly that might act as climate refugia? (3) How do opportunities for forest connectivity restoration overlap with observed patterns of snow persistence, a key habitat attribute for snow-dependent species? This process uncovered a lot of primary as well as derived climate variables of interest. In addition to typical variables representing changes in temperature and precipitation, variables describing the loss of winter and extreme precipitation were top of mind for many. We chose a few key climate variables that described important climate drivers to include in our viewer and demonstrate integration of connectivity products with several of these.

Both temperature and precipitation variables were highlighted as important factors that influence habitat and movement of plants and animals in both prairie and forest ecosystems in the region. For temperature we included the variables current mean annual temperature (1991-2020) and change in mean annual temperature (1991-2020 to 2041-2070). Because the minimum temperatures and winter temperatures appear to be changing the fastest in the region (Runkle et al. 2022), we also included current winter minimum temperature (1991-2020) and change in winter minimum temperature (1991-2020 to 2041-2070). For precipitation we included current Hogg's climate moisture index (1991-2020), the change in climate moisture index (from 1991-2020 to 2041-2070), current mean summer precipitation (1991-2020) and change in mean summer precipitation (from 1991-2020 to 2041-2070). The climate data for current mean annual temperature, winter minimum temperature, mean summer precipitation, Hogg's climate moisture index, frost free period, and percent of precipitation as snow were compiled from Adapt West's Climate Adaptation Data Basin portal (Wang et al. 2016, AdaptWest Project 2022, Mahony et al. 2022). The projected change values for these variables were calculated as the differences between the projected future values (2041 – 2070) under a moderate emissions scenario (CMIP6 SSP 2-4.5, 13 climate model ensemble) and current climate normals (1991-2020). The time frame and choice to use moderate emissions scenarios reflect the preferences of our AC.

Several AC members were interested in the impacts of changes in extreme precipitation events, which are important drivers of impacts from agriculture on freshwater water quality that tie in with several of our ecosystem service values. In the viewer, we included current number of days with greater than two inches of precipitation (1991-2020) and the change in number of days with greater than two inches of precipitation (from 1991-2020 to 2041-2060). These datasets were obtained from Dan Vimont at the University of Wisconsin, and follow methods described in Notaro et al. (2014) and Kirchmeier-Young et al. (2016).

For loss of winter, we incorporated current duration of frost free period (days per year; 1991-2020), change in frost free period (from 1991-2020 to 2041-2070), current percent precipitation as snow

(1991-2020), change in percent precipitation as snow (from 1991-2020 to 2041-2070), and current snow season length (2003-2020). The climate data for snow season length was compiled from Gudex-Cross et al. (2021). This layer depicts the average snow season length, in days, for the period 2003-2020. The spatial coverage of the annual Winter Habitat Indices (WHIs) varies due to cloud cover, and pixels with a mean snow season length (2003-2020) of less than two weeks are masked out.

Focal Area Restoration Connectivity Opportunity Areas

Evaluating the potential connectivity benefit of restoration actions requires a dynamic approach, which is an important and rapidly evolving direction in connectivity modeling (Jennings et al. 2020). We used a simulation-based approach that was developed in the Central Appalachians (Clark et al. 2023). This approach simulates how restoration actions fill critical habitat gaps or remove barriers to movement.

After a series of large and small-group discussions, we identified a set of connectivity questions (Table 1), and two groups of AC members that were willing to engage with us to do “deep dives” on connectivity opportunity identification in their focal landscapes. For these two focal area geographies, we worked with a sub-team of the Advisory Committee to understand the restoration context of the landscape, and using their input, we conducted a detailed restoration analysis (Fig. 4). For Glacial Lakes, we modeled restoration for prairie connectivity, and for Root River we modeled restoration for both forest and prairie connectivity, as this landscape is a transition zone where practitioners are doing restoration for both system types.

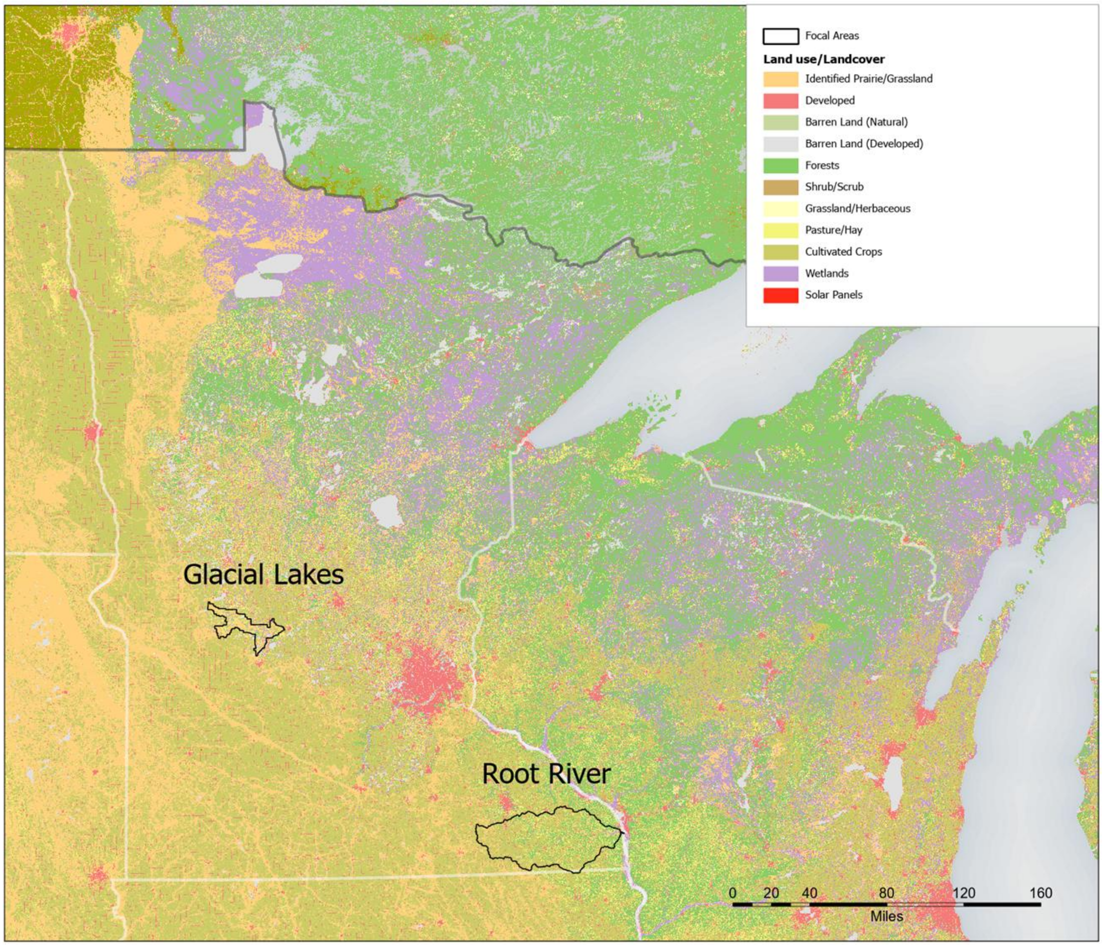

Figure 4. Location and landcover of the Glacial Lakes and Root River focal areas within the project area.

According to the Minnesota Prairie Conservation Plan (Chaplin 2018), the Glacial Lakes landscape covers ~208,000 acres, with ~10,000 acres of native prairie, ~88,000 acres of other grassland, and~ 36,000 acres of wetland. The Nature Conservancy owns and manages ~ 4,000 acres, the State of Minnesota manages ~ 11,000 acres, and the federal government manages ~ 12,000 acres. Most of the land within the Glacial Lakes landscape is in private ownership. The dominant land use is row crop agriculture on the cultivated lands and livestock grazing on remaining grassland (Fig. 5). The most intact remaining natural areas are generally in areas with steep topography or very droughty soils. Steep hillsides within the Alexandria moraine retain large, unplowed areas with diverse plant communities.

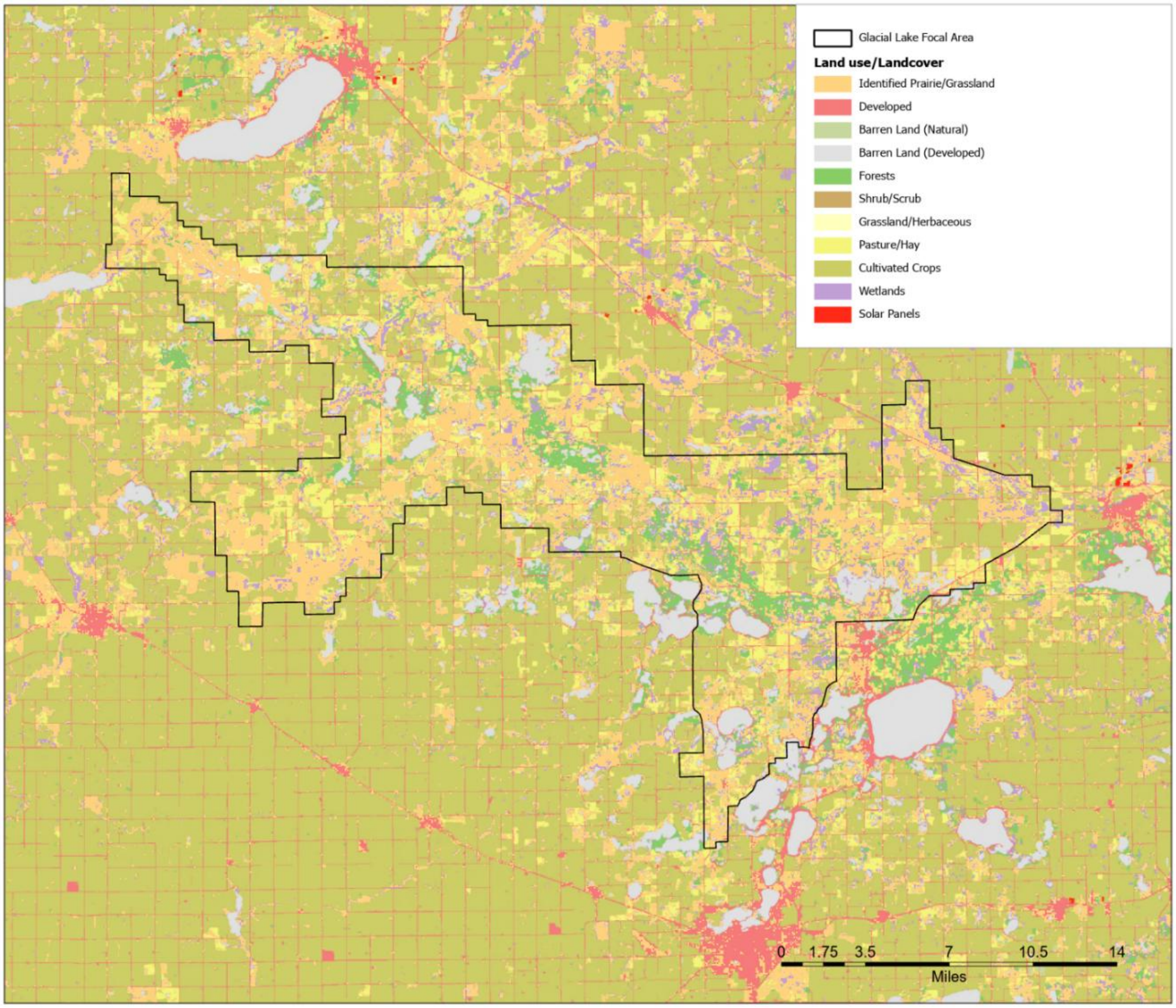

Figure 5. Augmented landcover for the Glacial Lakes focal area using the 2023 National Landcover Database as the foundation.

In discussions with an AC sub-team focused on the Glacial Lakes landscape, we learned that local conservation practitioners have identified three primary challenges to the area, the conversion of prairie and wetland to row crop agriculture and energy, loss of biodiversity (e.g., woody encroachment, pesticides, etc.), and supporting landowners in pursuing grass-based livelihoods. To address these challenges, practitioners have identified four high-level conservation and adaptation strategies: 1) managing ecosystems for biodiversity, 2) improving or maintaining connectivity 3) enhancing the function, ecological integrity, and connectivity of streams, and 4) supporting all dimensions of local communities by equitably promoting nature-based livelihoods, cultural values, and economies (TNC 2024).

The connectivity and ecosystem service modeling in this project will help address both the second and third strategies listed above. The loss of so much of the tallgrass prairie in this area highlights the need to maintain what remains and restore where possible. Therefore, improving the connectivity of prairie and wetlands within the Glacial Lakes focal area is an important climate adaptation strategy. Connectivity between concentrations of intact prairie and wetlands is currently limited, and therefore, improving connectivity will mean reconstructing prairie and wetland in strategic places. Because wetlands, lakes, and streams are a prominent feature in this conservation area, restoring prairie will also improve water quality creating climate adaptation benefits for terrestrial and aquatic biodiversity.

To simulate the change in connectivity or ecosystem services, we identified "restoration units" defined by land cover type, a feasible size for restoration projects, and a method for delineating units (e.g., parcels, random blocks). First, we created a fishnet of square parcels 800m per side, approximating 64 hectare (~154 acre) "farm" parcels as an actionable restoration unit (Fig. 6). In the Glacial Lakes there were 1,448 "farm" parcels modeled for restoration. We then filtered these by total agricultural area within the restoration unit, defining agricultural area in the NLCD (USDA 2023). For the Glacial Lakes focal area analysis, we filtered these units using Land Capability Classes to remove Class 1 and 2 from the restoration units to remove prime farm from the analysis (Soil Survey Staff 2023). For the Root River focal area analyses we used any agricultural land identified in the NLCD.

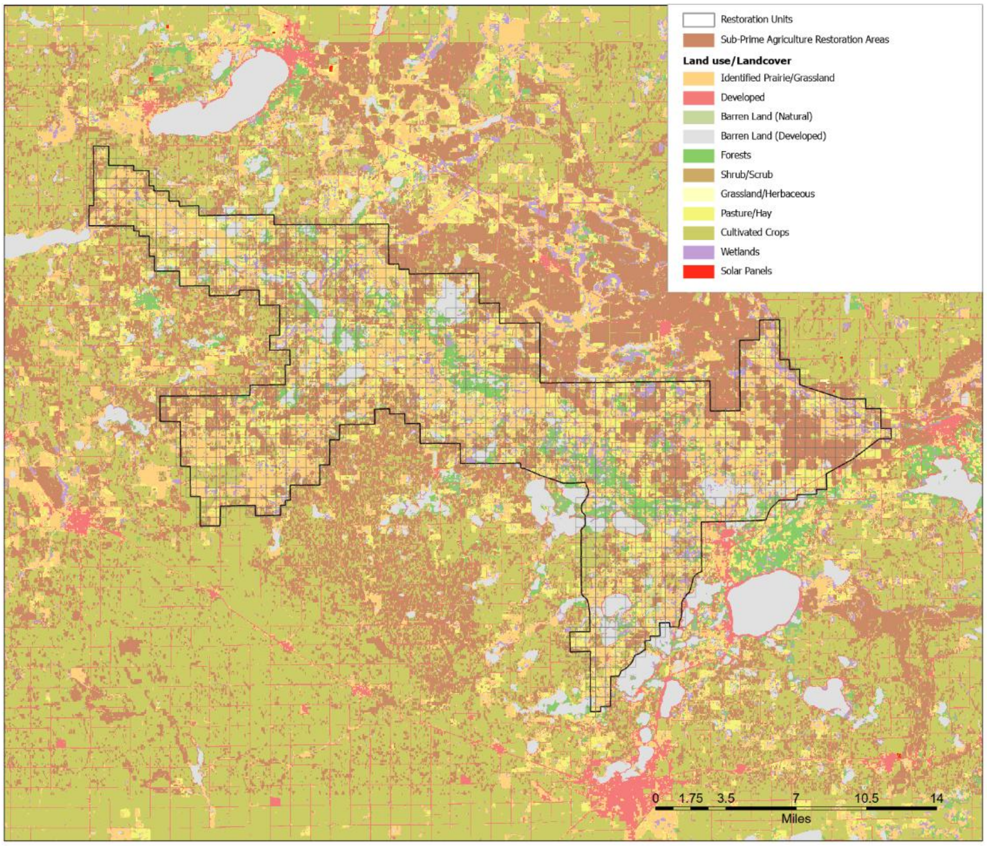

Figure 6. Glacial Lakes focal area showing the 64-hectare restoration units and the distribution of subprime agricultural land within the focal area.

The Root River focal area is in the Driftless region, a unique landscape where oak forest and woodland, maple-basswood forest, prairie, and row crop agriculture all interface (Fig. 7). This creates areas of high biodiversity value and poses challenges when facing restoration decisions. The Root River AC sub-team asked "how and where should we prioritize restoration for the different vegetation communities?" They noted that agricultural practices such as silvopasture and agroforestry are on the rise in the region. While these practices are focused on diversifying and improving agricultural outputs, they have many biodiversity benefits as well. Those biodiversity benefits might be magnified if targeted to areas where restoration of prairie or forest could have connectivity value for adjacent habitat. From the input of the sub-team, we used connectivity and ecosystem service models to inform conservation practitioners about tradeoffs between restoration for forest, prairie, and ecosystem services.

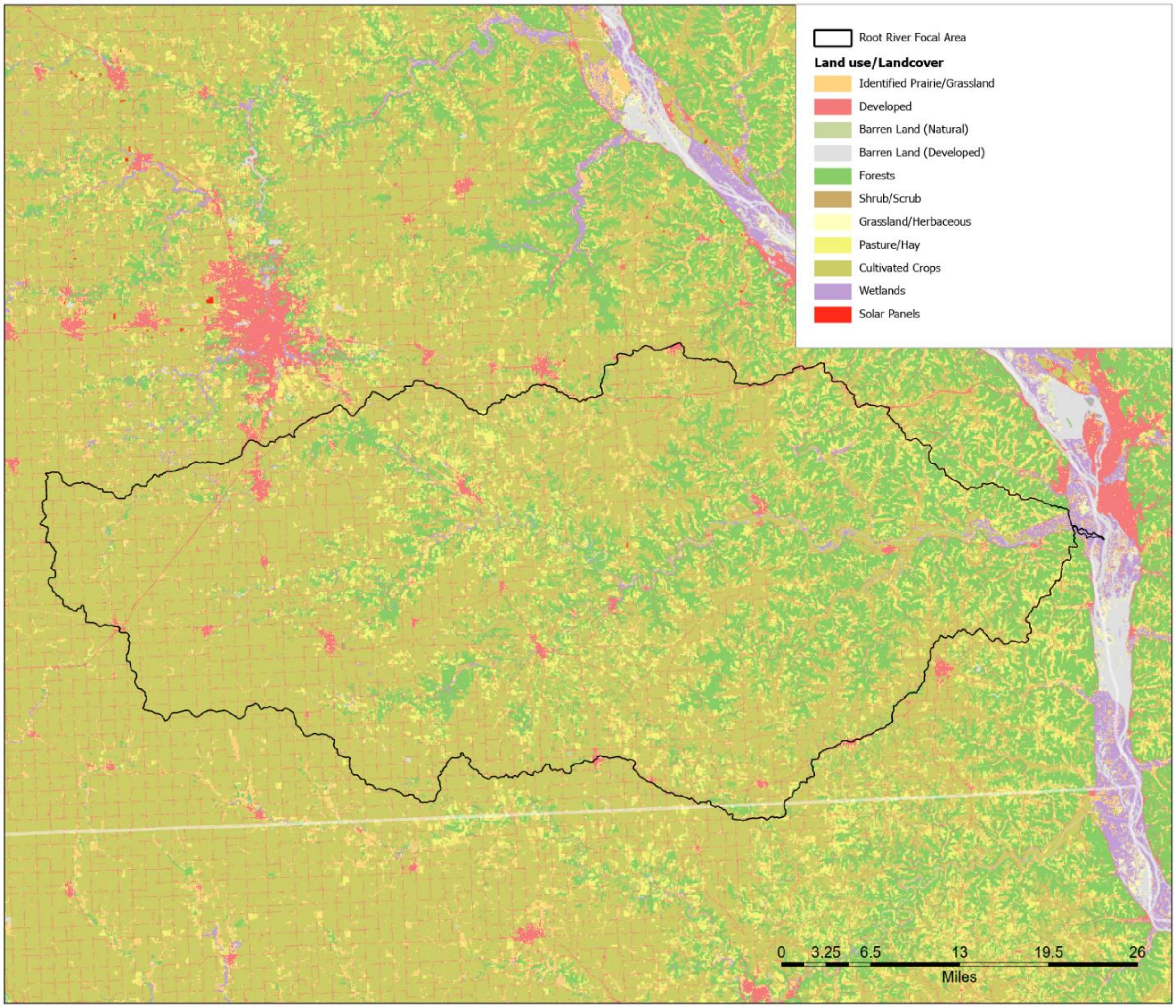

Figure 7. Augmented landcover and land use of the land in the Root River watershed focal area.

Once restoration units were delineated, we quantified the change in connectivity with restoration for each "farm" parcel. First, we changed the resistance value of restorable landuse in each "farm" to low resistance (simulating restoration to natural land use – prairie or forest). Then we ran the Circuitscape model for each restoration scenario and quantified the resulting cumulative current flow magnitudes, the change in flow relative to the original value, and assessed how the flow contributes to the network.

The computationally intense nature of this dynamic connectivity modeling currently limits the geographic scope over which these analyses are feasible in the given timeframe and budget, which is why we could only do this analysis for connectivity at this focal area scale.

The size of the root river focal area (there are around 7,000 “farm” units in Root River focal area) required prioritization of which units were run through the restoration modeling workflow. For both the prairie and the forest scenario we ran the restoration scenarios at 9x the scale (3,200 meters by 3,200 meter grid, or 1,386 ha) to identify zones within the overall focal area that had the highest potential to increase connectivity. The areas that had connectivity benefits at this scale (areas that had high flow, and for which the change in flow with simulated restoration created more diffuse flow) were then run at the individual “farm” level for both the forest (897 “farms”) and prairie (862 “farms”) scenarios.

Ecosystem Services

To account for co-benefits of habitat restoration, we evaluated the changes in ecosystem services resulting from prairie or forest restoration actions, focusing on water quality (nitrate, phosphorus, and sediment loading), wild bee habitat, and carbon storage. First, we generated project-wide maps indicating the current status of ecosystem services and potential benefits. Baseline ecosystem service results were derived from three models in the InVEST® modeling suite: Sediment Delivery Ratio (SDR), Nutrient Delivery Ratio (NDR), and Crop Pollination (Natural Capital Alliance 2025). InVEST models run using a land use map, an accompanying set of spatial inputs, and other parameters specific to each model’s ecological production functions. Data inputs are summarized in Table 4. Models were run on the Cropland Data Layer (USDA 2023) at a 30m raster resolution and aggregated to a gridded vector layer of 64-hectare square parcels (the “restoration units” explained above). Parcels comprised of less than 50% agricultural land were excluded from the analysis.

We then assessed the potential benefit of each restoration unit by calculating the marginal ecosystem service value of habitat restoration for each service. Marginal value results were calculated at the parcel level from regression models (for nitrogen and phosphorus, based on NDR model intermediates) or derivative versions of the original InVEST model functions (Crop Pollination, SDR, Carbon). We assessed two scenarios: prairie restoration and deciduous forest restoration. For the prairie scenario, we replaced agriculture with high-quality prairie (Cropland Data Layer 182, with improved biophysical parameters for each model). For the deciduous forest scenario, we replaced agriculture with deciduous forest (Cropland Data La yer 141).

Table 4. Ecosystem service model input data

Datatype	Description	InVEST Models	Data Source
Landcover	Landcover classification (raster).	NDR, SDR, Pollination, Carbon	CDL 2023 (USDA 2023)
Digital Elevation Model (DEM)	Elevation dataset (raster)	NDR, SDR	National Elevation Dataset (Gesch et al. 2018)
Precipitation	Annual precipitation (raster).	NDR	WorldClim 2.1 annualized precipitation (Fick and Hijmans 2017)

Watersheds	Watershed boundaries (vector).	NDR, SDR	National Watershed Boundary Dataset (USGS 2022)
Rainfall Erosivity (R Factor)	Annual erosive impact of rainfall on soil, used in the RUSLE equation	SDR	Global Rainfall Erosivity database (GloREDa) (Panagos et al. 2023)
Soil Erodibility (K Factor)	The ease with which soil erodes during rainfall, used in the RUSLE equation.	SDR	Derived from ISRIC SoilsGrid 2.0 data (Poggio et al. 2021) using the algorithm from Sharpley and Williams 1990 (Sharpley and Williams 1990)

Ecosystem Service Modeling Methods

NUTRIENT EXPORT

The InVEST NDR model characterizes expected long-term, steady state flows of nutrients from the landscape to local waterways. It computes a map of nutrient delivery ratios—0 to 1 indices representing the ratio of nutrients expected to reach the local watershed from each location—based on precipitation-based runoff potential, upslope contributing areas, hydrologic connectivity, topography, and landcover-based nutrient retention potential along downstream flowpaths. This ratio is multiplied against the expected nutrient loading on each landcover pixel: any residual nutrient is considered exported to the local watershed. This model does not include instream processes, point-source pollution, or groundwater flows of nutrients. There are two outputs from this process, one for phosphorus and one for nitrogen: expected annual phosphorus or nitrogen export in kg/yr.

We parameterized this model using a base set of parameters from Han et al. (2021), adjusting the nutrient loading parameters for all crops based on county-level data on fertilizer use (Cao et al. 2024). County-level data on nutrient loading per crop was averaged to the agroecological zone (Fischer et al. 2021) to provide regionally-appropriate fertilizer use estimates—any crops not included in an agroecological zone average were assigned the national average loading from all counties with that crop.

To calculate marginal value—the phosphorus and nitrogen retention benefits—of habitat restoration, we developed a regression analysis to approximate expected nutrient retention based on existing intermediate outputs of the baseline run of the InVEST NDR model. We randomly selected a sample of 64-hectare parcels (n=9,683) and modeled nutrient export for both the baseline and restoration scenarios using the InVEST NDR model on a 3-kilometer buffer surrounding each parcel. For each restoration scenario (prairie, deciduous forest), we replaced all agricultural areas within the parcel with the corresponding restoration habitat landcover type before running InVEST on the parcel and surrounds. Any differences in nutrient export between the baseline and restoration scenarios, either with the parcel or upslope, can be directly attributed to the restoration actions on that parcel as no other input changed between InVEST model runs. The resulting total change in nutrient export was regressed to model intermediates (e.g., topographic connectivity index, normalized precipitation rate; Table 5) from the original baseline run aggregated to the parcel boundaries and the relative change in aspatial model parameters between baseline and restoration (e.g., change in nutrient load per pixel, change in nutrient uptake efficiency per pixel; Table 5). Regression results were strong for both nitrogen

(r^2=0.82) and phosphorus (r^2=0.84). We applied the output regression equations to all parcels across the study area to generate maps of expected annual nutrient retention (kg/yr; on-site reductions and upslope capture) from agricultural areas restored to prairie or deciduous forest.

Table 5. Regression variables for InVEST NDR marginal value assessment.

Variable	Nitrogen
(1 - effective_retention_[nutrient]) * load_[nutrient]	-0.40**
ic_factor	-344.88**
runoff_proxy_index	-546.43**
eff_ [nutrient][1] - effective_retention_ [nutrient]	-309.30**
load_ [nutrient][2] - load_ [nutrient]	1.02*
Constant	-472.34**
R-squared	**0.82**

** P< 0.001; * P<0.01

Note: Variable names reflect the filenames of InVEST NDR intermediate output rasters. Nomenclature "_[nutrient]" indicates where a filename will be denoted with "_n" for nitrogen or "_p" for phosphorus.

SEDIMENT EXPORT

The InVEST SDR model characterizes the annual loads of sediment delivered from the landscape to local waterways as well as where vegetation contributes to local landscape retention. It computes a map of Sediment Delivery Ratio —0 to 1 indices representing the proportion of soil loss that reaches the stream from each location—based on upslope contributing areas, hydrologic connectivity, topography, and landcover-based sediment retention potential along downstream flowpaths. This ratio is multiplied against the expected sediment loss from each landcover pixel as calculated by the Revised Universal Soil Loss Equation (RUSLE, comprised of rainfall erosivity, soil erodibility, slope length-gradient factor, and cover management and support practice factors from landcover; Renard and Freimund 1994): any residual sediment is considered exported to the local watershed. This model does not include gully, bank, or mass erosion nor does it include instream sediment deposition processes. This model output quantifies the expected annual sediment export to the watershed in tons/ha/yr.

We parametrized this model by combining a base set of parameters (USLE C and P factors) for natural and developed lands (Chaplin-Kramer et al. 2016) with crop-specific parameters recommended by USDA documentation (NRCS-Oklahoma 1998).

Change in sediment export that reaches the stream from a parcel is a function of the parcel's change in USLE soil loss multiplied by its Sediment Delivery Ratio. Changes in USLE cover management (C) and support practice (P) factors between baseline and restoration scenario landcovers dictate the change in soil loss at the parcel, some of which is retained along the downslope path to the stream as determined by the Sediment Delivery Ratio. We calculated marginal value using the following equation:

$$\Delta sediment\ export = \Delta CP * RKLS * SDR$$

Where:

ΔCP is the difference between the multiplied USLC C and P factors of the restoration landcover class and the parcel's average multiplied USLC C and P factors (in agricultural areas only)

RKLS is the rest of the RUSLE equation, which does not change between scenarios

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[1] This is the retention efficiency parameter for the restoration scenario landcover type.

[2] This is the nutrient loading parameter for the restoration scenario landcover type.

And *SDR* is the average sediment delivery ratio within the agricultural areas of the parcel

Changing a parcel's USLE C factor impacts sediment delivery ratios in—and thus sediment export from—upslope parcels. This impact is not included in this analysis of marginal value here due to the computational constraints of propagating changes in sediment delivery ratio upslope at the pixel scale for each parcel. Thus, these marginal values represent a conservative estimate of soil retention services.

WILD BEE HABITAT QUALITY

The InVEST Crop Pollination model translates landcover into an index of wild bee habitat quality based on bee nesting and foraging behaviors. The model converts each landcover type into its expected provision of various nesting substrates (stem, ground, cavity, etc.) and seasonal floral resources. A guild table links specific bee species (or more generalized typologies) to nesting requirements, seasonal foraging behavior, and typical flight ranges; the model computes each species' habitat quality as a function of floral resources available within foraging range of nesting sites: good nesting sites with plenty of surrounding floral resources receive high habitat quality scores, while sites with either minimal nesting potential or sparse floral resources receive low scores. The model output is estimated wild bee habitat quality in agricultural areas at a 30-meter resolution, averaged to the 64-hectare grid square (0 to 1 index, with a 1 indicating high abundance). We parameterized this model based on work by Koh et al. (2016).

We calculated marginal value of restoration for wild bee habitat quality following work by (Lonsdorf et al. In prep) using the following equation:

$$\frac{\delta P_i}{\delta LC_i} = \frac{\delta N_i}{\delta LC_i} \frac{\sum F_j e^{-\frac{D_{ij}}{\alpha}}}{\sum e^{-\frac{D_{ij}}{\alpha}}} + \frac{\delta F_i}{\delta LC_i} \frac{\sum N_j e^{-\frac{D_{ij}}{\alpha}}}{\sum e^{-\frac{D_{ij}}{\alpha}}}$$

Where:

P = wild bee abundance (index, 0-1)
LC = land cover (indicating a change in parameters)
N = nesting resources (index, 0-1)
F = floral resources (index, 0-1)
$D_{i,j}$ = distance between sites *i* and *j* (meters)
α = foraging radius for wild bee species (meters)
i = pixel of interest
j = pixel within foraging distance of pixel *i*

This equation, originally adapted for pixel-level assessments, can be adapted to the parcel scale by substituting parcel-level averages for each component variable (e.g., nesting resources, floral resources). It is a direct derivative of the original InVEST Crop Pollination model with respect to the changes in nesting and floral resources caused by a change in landcover.

CARBON STORAGE

The InVEST Carbon model reclassifies landcover data into expected carbon stored in different pools (i.e., aboveground and belowground biomass) from a parameter table provided by the user. We parameterized our study area based on data from (Spawn et al. 2020), taking the average carbon storage values per landcover type using 2010 Cropland Data Layer landcover data. Any missing values were given a reasonably conservative estimate from another similar landcover type. We applied this lookup table to the 2023 Cropland Data Layer and aggregated the results for all agricultural pixels to each parcel.

We assessed the marginal value of restoration by subtracting the total carbon stored in the agricultural areas of a parcel from the total carbon stored in the same amount of land under each restoration type, calculated by multiplying the agricultural area (in hectares) by the carbon storage parameter for the restoration type (in tons/hectare).

PRIORITY AREA SELECTION

Selecting priority areas for restoration based on ecosystem service benefits involves weighing all services against each other based on stakeholder preferences and selecting the highest performing areas. We selected the top 10% of all parcels for each ecosystem service individually to create individual ecosystem service priority area maps, then created an evenly weighted composite ecosystem service score by normalizing each service to a 0-1 index and taking the weighted average score across all services. We created a composite priority area map with the top 10% of parcels according to the composite score.

Integration

We used several approaches for illustrating how practitioners could integrate connectivity, climate, and ecosystem service data. Many of these involve simple overlays in the data viewer, where we provide a method for interested parties to see our results and toggle through related maps without requiring data downloads, etc. In particular, we translated the top results of our scenarios into transparent sets of township-scale units that can easily be overlaid upon any of the other datasets (climate factors, ecosystem services, connectivity products) to allow users to see how different patterns and priorities overlap. In our results section, we further demonstrate integration of the connectivity results for scenarios 1 and 3 with an integrated ecosystem service benefit map in which township units are color-coded based on whether they fall in the top quartile of value scores for four of the five services (all but carbon, which was least variable across opportunity areas).

Finally, we integrated connectivity and ecosystem services to facilitate cross-stakeholder planning and coordination using a multi-objective analysis that identified restoration areas that score highly for both connectivity and ecosystem services. The analysis was conducted separately for the two restoration scenarios, prairie and forest. Each parcel received a composite score for each objective (connectivity and ES) by aggregating and normalizing the relevant sub-objectives. For connectivity, the included sub-objectives were the change in total flow and the change in the standard deviation of flow across the parcel. For ecosystem services the sub-objectives were sediment retention, nutrient filtration, carbon storage, and pollinator support. Each sub-objective was normalized to be between 0 and 1, and the normalized sub-objectives were summed to provide the parcel-level objective scores.

To characterize the trade-off between restoration strategies focused on one objective versus the other, we created weighted sum objective values by varying the relative weight placed on connectivity versus ecosystem services from 0% to 100% in equal steps, and at each combination selected the top 15% of parcels based on the resulting weighted score. This produces a family of candidate parcel sets that together trace a frontier of achievable outcomes. As the weight shifts toward connectivity, the selected set changes, and the aggregate ecosystem service benefits of the selection tend to decline, and vice versa.

Project Results, Analysis and Findings

We found diversifying the reasons for doing restoration in these landscapes can diversify the benefits for people and nature. While there are frequently co-benefits to restoring prairie or forest to improve connectivity for climate adaptation for plants and animals, our results also demonstrate that there are often tradeoffs among outcomes as well. Identifying locations for restoration that maximize connectivity, carbon, sediment retention, nitrogen retention, phosphorus retention, and wild bee habitat benefits was not possible. However, identifying the best restoration options to improve connectivity and using the ecosystem services to choose among those options, can often increase the value of that restoration for water quality or wild bee habitat. The results from this study will allow restoration practitioners to better target restoration regionally and locally to benefit the connectivity of habitat and climate adaptation of plants and animals while also improving the co-benefits of these restorations for water, climate mitigation, and pollination services. Below we present and discuss the results in the same order as the methods section, connectivity (current, regional, focal), ecosystem services, and then integration.

Connectivity Results

As connectivity is the climate adaptation strategy of interest in this project, the connectivity questions were the primary driver behind how we presented and integrated results. As described above, we developed two related sets of connectivity model products, the region-wide assessments based only on current landcover, and local-scale assessments that simulate restoration of agriculture to prairie or forest. From the regional analyses, we present the ecosystem-specific connectivity maps, and the results of our regional opportunity area scenarios. Following those results, we present products from our assessment of restoration opportunities at a farm-sized scale within the two focal areas.

Ecosystem-specific Structural Connectivity

As might be expected, the connectivity maps parameterized for forest and prairie ecosystems look very different. For both ecosystems, we show the wall-to-wall Circuitscape continuous or “raw” output, as well as a categorized map where this product has been classified into connectivity flow values representing different degrees of connectivity for plants and animals in that ecosystem.

For the continuous wall-to-wall outputs, the highest flow values (dark blue) indicate locations where relatively large volumes of current have become concentrated in lower resistance areas. Moderate flow areas (green) indicate places with high movement potential that is evenly distributed, suggesting “intact” natural systems and many possible movement pathways. The yellow to brown gradient indicates increasingly strong “deflection” of current flow from higher resistance areas (e.g., in this case, agriculture, cities) such that only low current flow remains. The current that is “pushed out” of these higher resistance areas contributes to the high current magnitudes in the concentrated flow (blue) areas (Figs. 8 and 9, left panels). We described the categorization approach, and interpretation of the categories in more detail in previous sections (see page 14). In short, concentrated flow areas capture the highest flow rates and indicate constraint in high value regions, while moderate value “diffuse” flow zones suggest intact natural landscapes with few barriers. Constrained flow areas are a lower magnitude set of concentrated flow, suggesting constraints in places where the overall amount of movement potential is relatively low compared to the concentrated or diffuse category.

The patterns of prairie connectivity across the project area are dramatically different both in terms of geography and dominant types of existing connectivity categories (Fig. 8). The most connected prairie areas showing the dark blue diffuse flow are on the western fringes of the project area with a few small places within patches high concentrated flow across the Dakotas, northern Minnesota and northern Missouri. Most of the prairie connectivity in the project area is represented as concentrated or constrained due to the amount of agricultural row crop landcover in the region. This leaves a lot of room for restoration opportunity for prairie.

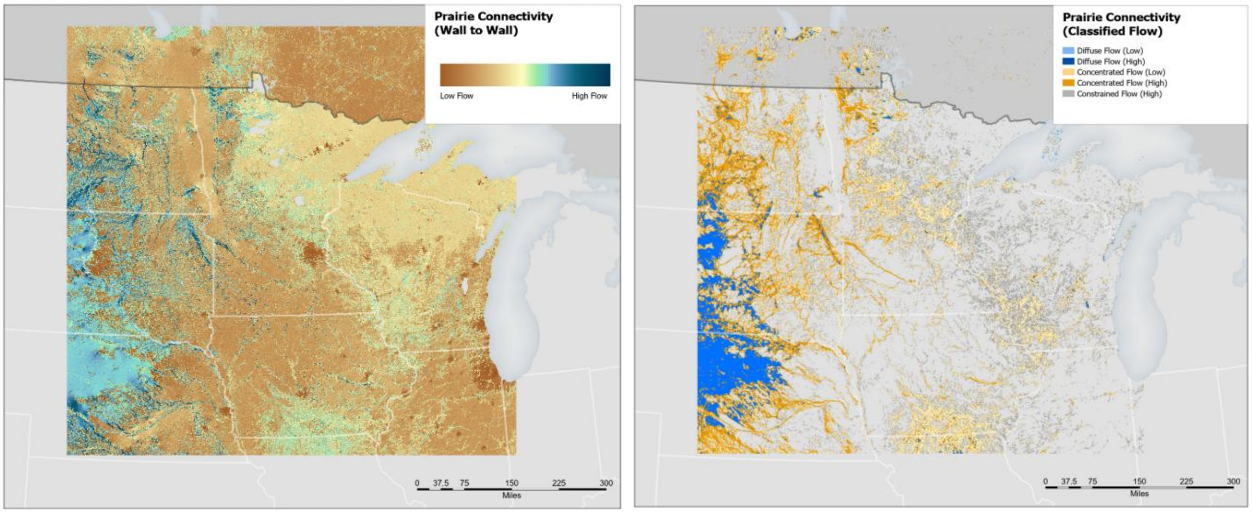

Figure 8. Circuitscape output based on resistance surfaces parameterized for prairie ecosystems (Table 2). The left panel shows the continuous wall-to-wall model output, and right panel is the same values classified into different categories of connectivity value.

Across the project area, forest connectivity is greatest in northeastern Minnesota and northern Wisconsin (Fig. 9). The large amount of dark blue and orange in the classified map indicates relatively good connectivity for forest organisms, particularly in areas closest to the Great Lakes. As you move south or west from the Great Lakes, the connectivity becomes more concentrated or dissipates altogether, particularly in central Wisconsin. This is partially due to conversion of landcover to non-forest uses and partially a transition into the prairie ecosystem to the south and west.

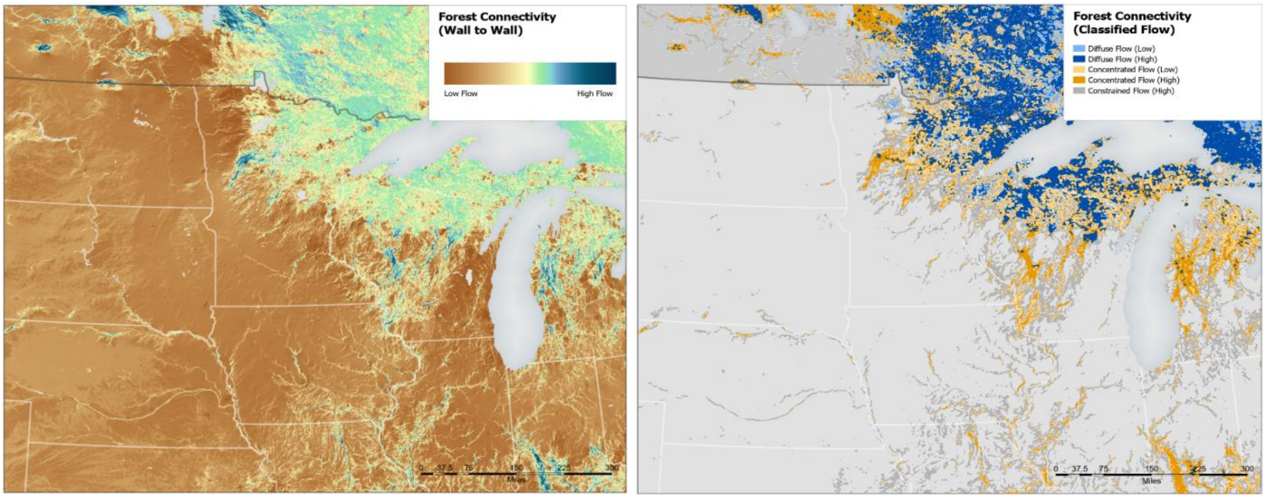

Figure 9. Circuitscape output based on resistance surfaces parameterized for forest ecosystems (Table 3). The left panel shows the continuous wall-to-wall model output, and the right panel is the same values classified into different categories of connectivity value.

As an early application "result," the regional prairie and forest connectivity products developed in this project were used by the Minnesota Department of Natural Resources as part of their State Wildlife Action Plan update. These data were incorporated into their Conservation Action Network map. A description of how these data were used in the plan from Daren Carlson, the State Wildlife Action Plan Monitoring Coordinator,

> *"The Conservation Action Network is a spatial prioritization map developed for Minnesota's 2025-2035 State Wildlife Action Plan. It is made up of 16 geographical layers representing high quality/important biodiversity core areas at the species, habitat, and landscape/ecosystem scales. In addition to the biodiversity cores, areas of high diffuse and concentrated flows for prairies and forests developed for the "Mapping climate-informed habitat restoration priorities with multi-sector benefits for 3 Upper Midwest ecoregions" were included to provide potential connections between the biodiversity cores. These 16 core and 2 connectivity layers were then scored using 5 scoring metrics representing lakes (lake health scores), streams (fish/invertebrate Indices of Biological Integrity), landscapes/ecosystems (ranked Sites of Biodiversity Significance), and richness of species in greatest conservation need (SGCN)."*

Regional Connectivity Restoration Opportunity Areas

To demonstrate integration of connectivity model results with other types of data that would potentially be important drivers of restoration decisions, we produced maps representing five conservation scenarios. The prairie opportunity scenario identified broad expanse of township-scale units (36 square miles, 22,773 acres) with high values for both criteria (more than 5000 acres of agriculture with concentrated prairie flow, and more than 5000 acres of prairie that could benefit from improved connectivity; Fig. 10). These areas tend to occur along the margins of the agricultural zones, with a high concentration in North and South Dakota and Nebraska where the connectivity values shift toward large expanses of diffuse flow. This size cut-off was arbitrary – the search image could be expanded or constrained as indicated by state-specific criteria, and/or a user's specific goals and budget. In the panels below the output map, we illustrate an overlay of the top locations with two of the ecosystem service benefit maps. With this approach, which is enabled in our data viewer, a user could visually scan the different high benefit units (transparent boxes) to find places where they would also be likely to find farm fields where restoration would have particularly high benefits for reducing sediment or phosphorus loading to nearby waterbodies (Fig. 10; other variables are available in the viewer).

Our second scenario, "prairie refugia" (Fig. 11) constrained the selection of township units to those that included just the higher level of categorized current flow (concentrated) and only counted acres of grassland represented as "undisturbed" in Barnes et al. (2025). As expected, this method for filtering our datasets highlights a much smaller set of "best" township units, again primarily in North and South Dakota and Nebraska. Here we again used 5000 acres as our cut-off value for both variables. This narrow search image might be appropriate for identifying locations where connectivity could be enhanced with the goal of supporting prairie refugia, so in Figure 11 we illustrate a pair of climate overlays that are possible in the viewer, a comparison with projected change in a key moisture index, and the current gradient of winter minimum temperature.

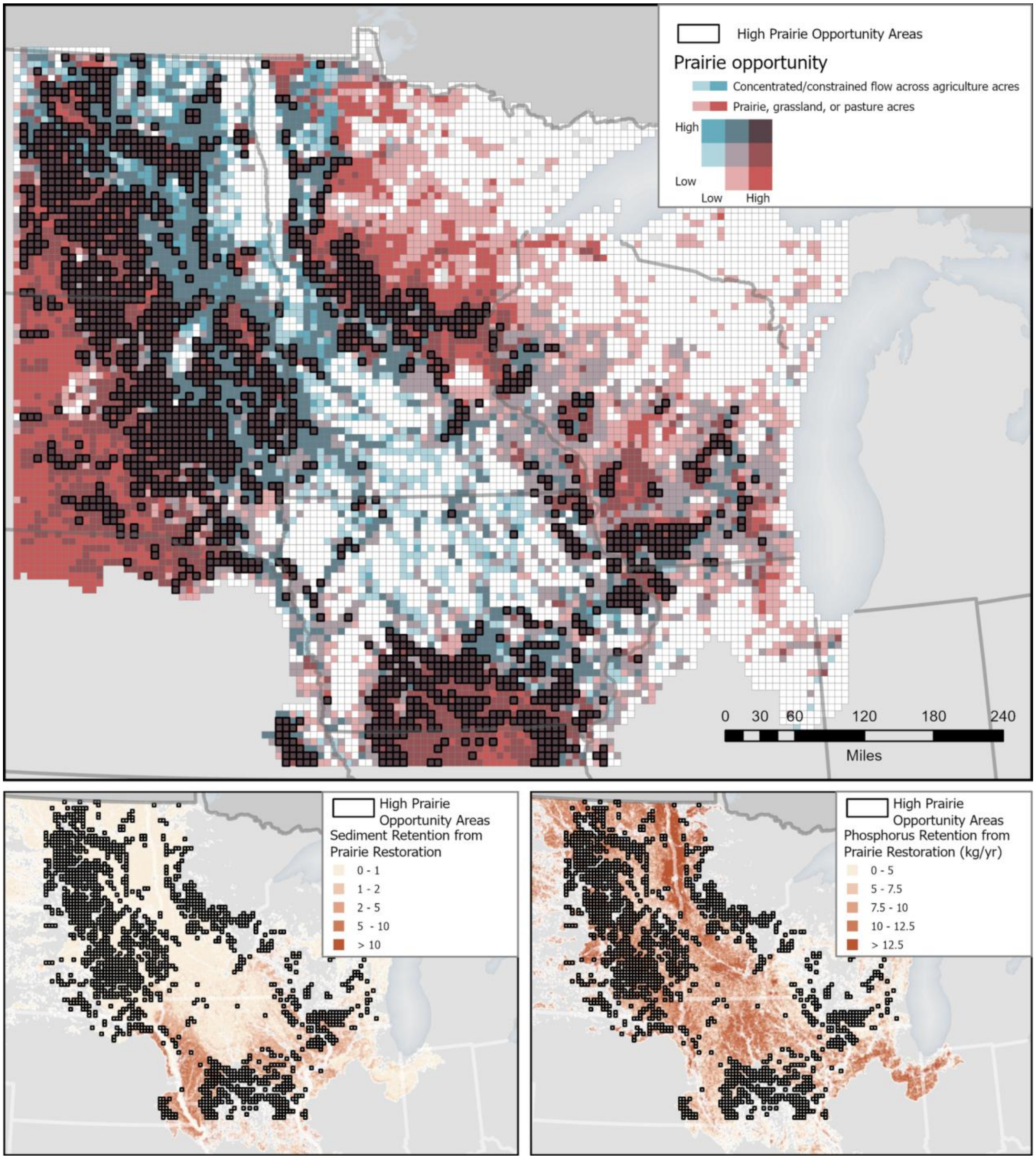

Figure 10. "Prairie opportunity" scenario results. The upper map shows the results of scoring our township-sized spatial units based on the amount of "restorable" (agricultural) land that co-occurs with concentrated or constrained flow from our connectivity model for prairie (teal color ramp) and for amount of grassland (broadly defined) in the same units (red color ramp). For both datasets, category breaks were set at 2000 and 5000 acres between low-medium, and medium-high, respectively. The outlined cells are "high-high" locations, which we suggest represent the "best" regions for further evaluation of multi-site restoration projects. To help further discriminate between these high value opportunity areas, we demonstrate integration with ecosystem service benefits associated with restoration, with sediment retention benefits on the left, and phosphorus retention values on the right.

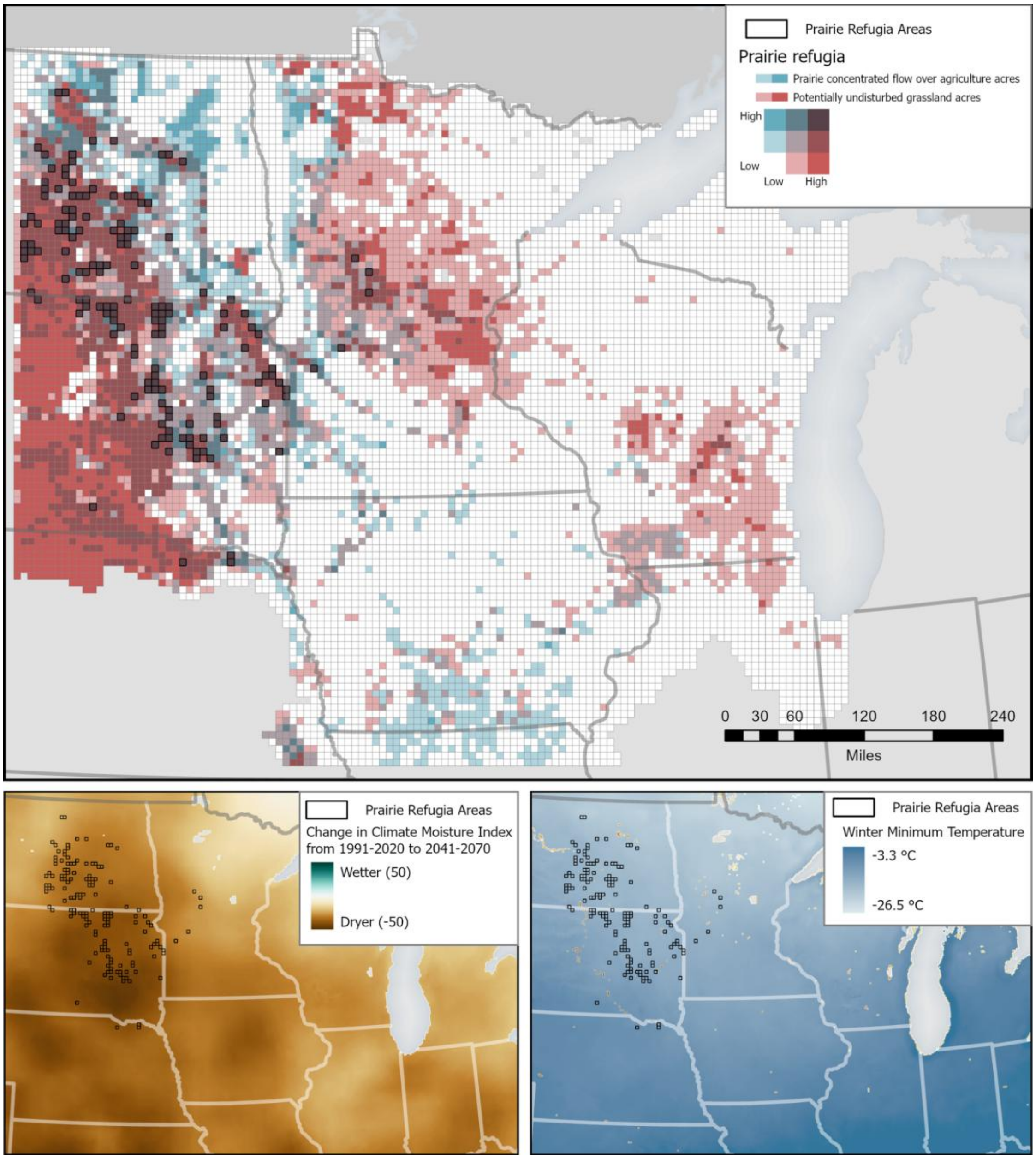

Figure 11. "Prairie refugia" scenario results. The upper map shows the results of scoring our township-sized spatial units based on the amount of "restorable" (agricultural) land that co-occurs with concentrated flow from our connectivity model for prairie (teal color ramp) and for amount of undisturbed grassland in the same units (red color ramp). For both datasets, category breaks were set at 2000 and 5000 acres between low-medium, and medium-high, respectively. The outlined cells are "high-high" locations, which we suggest represent the "best" regions for further evaluation of multi-site restoration projects based on these criteria. To demonstrate evaluation of climate refugia potential, we demonstrate integration with projected change in climate moisture index (left), and location relative to the winter minimum temperature gradient. Climate data from Adapt West's Climate Adaptation Data Basin portal (Wang et al. 2016, AdaptWest Project 2022, Mahony et al. 2022).

The forest connectivity benefits scenario (Fig. 12) was similar to the prairie opportunity scenario, in that it was intended to highlight a relatively large number of high value areas that could be further filtered using additional variables. There distribution of forests in our focal region is concentrated in Wisconsin and Minnesota, and overall there are fewer areas of concentrated and constrained flow (but a large expanse of diffuse flow) in the region. In particular, there is not much concentrated and constrained flow that occurs over agriculture, as shown in Table 3. So, our "restoration opportunity" township units for this system are more limited. Relative to the grassland scenarios, we set our thresholds for the connectivity variable and the forest area variable lower: 300 acres of concentrated forest flow over agriculture, and 3000 acres of forest that could benefit from improved connectivity (Fig. 12). The lack of flow over agriculture, and our choice to focus on concentrated flow produced a set of high value connectivity locations that indicate a narrow corridor north from Iowa and Illinois toward the highly connected forests of northern Wisconsin and Minnesota (Fig. 12). In the panels below the forest connectivity benefits output map, we again illustrate an overlay of the top locations with two of the ecosystem service benefit maps, the results for nitrogen retention and carbon benefits.

In scenario 4 (Fig. 13), we further constrained our forest connectivity opportunity areas by integrating a habitat rule within the township unit filtering process. We used the same area-based criteria as the scenario above but only counted forest acres that had more than 120 days per year of snow cover (on average), based on the Silvis lab snow season length dataset for the years 2003-2020 (Gudex-Cross et al. 2021). In this map, only nine units were selected, with most along the southern edge of the high snow duration zone

Our final scenario (Fig. 14) considers a situation where restoration to improve connectivity for either forest or prairies could have high benefits and could potentially lead to actions by one group of practitioners that reduce options for the other system. Here we simply intersected the top set of locations from the two more general scenarios above, scenario 1 for grasslands, and scenario 3 for forests. These set of locations generally occur along the prairie-forest transition zone in Wisconsin and Minnesota but also highlight mixed-matrix areas in Iowa.

Integration of Regional Opportunity Areas and Ecosystem Services

Three final figures in this section illustrate additional approaches for integrating connectivity and ecosystem service datasets to support conservation decisions beyond the simple overlays shown in Figures 10 and 12. Note that a more explicit comparison of trade-offs related to connectivity and ecosystem services is presented following the ecosystem services section, but we present these simpler approaches here because they relate to the regional scale scenarios.

In Figures 15 and 16, we show the top results of the prairie opportunities, and forest connectivity benefits scenarios, respectively, over system-specific integrations of ecosystem service benefits. To produce these map, we identified the township units that were in the top quartile of benefits for each restoration-benefit of ecosystem services layer, and then color coded the results using transparent overlays for each service on its own – yellow for nitrogen, pink for phosphorus, blue for pollinator habitat, and gray for sediment. As the least variable service, carbon was left out of this mapping, as five colors would be challenging to visualize. For a few rare combinations with multiple top scores, we added additional colors to the range produced by the transparent overlays so they could be detected. Together these maps highlight many opportunities to achieve multiple benefits, with specifics that vary by region. Our last Figure (17) related to the scenarios contrasts the range of variation in ecosystem service values associated with just the top scoring township areas for each system type. Review of these plots can help practitioners evaluate ecosystem service benefit "scores" associated with a particular high connectivity opportunity unit relative to the range of values for other possible target locations.

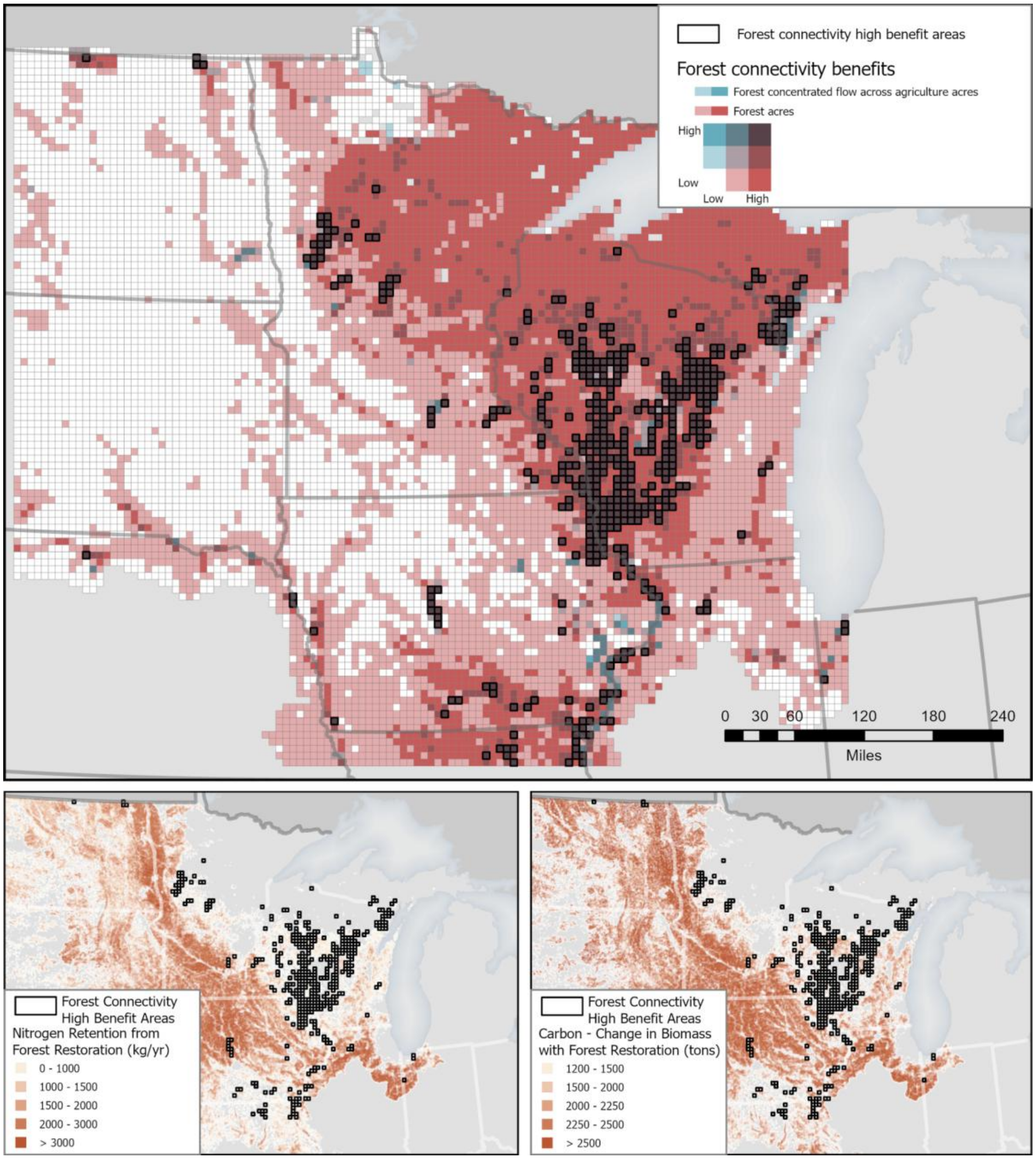

Figure 12. “Forest connectivity benefits” scenario results. The upper map shows the results of scoring our township-sized spatial units based on the amount of “restorable” (agricultural) land that co-occurs with concentrated flow from our connectivity model for forests (teal color ramp) and for amount of forest in the same units (red color ramp). Category breaks for concetrated flow were set at 50 and 300 acres between low-medium, and medium-high, respectively, while the breaks for forested acres were set at 200 and 3000. The outlined cells are “high-high” locations, which we suggest represent the “best” regions for further evaluation of multi-site restoration projects. To help further discriminate between these high value opportunity areas we demonstrate integration with ecosystem service benefits associated with restoration, with nitrogen retention benefits on the left, and increase in carbon retention values on the right.

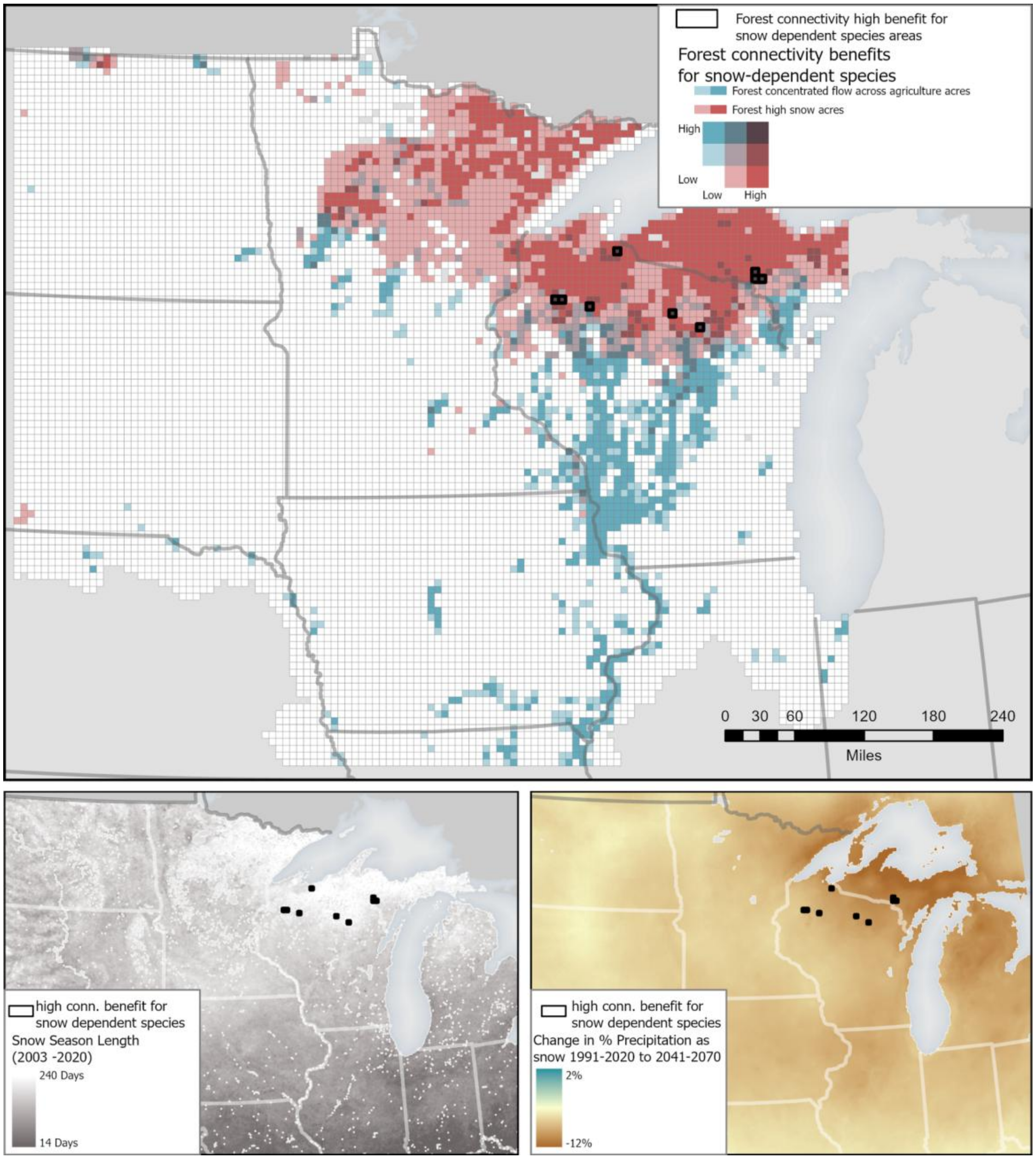

Figure 13. "Forest connectivity benefits for snow dependent species" scenario results. The upper map shows the results of scoring our township-sized spatial units based on the amount of "restorable" (agricultural) land that co-occurs with concentrated flow from our connectivity model for forests that occur in a zone with high snow duration (120 days; teal color ramp) and for amount of forest in the same units (red color ramp). Category breaks for concentrated flow were set at 50 and 300 acres between low-medium, and medium-high, respectively, while the breaks for forested acres were set at 200 and 3000. The outlined cells are "high-high" locations. The panels below show these units with the snow duration data (left) and projections for changes in percent precipitation expected to fall as snow (right). Source for snow data is Gudex-Cross et al. (Gudex-Cross et al. 2021). Projection of percent precipitation as snow data from Adapt West's Climate Adaptation Data Basin portal (Wang et al. 2016, AdaptWest Project 2022, Mahony et al. 2022).

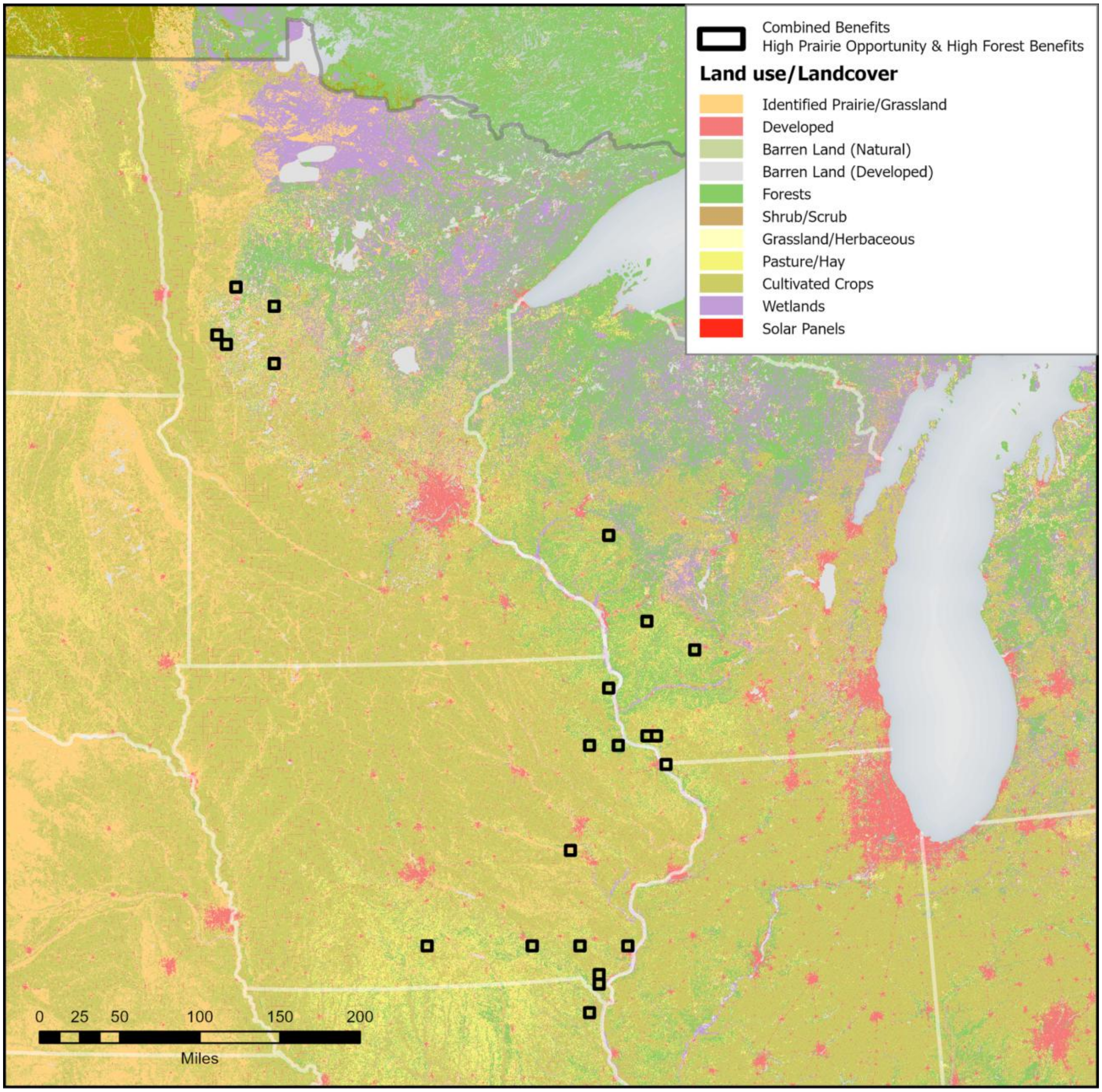

Figure 14. Intersection of priority areas from the prairie opportunities scenario (Fig. 10) and the forest connectivity benefits scenario (Fig. 12). These are shown over the landcover dataset that provided the basis for our resistance surface. In this subset of units, we suggest it is particularly important for restoration practitioners focused on prairies and forests to coordinate their actions to avoid reducing connectivity for their non-target system type.

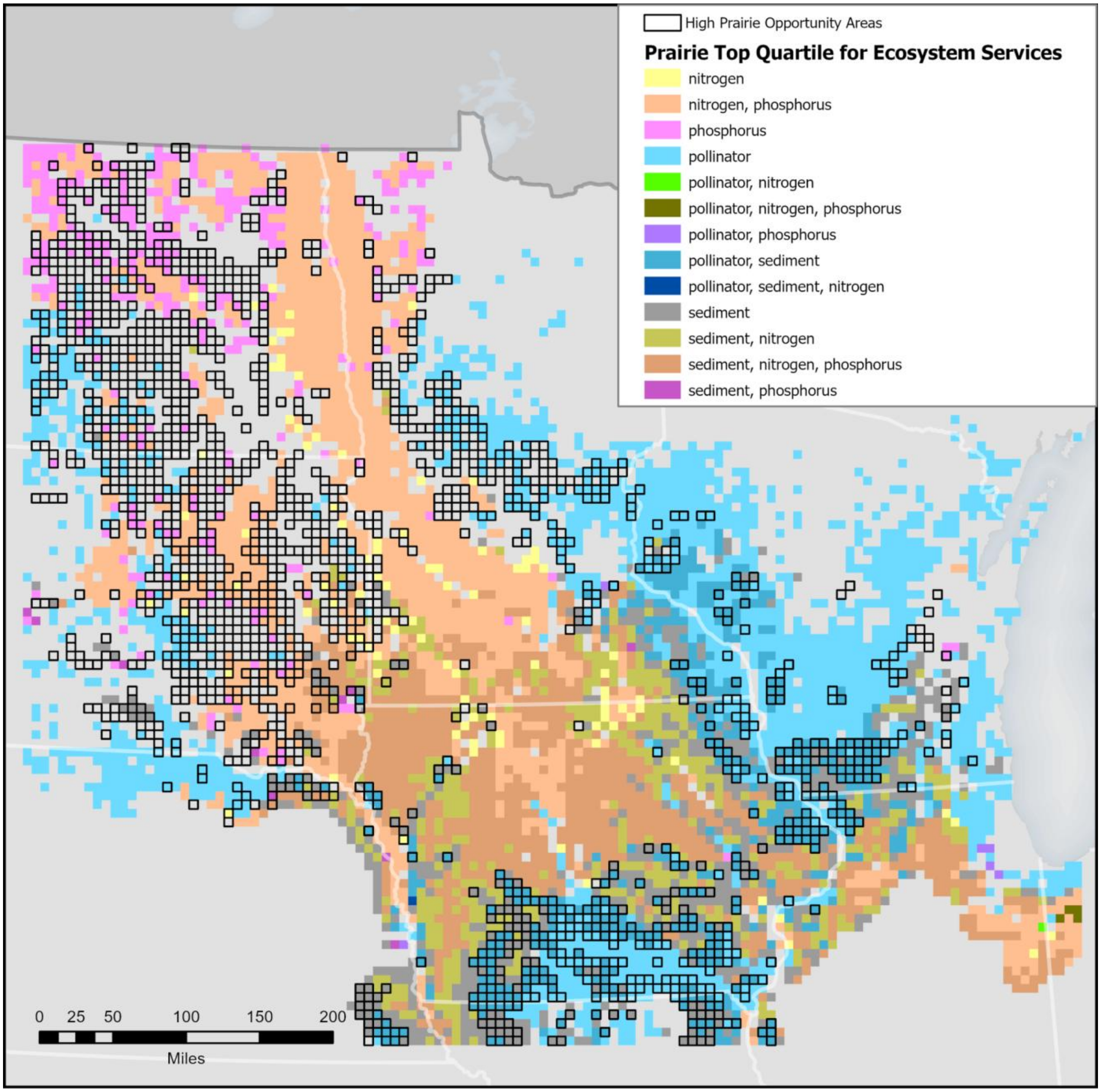

Figure 15. Top results of the prairie opportunities scenario (see Figure 10) shown overlaid upon an ecosystem-specific integration of ecosystem service benefits. To produce this map, we identified the township units that were in the top quartile of for four of the ecosystem service benefits layers, and then color-coded the results using transparent overlays for each service – yellow for nitrogen, pink for phosphorus, blue for pollinator habitat, and gray for sediment. Intermediate colors represent units in the top quartile for multiple services. For a few rare combinations with three top quartile scores, we added additional colors to the range produced by the transparent overlays so they could be detected.

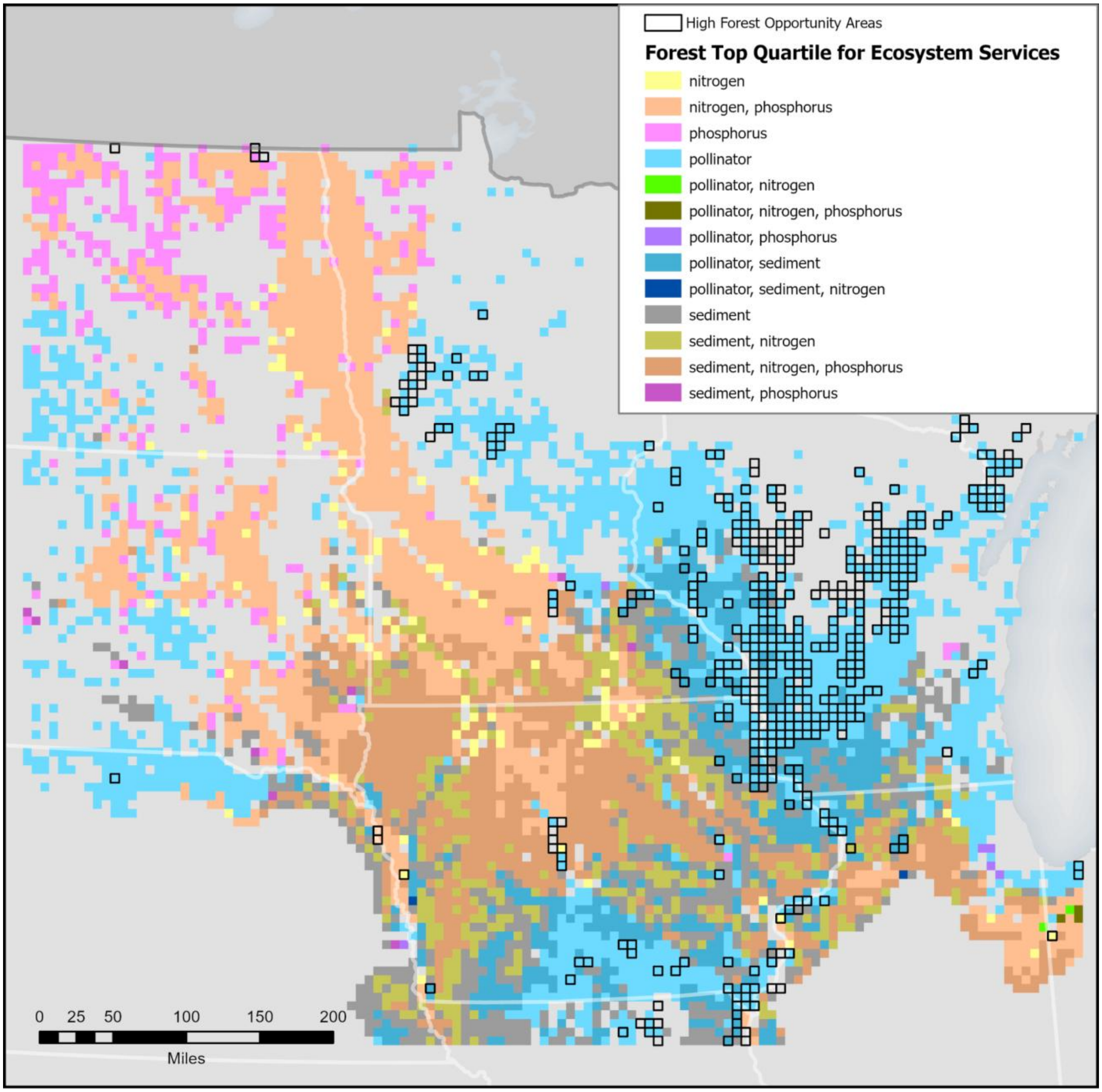

Figure 16. **T**op results of the forest connectivity benefits scenario (see Figure 12) shown overlaid upon an ecosystem-specific integration of ecosystem service benefits. To produce this map, we identified the township units that were in the top quartile for four of the ecosystem service benefits layers, and then color-coded the results using transparent overlays for each service – yellow for nitrogen, pink for phosphorus, blue for pollinator habitat, and gray for sediment. Intermediate colors represent sites in the top quartile for multiple services. For a few rare combinations with three top quartile scores, we added additional colors to the range produced by the transparent overlays so they could be detected.

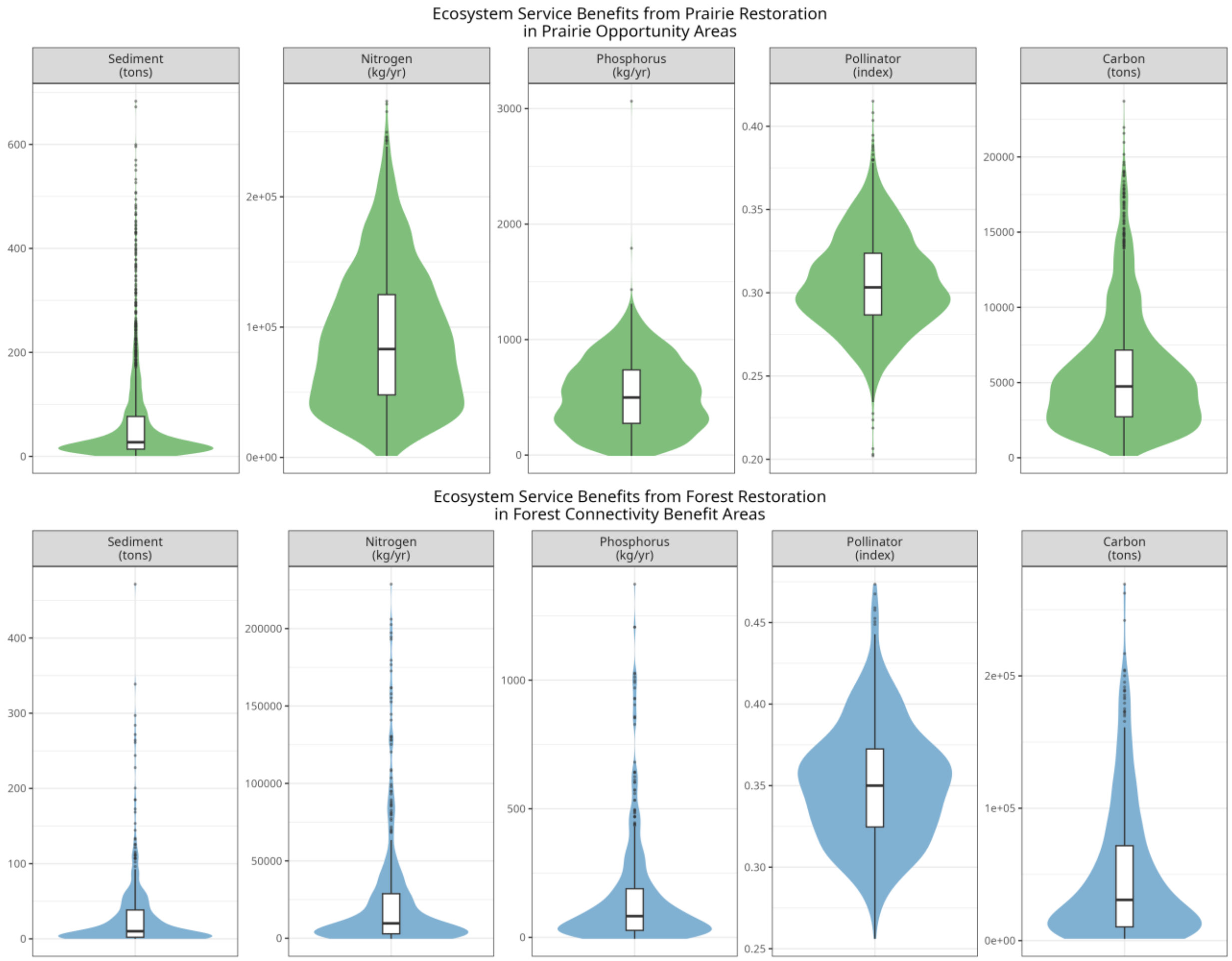

Figure 17. Range of variation in ecosystem service benefits from prairie (top panel) or forest (bottom panel) restoration. These violin plots combine a box plot (line inside the box is the median, and lower and upper bounds of the box are the first and third quartile) with a continuous probability density (colored ranges). Review of these plots can help practitioners evaluate ecosystem service benefit "scores" associated with a particular high connectivity opportunity unit relative to the range of values for other possible target locations.

Focal Area Connectivity Restoration Opportunities

The two focal areas had similar restoration questions and different landscape contexts, which allowed us to test how our methods worked across sites with different drivers of reduced connectivity (fragmentation by agriculture, and fragmentation by agriculture and another natural system). Overall we made significant updates to the methods described in Clark et al. (2023) for the Appalachians. Yet, while modeling the connectivity and ecosystem services for these sites was relatively straightforward, summarizing and sharing results concisely is a challenge.

For connectivity, there are multiple ways to summarize the results that represent different types of connectivity value. For example, if you want to focus on increasing the amount of diffuse flow or relieving pinch points you would focus on different connectivity metrics, which would also lead you to restore different areas. After discussions with the focal area teams, in all cases for this project we focused on increasing the amount of diffuse flow that builds on the existing connectivity of each of the focal areas.

Similarly, integrating the connectivity results with the ecosystem service results does not need to be complicated, but the number of ways these data could be integrated and shared is nearly infinite, and different partners are interested in different questions or may prioritize different ecosystem services creating a challenge for how to simply communicate these results. For this project, we focused on leading with restoration of connectivity as a climate adaptation strategy and quantifying the ecosystem service co-benefits of restoration for connectivity using the same set of assumptions and spatial units. Several approaches for integration were demonstrated in the previous section, focused on the regional-scale products. Many more ways to integrate these datasets to inform specific decisions are possible through the data viewer, and through additional analyses on downloaded data. Our connectivity and ecosystem service products allow partners to integrate these data in ways that align with their specific needs or interests, though it is important to recognize that they are built on sets of assumptions, spatial units, and rules crafted for particular restoration scenarios. Our next section describes the context and specifics of the focal area scenarios.

GLACIAL LAKES FOCAL AREA

According to the Glacial Lakes Advisory sub-team, The Nature Conservancy (TNC) has a goal of completing 2,100 acres (850 hectares) of high diversity prairie restoration within the Glacial Lakes and Lac Qui Parle core areas by 2030. If we assume half of those acres will fall within the Glacial Lakes core area, identifying the 1,050 acres (425 hectares) of restorable land with the greatest potential to improve connectivity would ensure those restorations are contributing their greatest climate adaptation benefit to the plants and animals in this landscape. The geology and topography of the Glacial Lakes area kept past conversion of prairie to row crop agriculture lower than in other parts of the state, and the current connectivity maps demonstrate this with the amount of dark blue flowing through the landscape (Fig. 18). This dark blue indicates some existing connectivity to build from with the restorations.

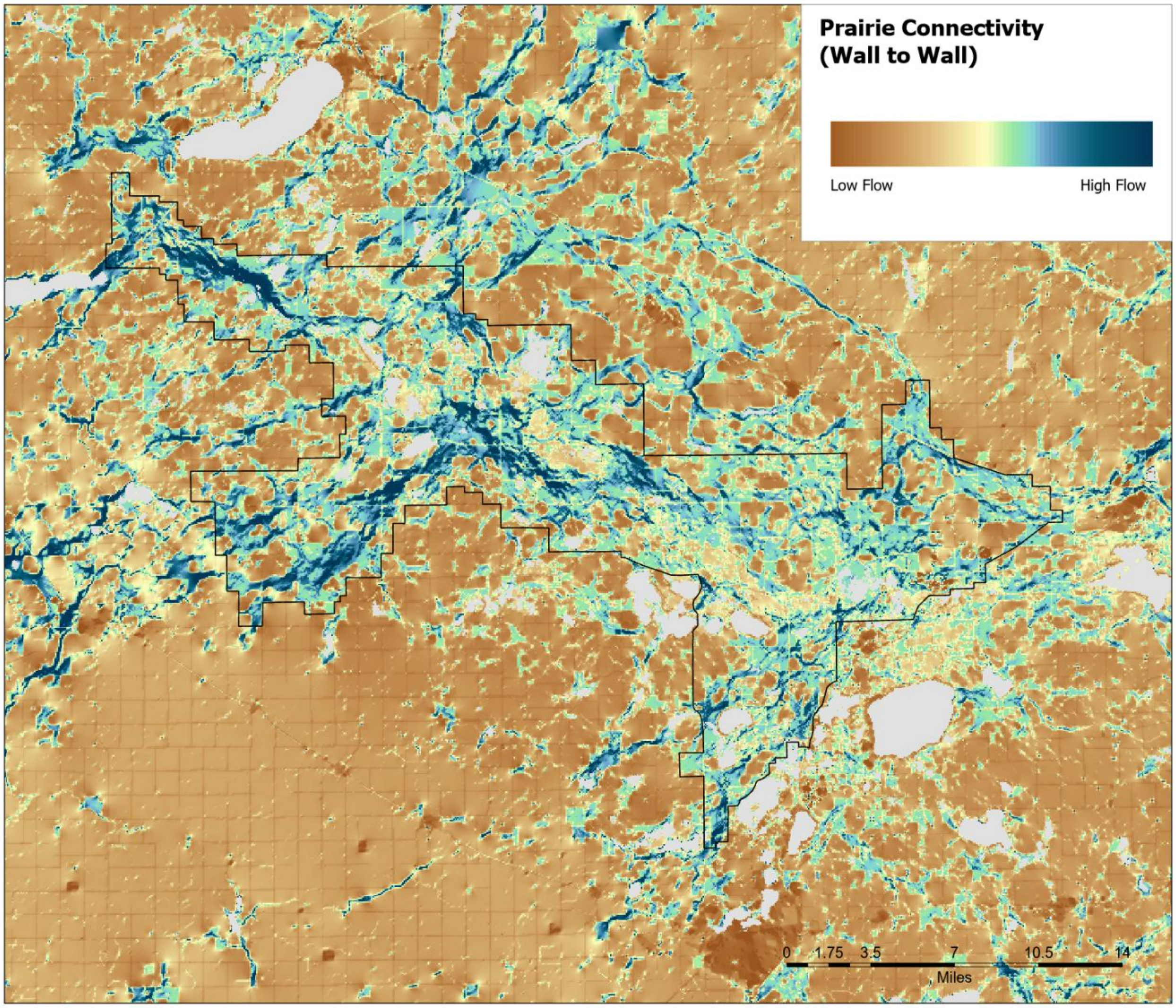

Figure 18. Wall to wall connectivity results for the Glacial Lakes core area (black outline). Dark blue are areas of high flow indicating existing connectivity; green and yellow are areas of lower flow indicating more fragmentation; brown areas indicate little to no flow indicating little to no connectivity or prairie habitat; the gray areas represent open water.

The team working in the Glacial Lakes landscape wanted us to focus restoration opportunity mapping on sub-prime cropland for two reasons. The first is that prime agricultural lands should stay agricultural lands because food production is also an important land use in this landscape. The second is cost. Restoration of agricultural lands for conservation purposes happens after protection of those lands, and doing protection on prime agricultural lands is cost prohibitive. Focusing on sub-prime cropland, we identified the top 20% of the 64 ha parcels that would improve connectivity (Fig. 19). Restoring the sub-prime cropland within these parcels would increase the amount of diffuse flow spreading out the flow in the Glacial Lakes connectivity network. Because there was already a core of concentrated flow to build from in this landscape, restoring the land in these top parcels would mean creating more opportunities for plants and animals to move between prairie locations.

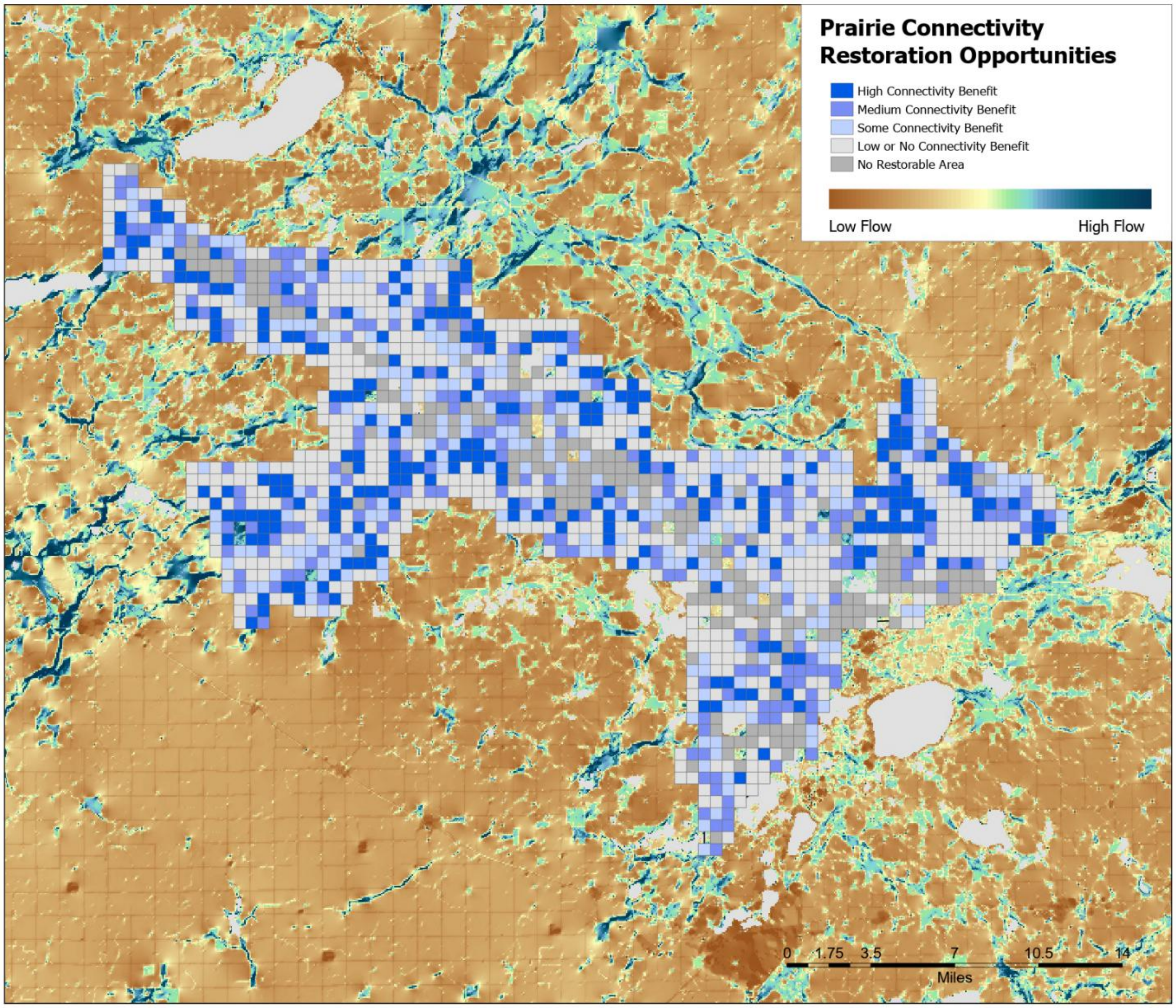

Figure 19. Connectivity benefit for each 64 hectare (~154 acre) farm parcels within the Glacial Lakes core area that contained 23.5% of sub-prime cropland. Dark gray parcels contained no restorable area; connectivity benefit is mapped as quintiles with the top 20% in the darkest blue. The low or no connectivity benefit (shown in grey) are the bottom two quintiles.

As you can see from Figure 19, the dark blue parcels fall along the edges of the currently mapped connectivity for the area. This makes sense given that spreading out the flow in the landscape was the goal. The amount of sub-prime agricultural land within the top 20% of parcels is 4090 ha, providing more opportunity areas to choose from than needed to meet their goal. This also allows the ecosystem services to factor into this decision.

ROOT RIVER FOCAL AREA

Although the Root River Advisory sub-team is primarily focused on reforestation in the region, our results indicate that their concerns about reforestation conflicting with prairie restoration efforts also happening in the region are not unfounded.

Current ecosystem connectivity for the Root River watershed is greater for forest than it is for prairie. There is less diffuse flow (dark blue) in the prairie connectivity network (Fig. 20) than there is the forest (Fig. 21). Connectivity for both ecosystems show up more strongly on the eastern side of the watershed than the west, but this pattern is strongest for forest connectivity. While weaker overall, the prairie connectivity extends further into the western part of the watershed. The very western part of this watershed is very dominated by row crop agriculture with little prairie or forest habitat remaining making connectivity nearly non-existent for forest and very limited for prairie in this part of the watershed (Figs. 20 and 21).

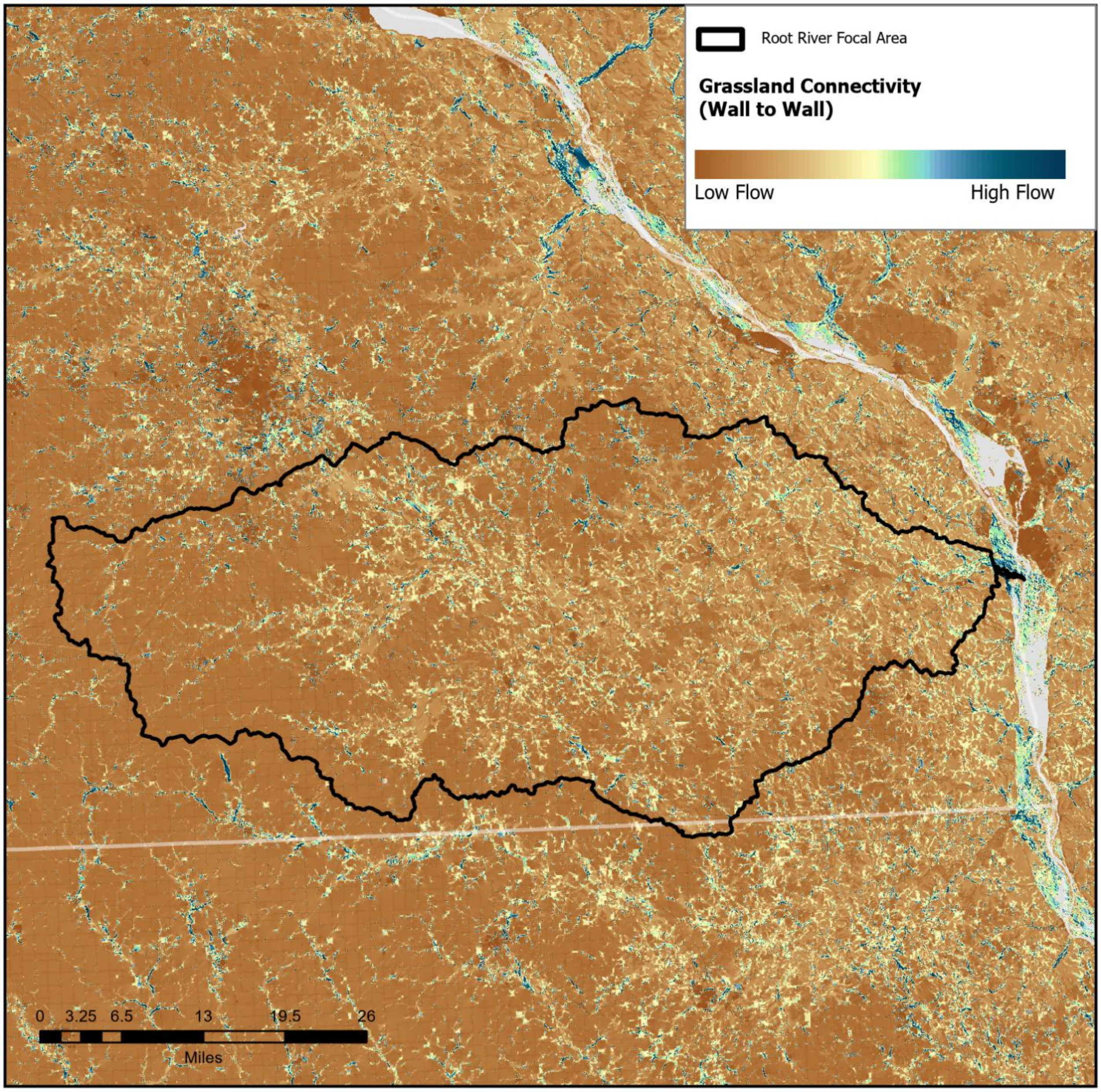

Figure 20. Wall to wall connectivity results for the Root River watershed core area (black outline). Dark blue are areas of high flow indicating existing connectivity; green and yellow are areas of lower flow indicating more fragmentation; brown areas indicate little to no flow indicating little to no connectivity or prairie habitat; the gray areas represent open water along the river.

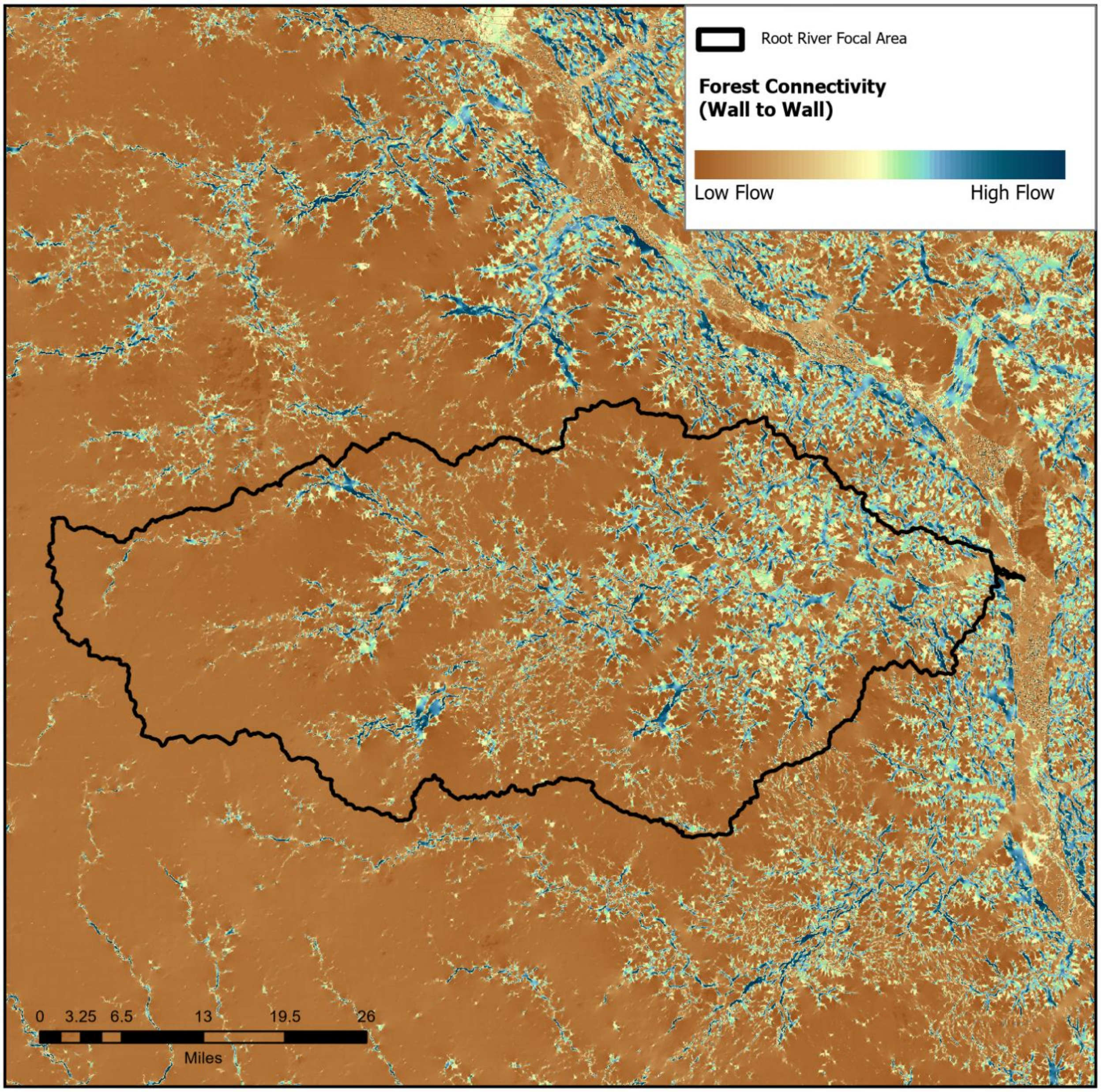

Figure 21. Wall to wall connectivity results for the Root River watershed core area (black outline). Dark blue are areas of high flow indicating existing connectivity; green and yellow are areas of lower flow indicating more fragmentation; brown areas indicate little to no flow indicating little to no connectivity or forest habitat.

We ran the Circuitscape model separately for prairie and forest and identified the top 20% of the 64 ha parcels that would improve connectivity for each (Figs. 22 and 23). The top 20% of forest parcels represents 4,713 ha (11,647 acres), and the top 20% of prairie parcels represents 6,260 ha (15,468 acres). Restoring the cropland within these parcels would increase the amount of diffuse flow spreading out the flow in the Root River connectivity network for forest (Fig. 23) or prairie (Fig. 22). The top parcels for forest restoration are more concentrated on the eastern side of the watershed (Fig. 23) because there was a core of diffuse and concentrated flow to build from on the eastern side. The top parcels for prairie restoration are somewhat more scattered across the entire watershed, reflecting the more dispersed pattern of current connectivity that prairie restoration would have to build from across the watershed. For both ecosystems, because there was already a core of concentrated flow to build from in this landscape, restoring the land in these top parcels would mean creating more opportunities for plants and animals to move between prairie locations.

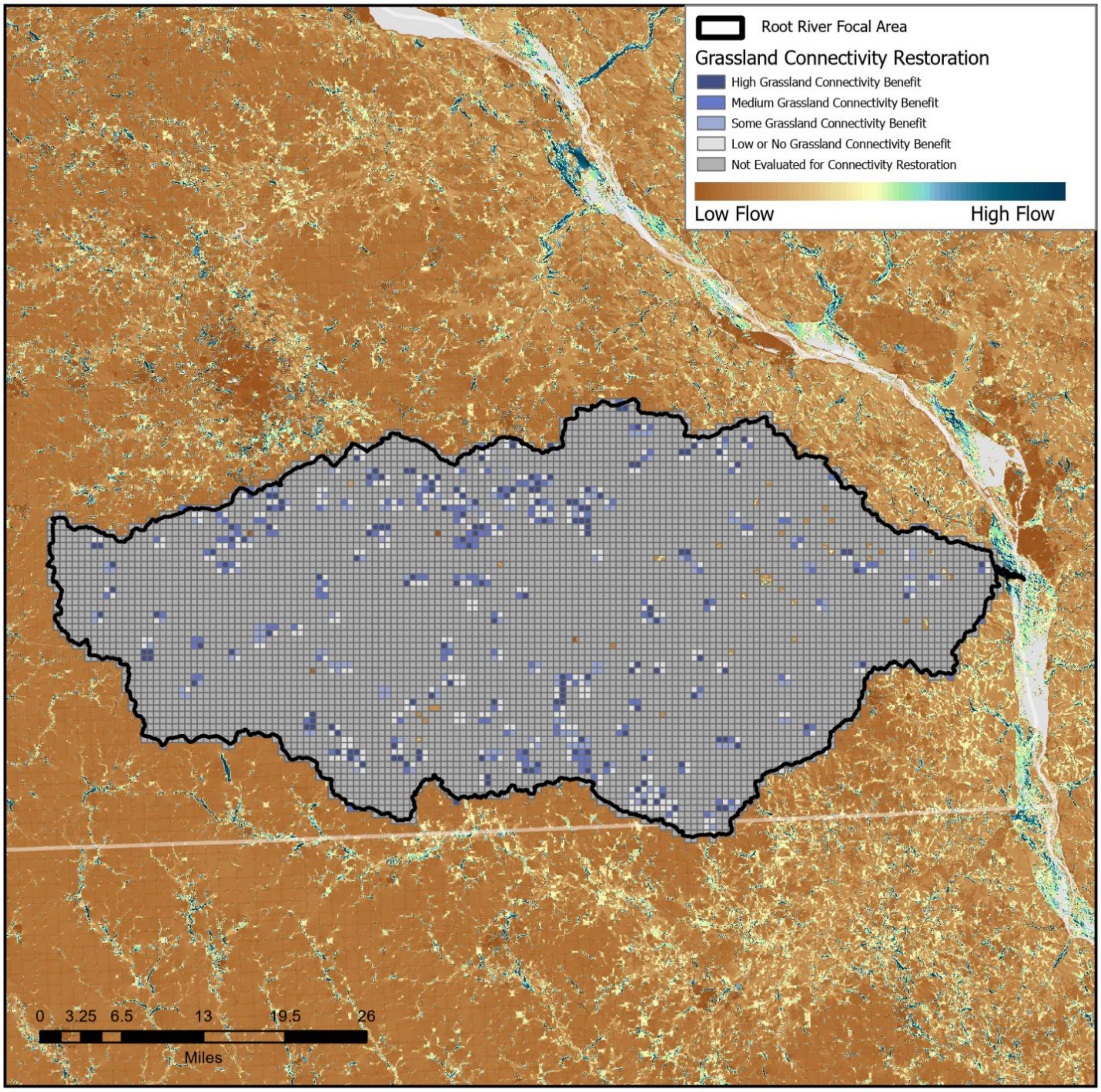

Figure 22. Connectivity benefit from prairie restoration for each of the selected 64 hectare (~154 acre) farm parcels within the Root River watershed. Connectivity benefit is mapped as quintiles with the top 20% in the darkest blue. The low or no connectivity benefit (shown in grey) are the bottom two quintiles.

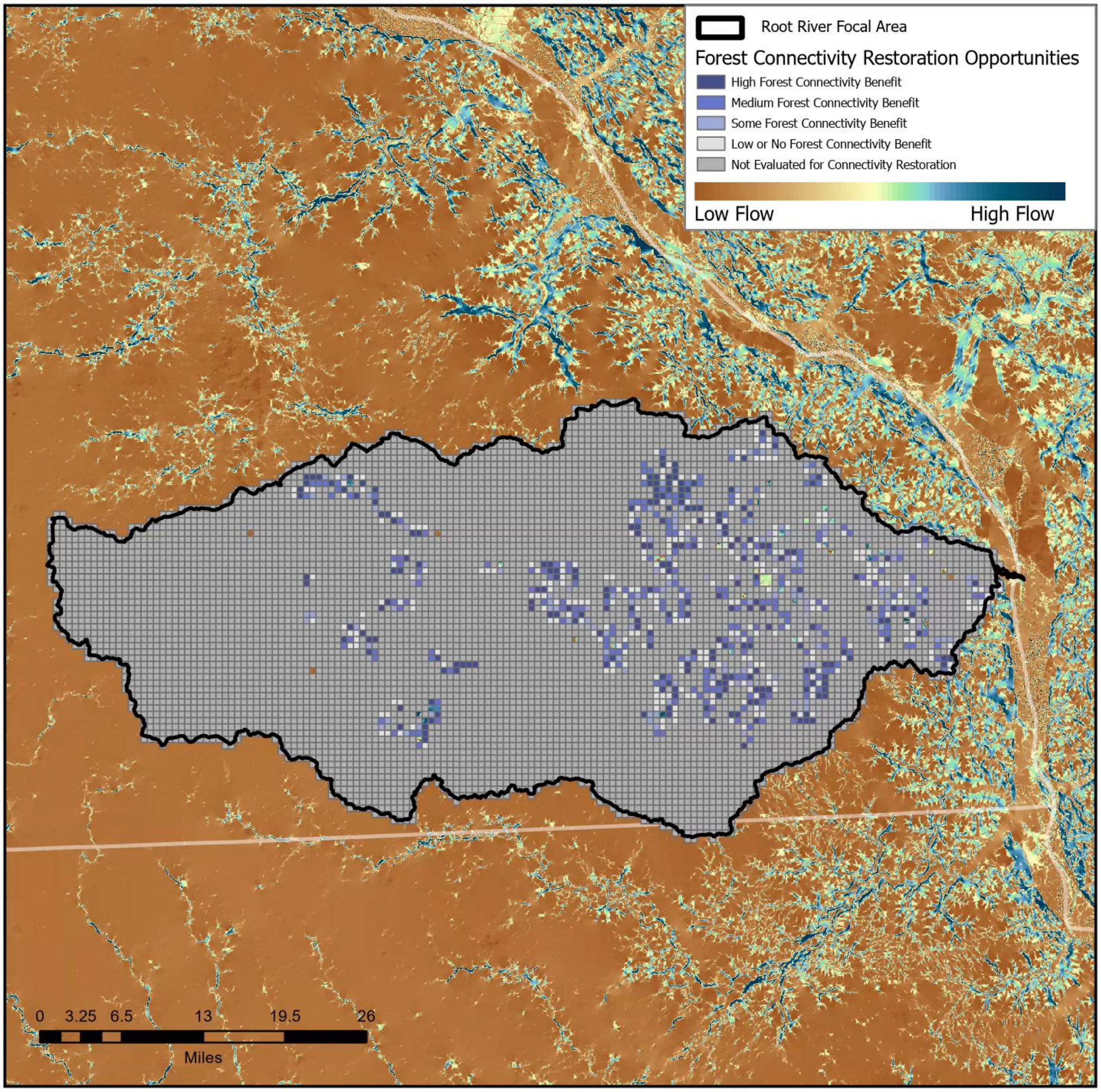

Figure 23. Connectivity benefit from forest restoration for each of the selected 64 hectare (~154 acre) farm parcels within the Root River watershed. Connectivity benefit is mapped as quintiles with the top 20% in the darkest blue. The low or no connectivity benefit (shown in grey) are the bottom two quintiles.

To evaluate the question of whether the best places for forest restoration in the watershed could impede prairie connectivity, we then looked at the intersection of these two maps. Of all the parcels identified in the top 20% for forest and prairie, only 32 parcels showed up in both analyses, representing a ~3% of the top parcels for each ecosystem (Fig. 24). While this number is low, it is not zero. These results indicate that conflict between prairie and forest restoration is not likely to be high in this watershed, but there are some places where it would be valuable to assess whether forest or prairie restoration is the most appropriate action. As always local context and conditions should help inform practitioners in these decisions.

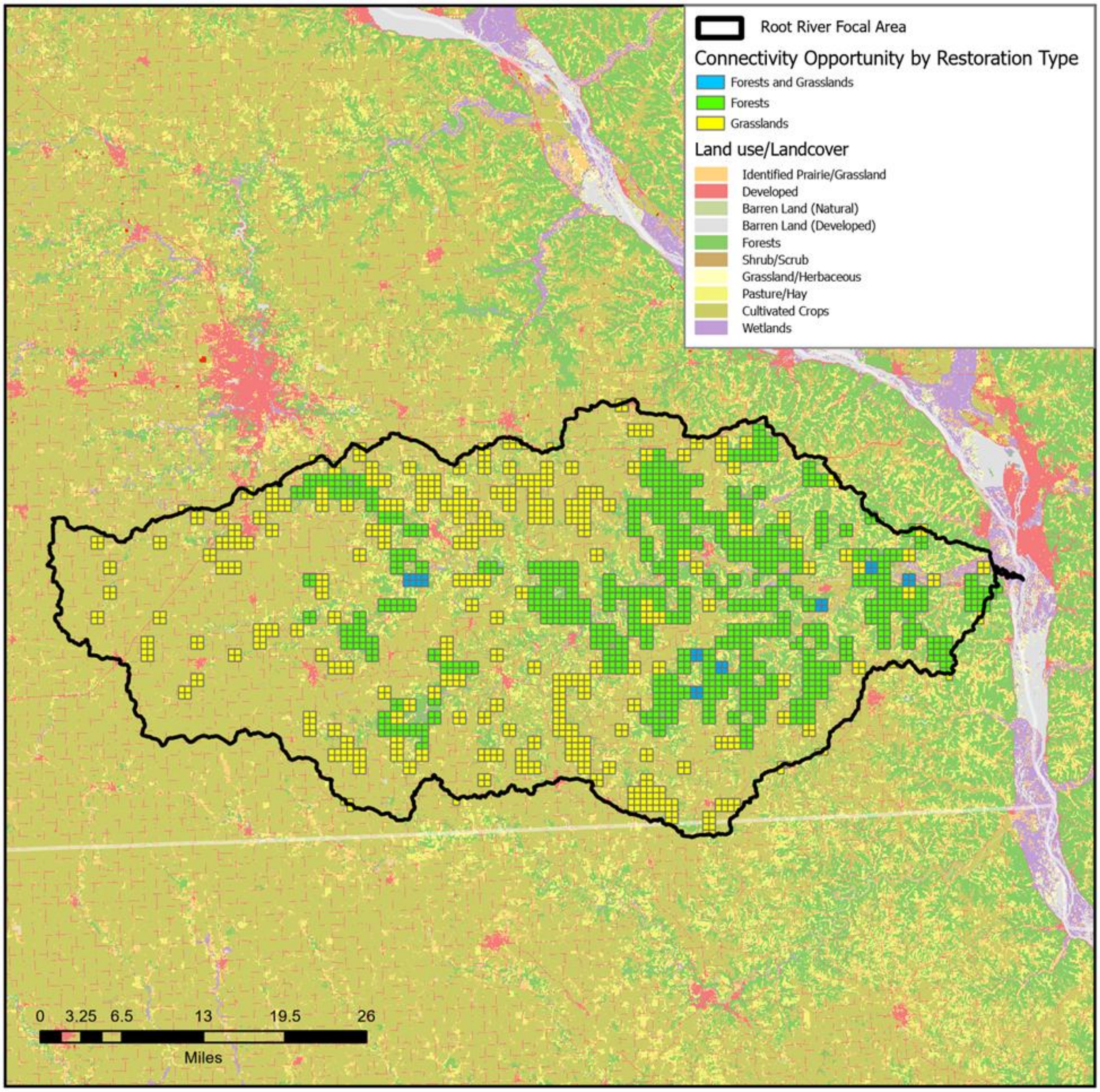

Figure 24. Map showing the top 20% of 64 ha parcels identified as forest (green) and prairie (yellow) restoration opportunity area. The parcels shown in blue appear in the top 20% results for both ecosystems.

Ecosystem Services Results

Impact of restoration type

The impacts of both restoration types (prairie, deciduous forest) were similar across most of the ecosystem services analyzed in this study. Prairie restoration caused slightly higher average improvements in sediment retention, nitrogen retention, and wild bee abundance; deciduous forest restoration had greater phosphorus retention and carbon biomass (above and belowground) storage

(Fig. 25). In general, the spatial patterns of ecosystem service benefits were similar across restoration types (see Figs. below). This is expected, as the differences in model parameters between prairie and deciduous forest are slight in contrast to those of agriculture—we expect the magnitude of benefits to change between restoration types but not necessarily the patterning.

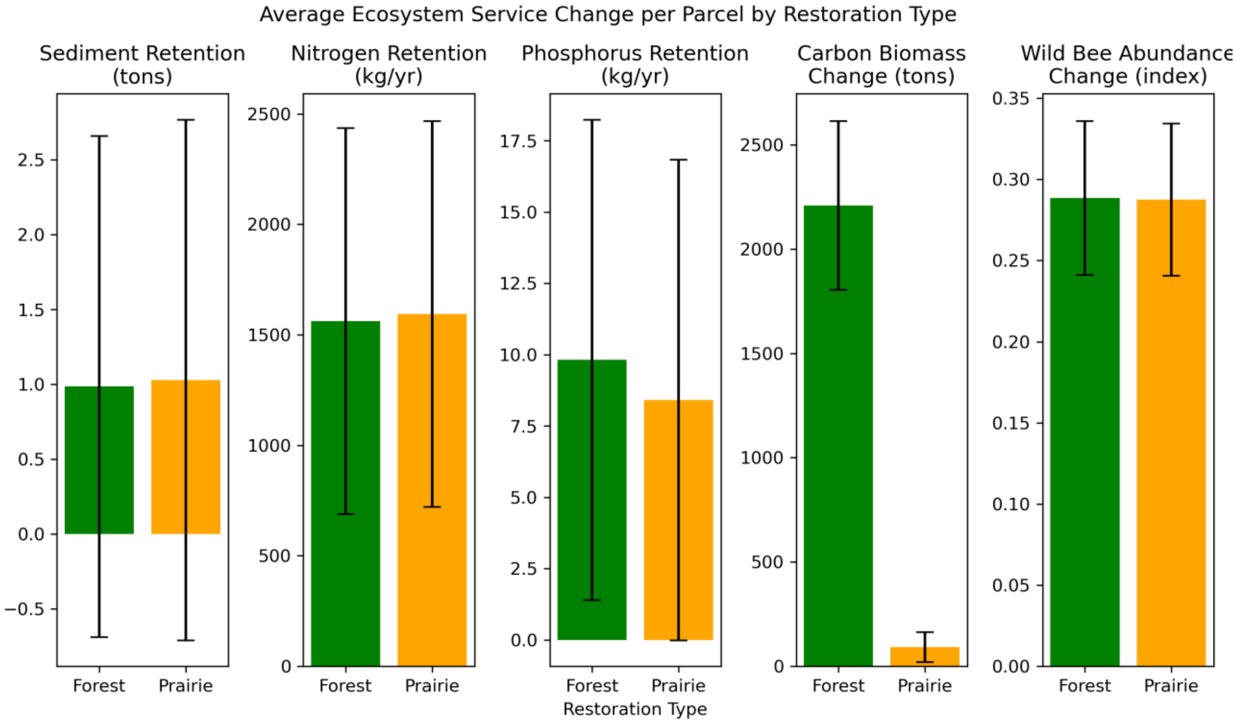

Figure 25. Average ecosystem service impact of restoration on an agricultural parcel across the study area, by restoration type.

RESTORATION EXTENT AND VIABILITY

To avoid presupposing the boundary between prairie and forest across the project area, the ecosystem service models were run assuming either prairie or deciduous forest could be successfully restored on any agricultural parcel within the region. However, in many locations one habitat type is preferred or one is simply not viable. Maps showing the ecosystem service impact of restoration do not take this preference or viability into account and instead show the potential of a single restoration type across the entire study area. Habitat viability was beyond the scope of this modeling exercise—the restoration-based ecosystem service benefits in areas in which a habitat type is not desirable or viable should be treated as overestimates. These maps are not meant as recommendation, and practitioners should use local context and information to determine whether prairie or forest restoration is the best option for any particular location.

Nutrient export and retention

BASELINE

The results of the baseline NDR analysis show the amount of nitrogen (Fig. 26) and phosphorus (Fig. 27) that is expected to reach local waterways in overland runoff each year, based on the 'current' agricultural landscape (ca. 2023). These are the baselines from which we can evaluate potential restoration scenarios. Since we are primarily interested in restoration activities on agricultural lands, we have only reported nutrient export from the agricultural areas of each 64-hectare grid square, and only grid squares with at least 50% row crop agriculture were modeled.

Generally, nitrogen export is highest in the corn and soy-dominated landscapes of southern Minnesota, most of Iowa, and northern Illinois (Fig. 26). Phosphorus export follows a similar pattern but with markedly higher export rates in the Red River Valley in northern Minnesota (Fig. 27).

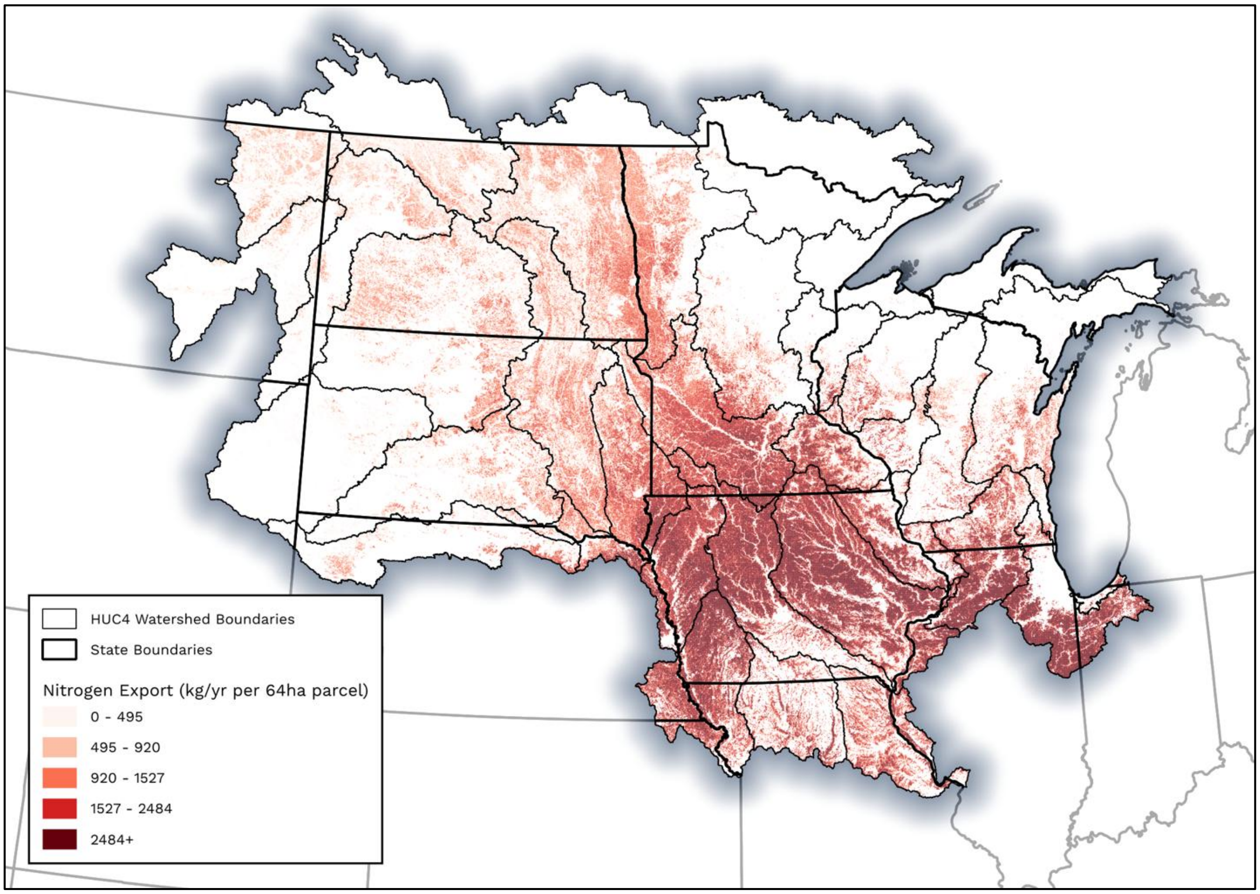

Figure 26. Baseline nitrogen export in surface runoff (kg/yr) from agricultural lands within each 64-hectare (~154 acre) farm parcel. Modeled using the InVEST NDR model on the 2023 Cropland Data Layer.

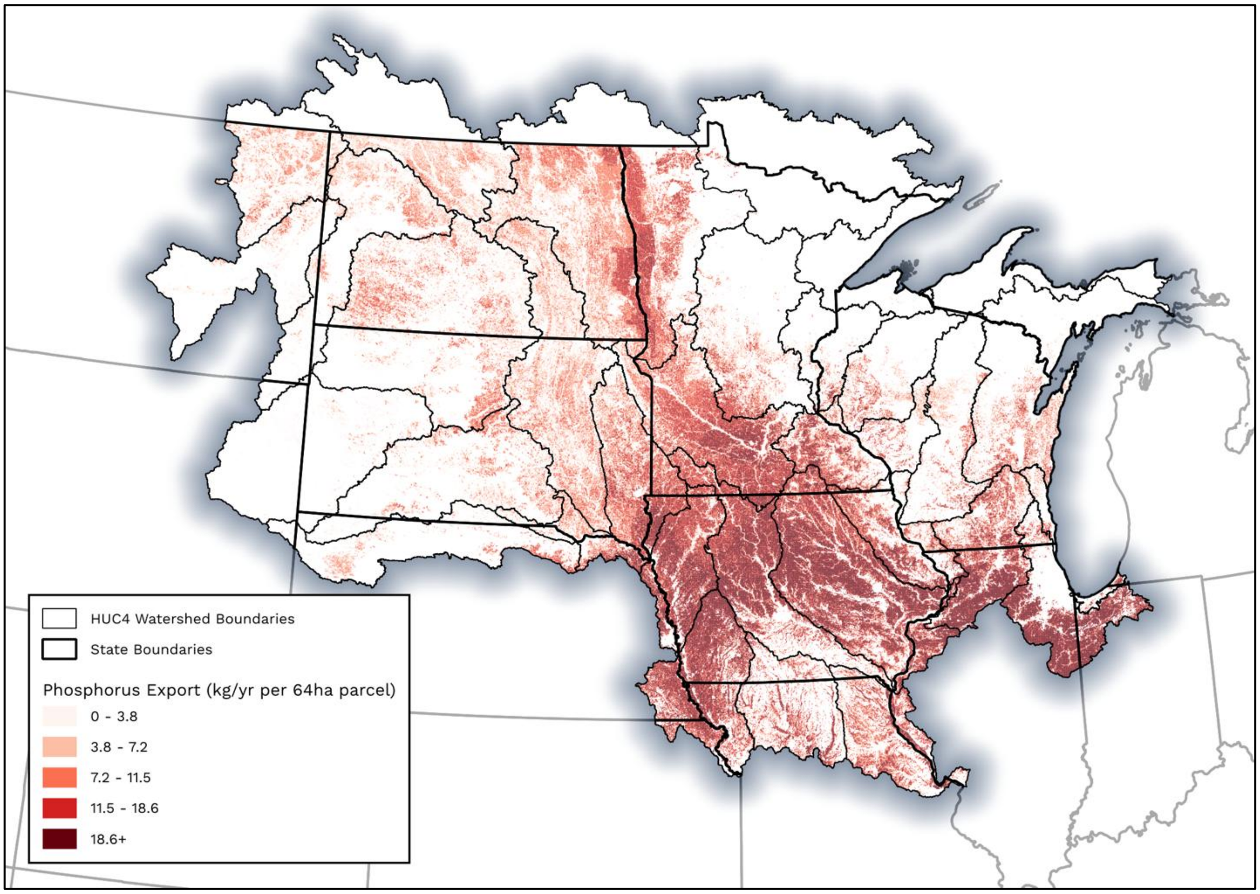

Figure 27. Baseline phosphorus export in surface runoff (kg/yr) from agricultural lands within each 64-hectare (~154 acre) farm parcel. Modeled using the InVEST NDR model on the 2023 Cropland Data Layer.

RESTORATION SCENARIO RESULTS

There is high variability in nutrient retention potential across the study area, with hot spots in the Red River and Minnesota River Valleys. Note that some areas show a net increase in export (i.e., a negative retention value). This is primarily driven by the Cropland Data Layer "Other Hay/Non Alfalfa" and "Alfalfa" categories, which are considered agriculture but have parameters more akin to existing prairie. This deviates from the assumptions of the regression analysis and causes small errors.

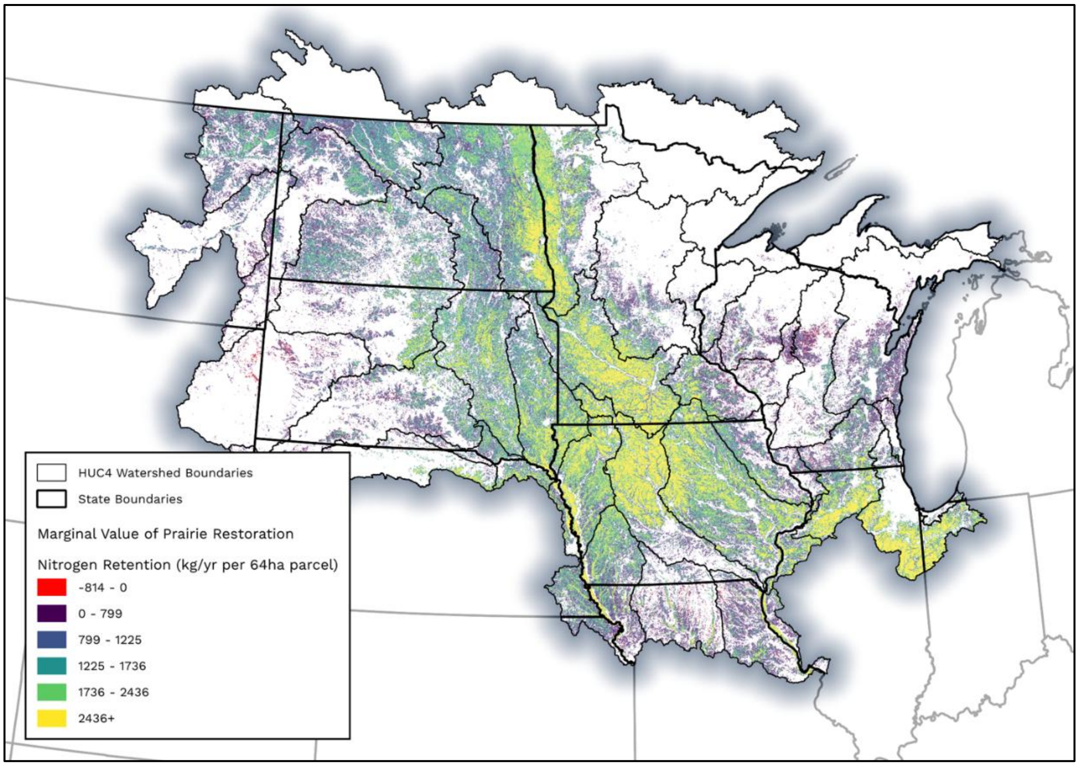

Figure 28. Expected annual nitrogen retention (on-site reductions and upslope capture) from agricultural areas restored to prairie within each 64-hectare parcel.

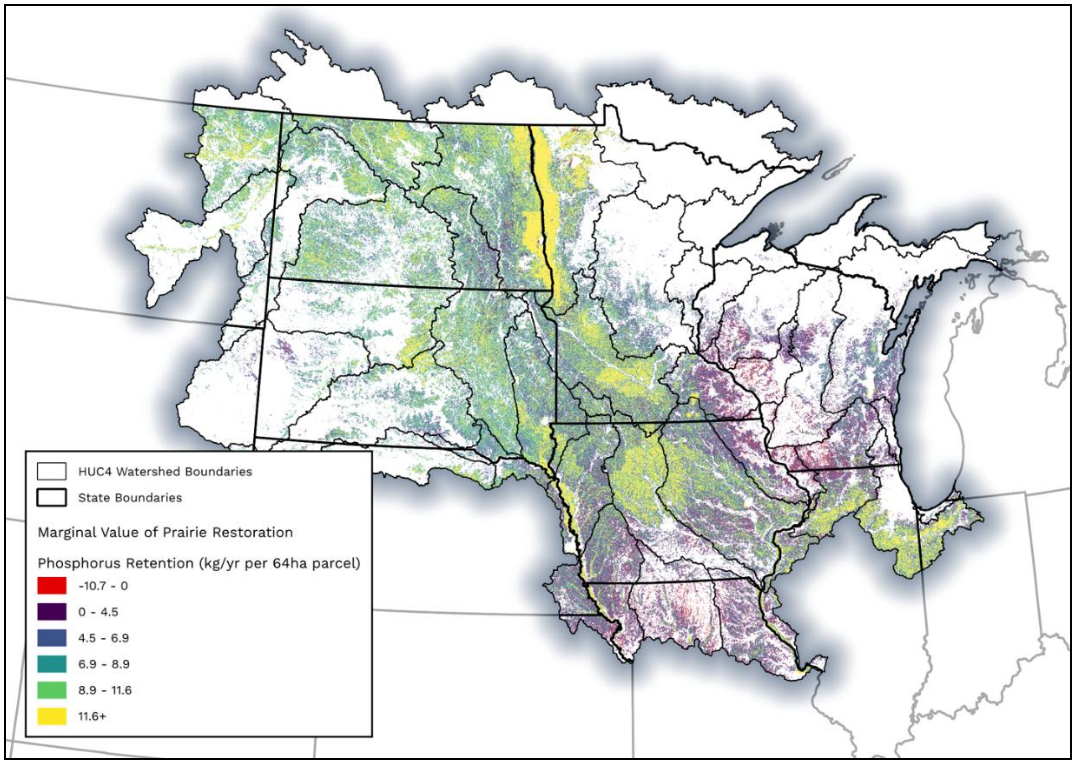

Figure 29. Expected annual phosphorus retention (on-site reductions and upslope capture) from agricultural areas restored to prairie within each 64-hectare parcel.

The above two maps (Figs. 28 and 29) show the amount of nitrogen and phosphorus respectively prevented from reaching local waterways in overland runoff each year due to restoring the agricultural land within each parcel to prairie. The subsequent maps (Figs. 30 and 31) show the same for deciduous forest restoration. Areas with higher retention (yellow) indicate either places where restoration removes significant on-site fertilizer burdens, captures significant upslope nutrient runoff, or both; areas with lower retention (purple) indicate low priority restoration areas, at least in terms of nutrient retention. These results are spatially independent, in that each parcel assumes no change in neighboring parcels. If two adjacent parcels have high retention potential, restoring one may reduce the retention potential of the other. This relationship is not depicted here due to computational constraints.

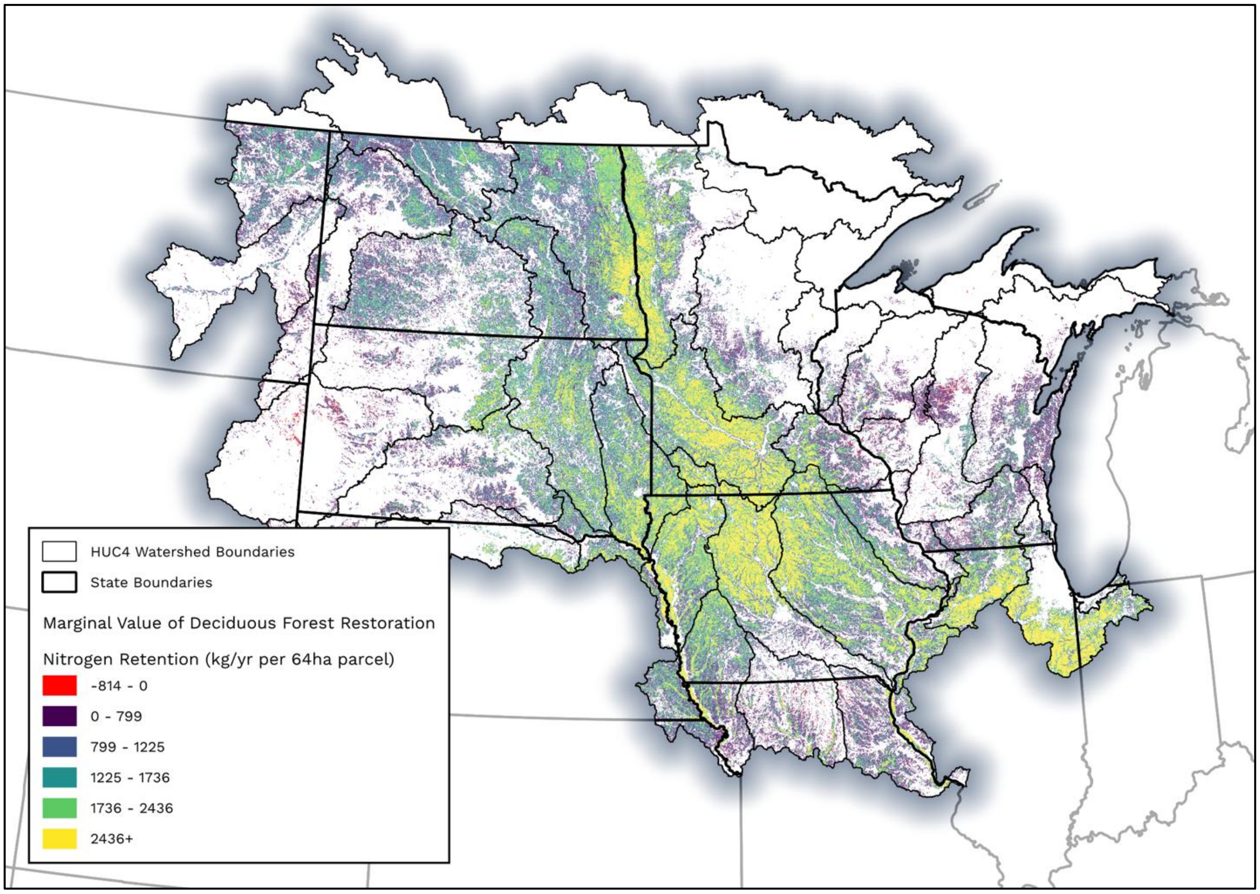

Figure 30. Expected annual nitrogen retention (on-site reductions and upslope capture) from agricultural areas restored to deciduous forest within each 64-hectare parcel.

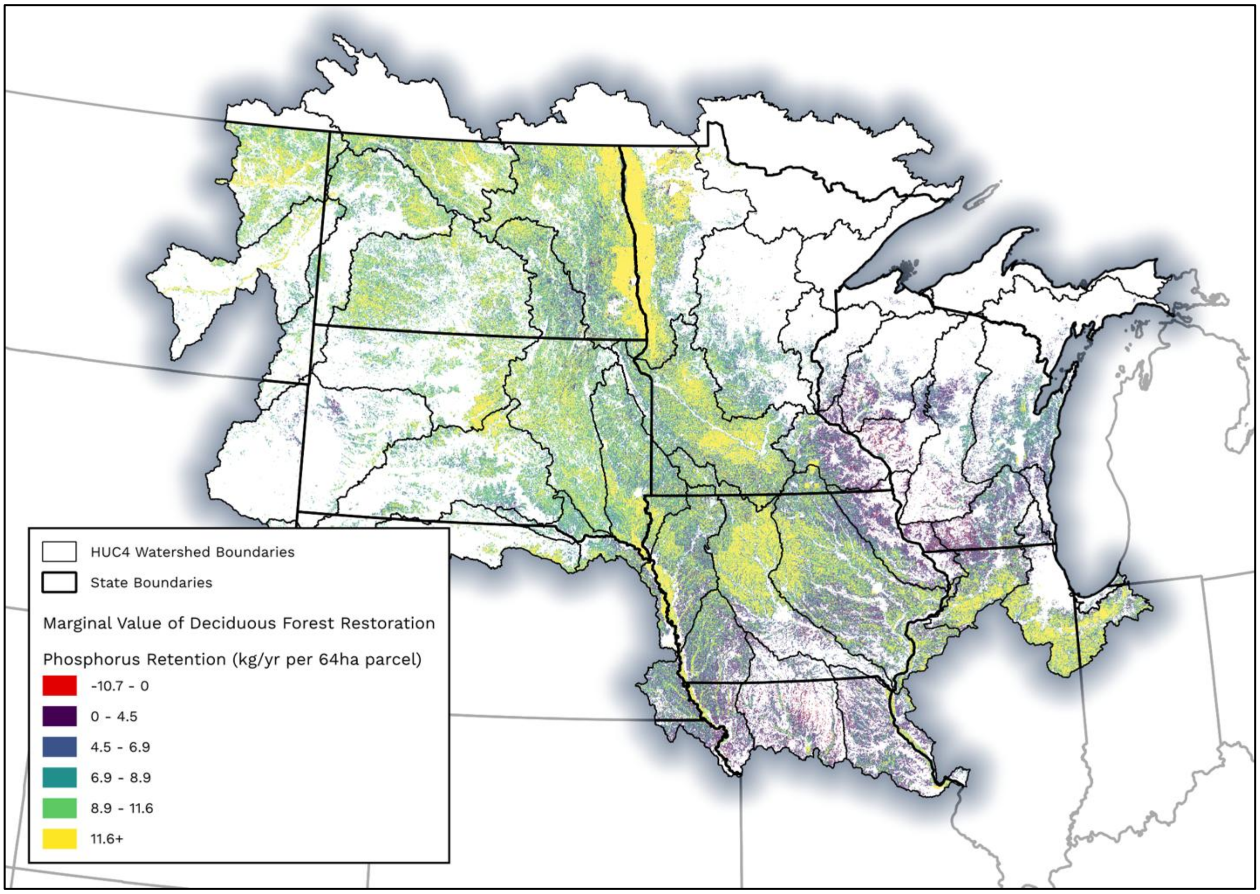

Figure 31. Expected annual phosphorus retention (on-site reductions and upslope capture) from agricultural areas restored to deciduous forest within each 64-hectare parcel.

Sediment export and retention

BASELINE

Expected annual sediment export from agricultural areas as modeled by the InVEST Sediment Delivery Model (SDR) at a 30-meter resolution, summed to the 64-hectare grid square shows a lot of variability across the region. This map (Fig. 32) shows the amount of sediment that is expected to reach local waterways from overland erosion each year, based on the ‘current’ agricultural landscape (2023). It is the baseline from which we can evaluate potential restoration scenarios: areas with high export (dark red) are potentially good target areas for restoration while areas with low export (light pink) are of lower priority. Since we are primarily interested in restoration activities on agricultural lands, we have only reported sediment export from the agricultural areas of each 64-hectare grid square, and only grid squares with at least 50% row crop agriculture were modeled.

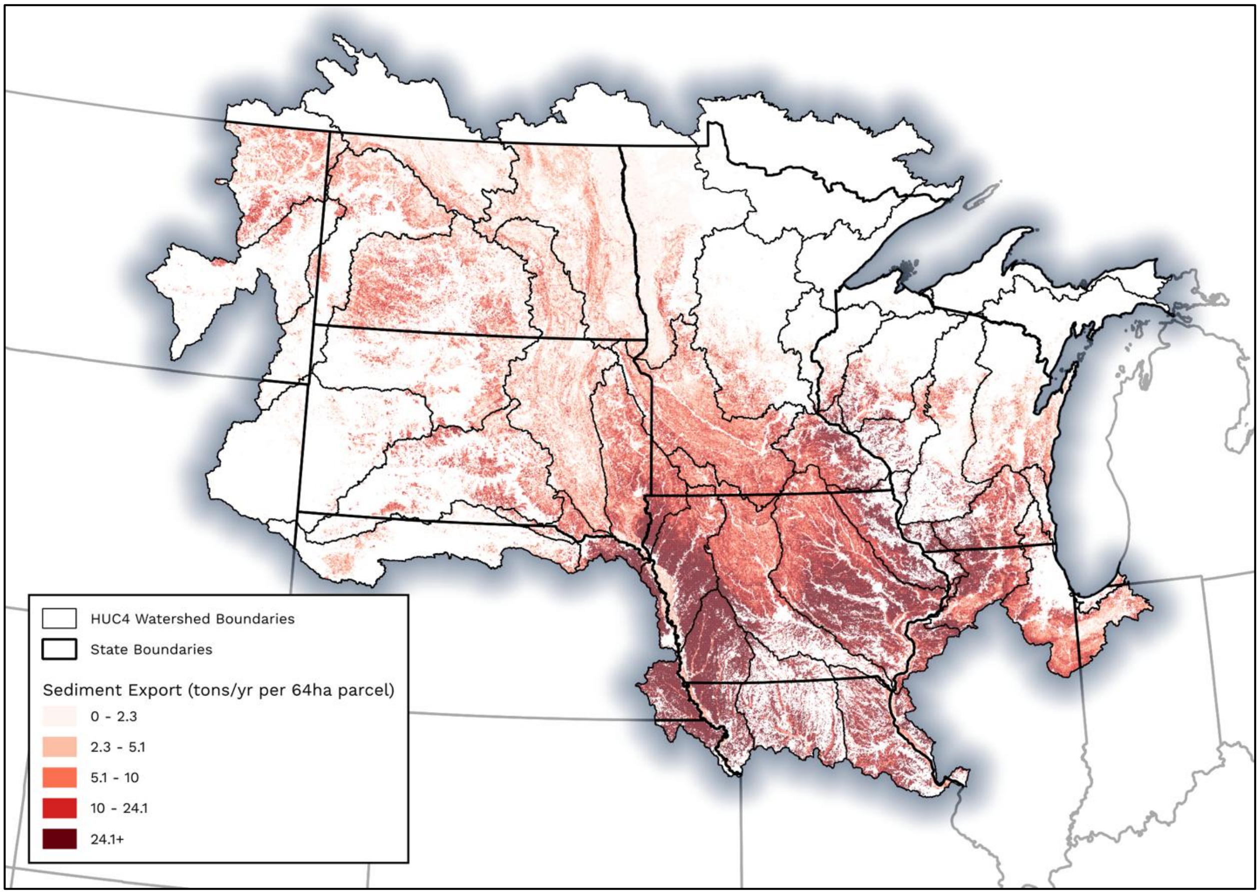

Figure 32. Baseline sediment export in surface runoff (tons/yr) from agricultural lands within each 64-hectare (~154 acre) farm parcel. Modeled using the InVEST SDR model on the 2023 Cropland Data Layer.

RESTORATION SCENARIO RESULTS

The following maps show the amount of sediment prevented from reaching local waterways in overland erosion each year due to restoring the agricultural land within each parcel to prairie (Fig. 33) and deciduous forest (Fig. 34) and prairie. Areas with higher retention (yellow) indicate either places where restoration removes significant on-site sediment loss, captures significant upslope sediment runoff, or both; areas with lower retention (purple) indicate low priority restoration areas, at least in terms of sediment retention. These results are spatially independent, in that each parcel assumes no change in neighboring parcels. If two adjacent parcels have high retention potential, restoring one may reduce the retention potential of the other. This relationship is not depicted here due to computational constraints.

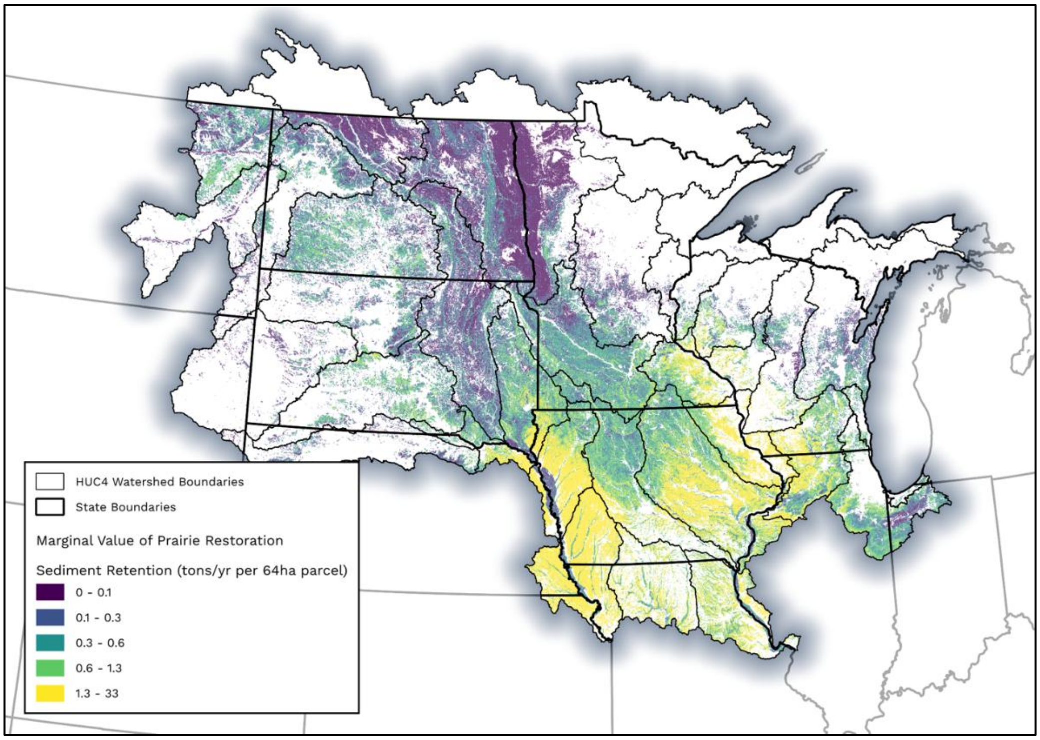

Figure 33. Expected annual sediment retention (on-site reductions only, no upslope capture) from agricultural areas restored to prairie within each 64-hectare grid square.

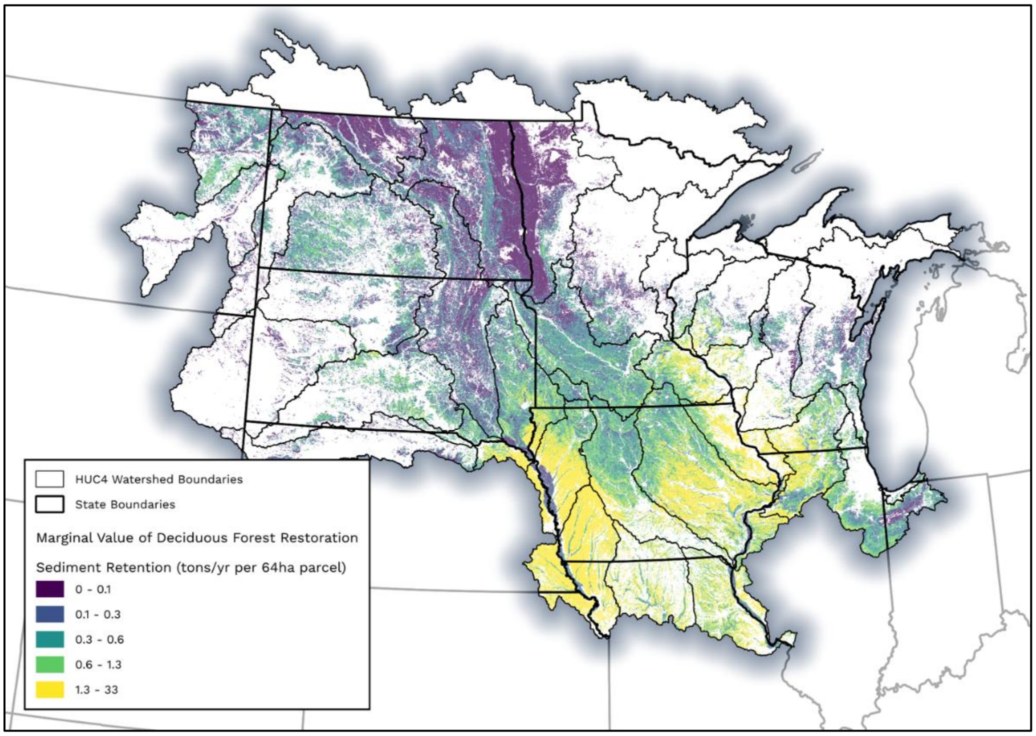

Figure 34. Expected annual sediment retention (on-site reductions only, no upslope capture) from agricultural areas restored to deciduous forest within each 64-hectare grid square.

Wild bee habitat

BASELINE RESULTS

This map (Fig. 35) shows the average wild bee habitat quality within the agricultural areas of each grid square, based on the ‘current’ agricultural landscape (2023). Areas with higher habitat quality (dark green) indicate either crop types that better support bee populations or agricultural areas adjacent to high-quality natural habitats, while low habitat quality areas (light green) indicate areas without landscape resources within bee foraging radii. Since we are primarily interested in restoration activities on agricultural lands, we have only reported habitat quality within the agricultural areas of each 64-hectare grid square. Only grid squares with at least 50% agriculture were modeled.

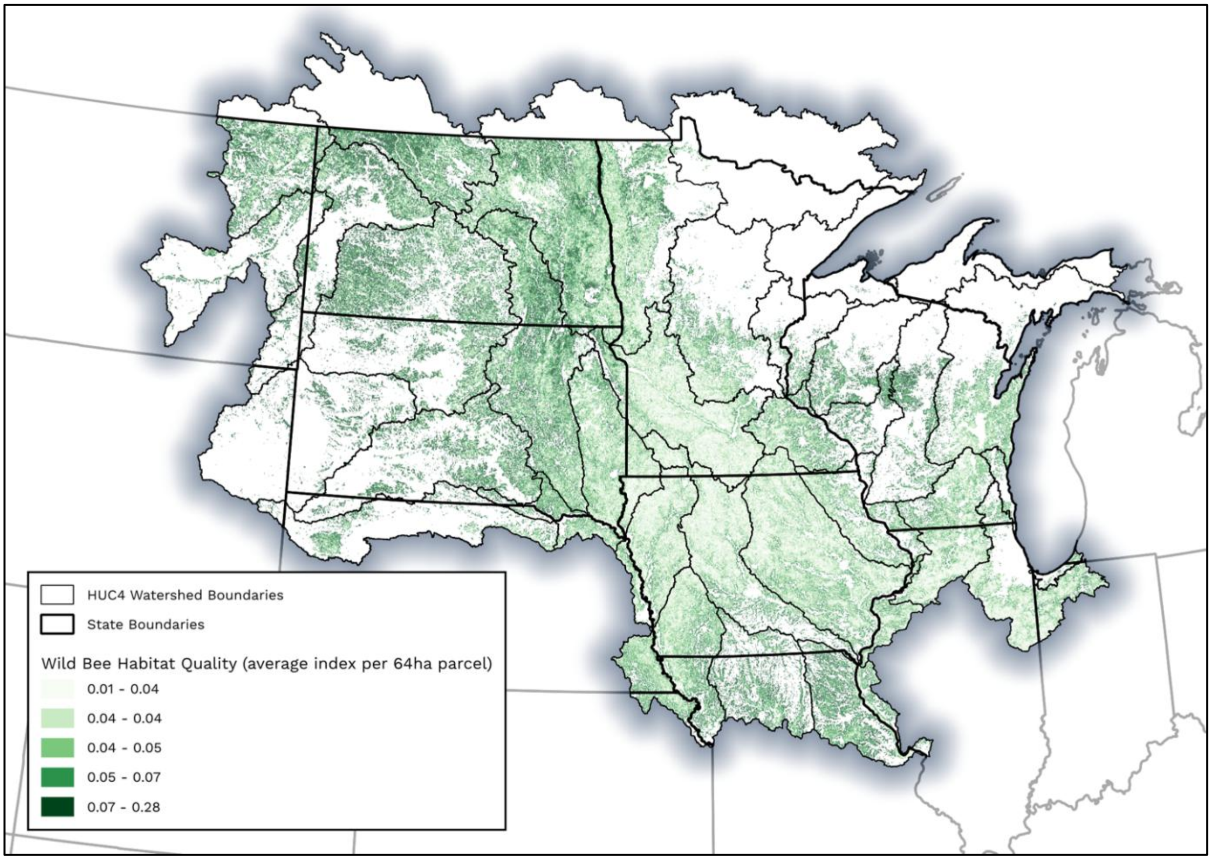

Figure 35. Baseline wild bee habitat quality (0-1 index, with anything above 0.3 considered high quality) on agricultural lands within each 64-hectare (~154 acre) farm parcel. Modeled using the InVEST Crop Pollination model on the 2023 Cropland Data Layer.

RESTORATION SCENARIO RESULTS

The following maps show the impacts of prairie (Fig. 36) and deciduous forest (Fig. 37) restoration on wild bee abundance. The InVEST model is an abstraction of the restoration value to local wild bee habitat. Restoration actions on each parcel typically improve nesting and floral resources on site, which translates to a direct increase in habitat quality. The increased floral resources also impact any nesting sites within foraging radius, leading to spillover impacts. Thus, areas with higher habitat quality increases (yellow) indicate places in which any direct habitat quality improvements are enhanced by adjacent high-quality habitats, while low habitat quality areas (purple) indicate places with limited landscape resources within bee foraging radii that would be improved by restoration.

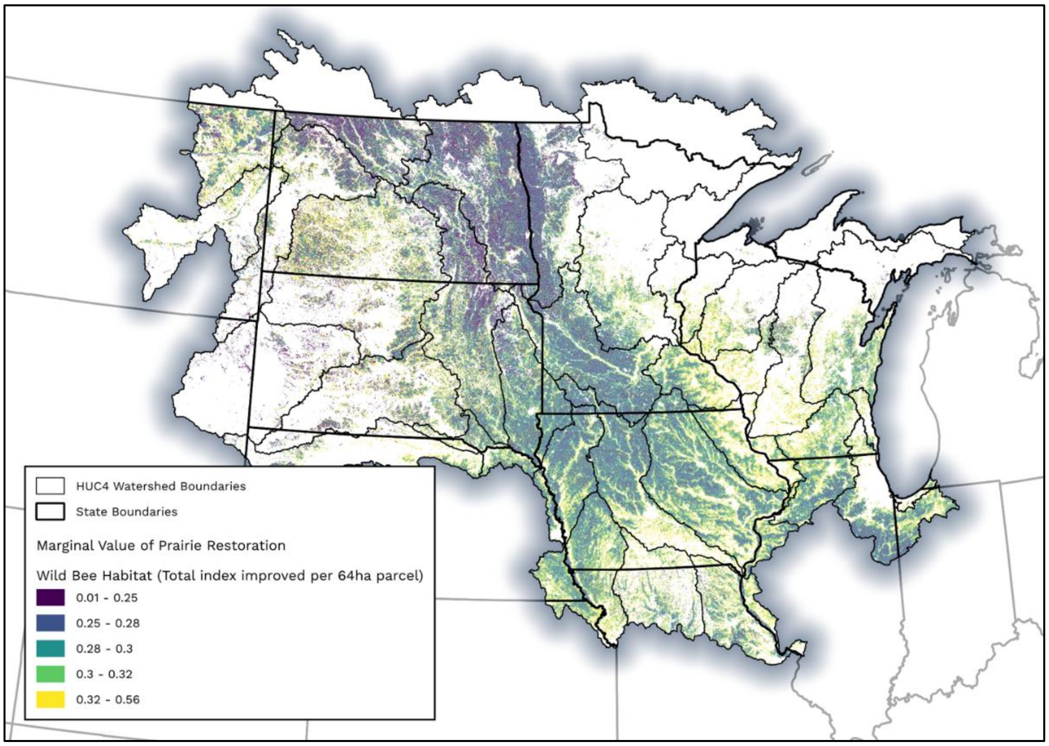

Figure 36. The average increase in wild bee habitat quality on and around the agricultural areas of each 64-hectare parcel attributable to prairie restoration.

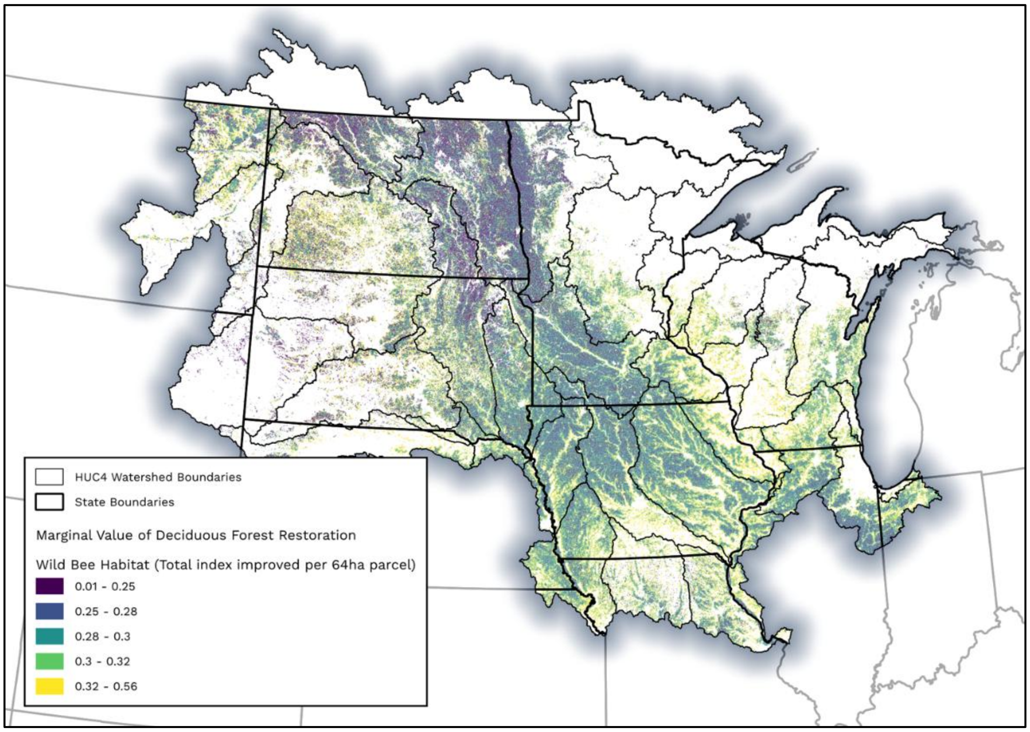

Figure 37. The average increase in wild bee habitat quality on and around the agricultural areas of each 64-hectare parcel attributable to deciduous forest restoration.

Carbon storage

BASELINE RESULTS

Figure 38 shows the amount of biomass carbon expected to be stored on the agricultural landscape, based on 'current' data (2023). It is the baseline from which we can evaluate potential restoration scenarios: areas with low storage (light green) are potentially good target areas for restoration while areas with high storage (dark green) are of lower priority. Since we are primarily interested in restoration activities on agricultural lands, we have only reported carbon storage from the agricultural areas of each 64-hectare grid square.

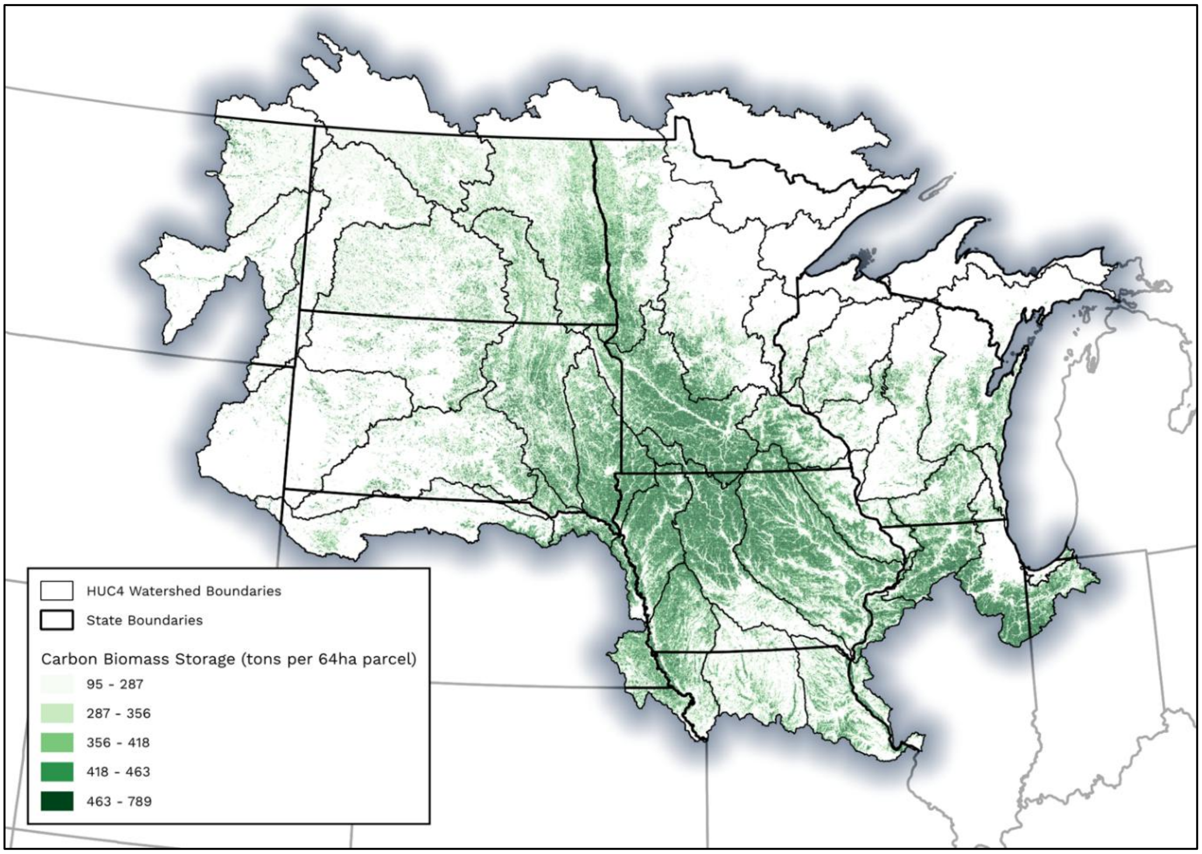

Figure 38. Baseline biomass carbon storage (tons; above and belowground biomass) on agricultural lands within each 64-hectare (~154 acre) farm parcel. Modeled using an adapted InVEST Carbon model on the 2023 Cropland Data Layer.

RESTORATION SCENARIO RESULTS

The following maps show the amount of biomass carbon expected to accrue once prairie (Fig. 39) or deciduous forest (Fig. 40) restoration has properly established in the agricultural areas of the parcel. Areas with higher storage increases (yellow) indicate high priority restoration areas while areas with lower storage increases (blue) indicate low priority, in terms of carbon storage.

Note that some areas show a net loss in carbon storage under restoration: these data are based on remote-sensed biomass carbon estimates in which some crop types in the region exhibited higher biomass carbon totals than prairie. This can be attributable to uncertainty or error in the carbon or land cover data products, especially as the grassland category from which prairie restoration was derived comprises a multitude of grassland types, from lawns to native prairie remnants.

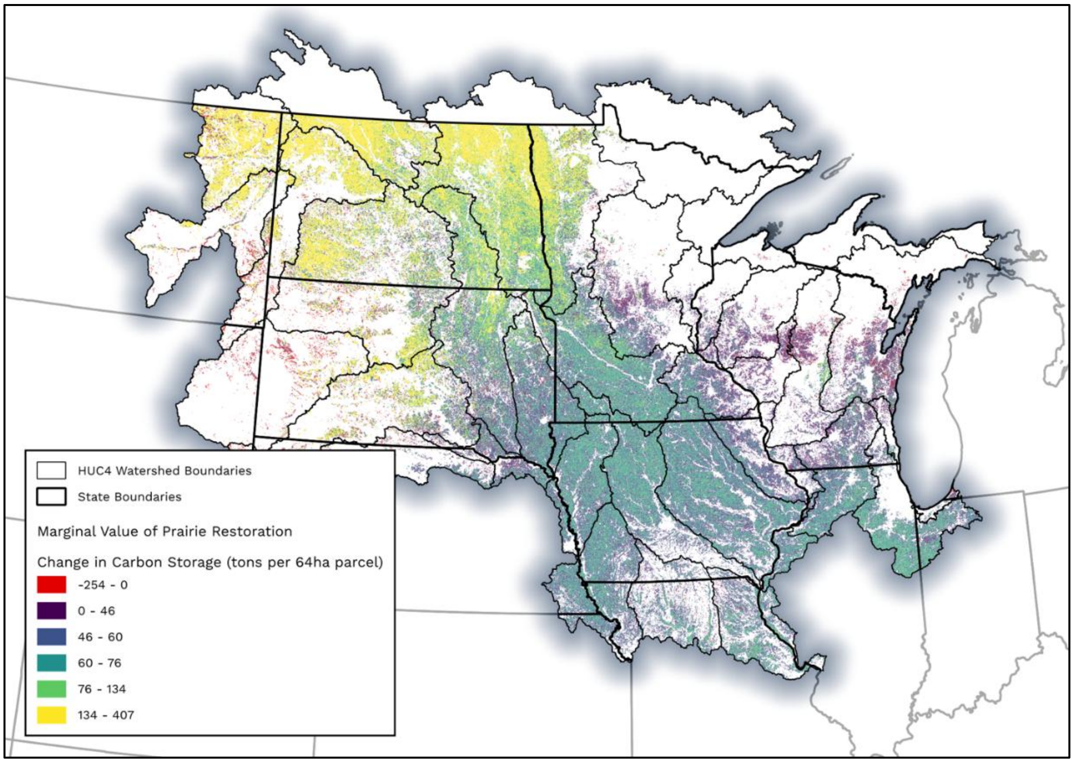

Figure 39. The expected change in stable-state biomass carbon storage due to prairie restoration on the agricultural areas of each 64-hectare parcel.

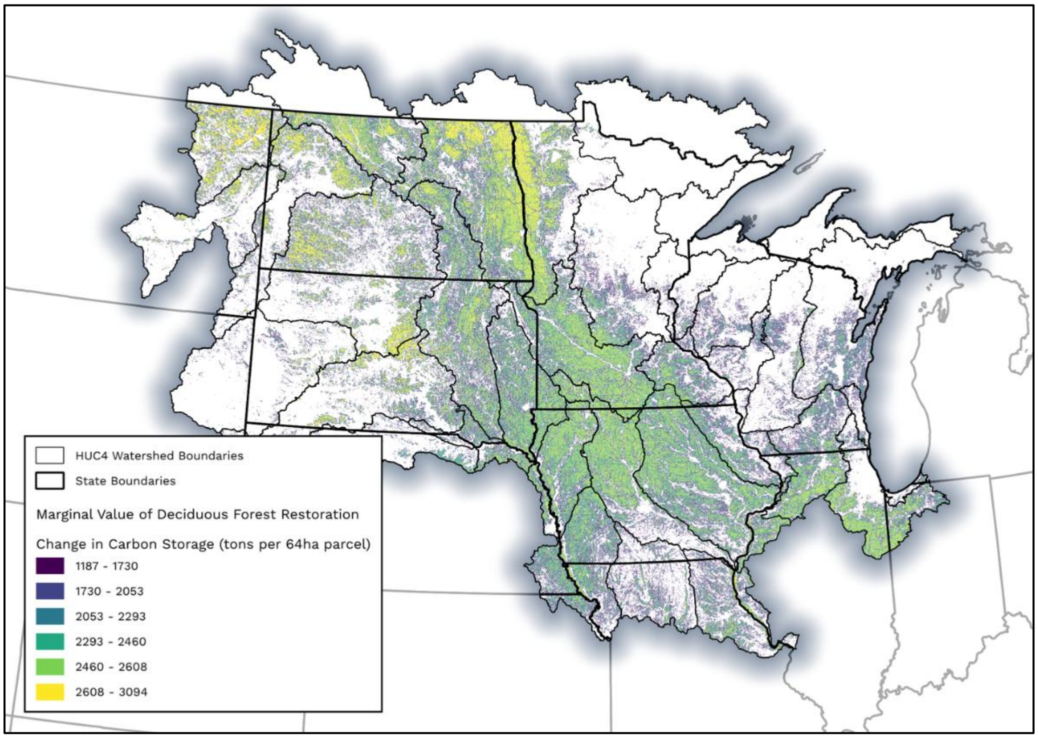

Figure 40. The expected change in stable-state biomass carbon storage due to deciduous forest restoration on the agricultural areas of each 64-hectare parcel.

Priority area selection

The following maps show the top 10% of parcels for sediment retention, nitrogen retention, phosphorus retention, wild bee abundance, and carbon biomass storage (Figs. 41, 42, 43, 44, 45, respectively) based on prairie restoration. Top 10% of parcels for all 5 ecosystem services are also available by state in Appendix A. Priority areas vary by service. Sediment retention benefits are clustered in Iowa and the Driftless area of Minnesota and Wisconsin. Nitrogen retention benefits are scattered across the main agricultural belt of Minnesota and Iowa while phosphorus retention benefits are more clustered in the Red River valley in northern Minnesota and eastern North Dakota. Wild bee abundance benefits are scattered across the entire region but tend to avoid the most dense agricultural areas. Carbon storage benefits are highest in the Dakotas.

The top performing parcels across all ecosystem services are scattered across the region (Fig. 46), with some clusters driven strongly by individual models (phosphorus in the Red River valley and sediment in Iowa).

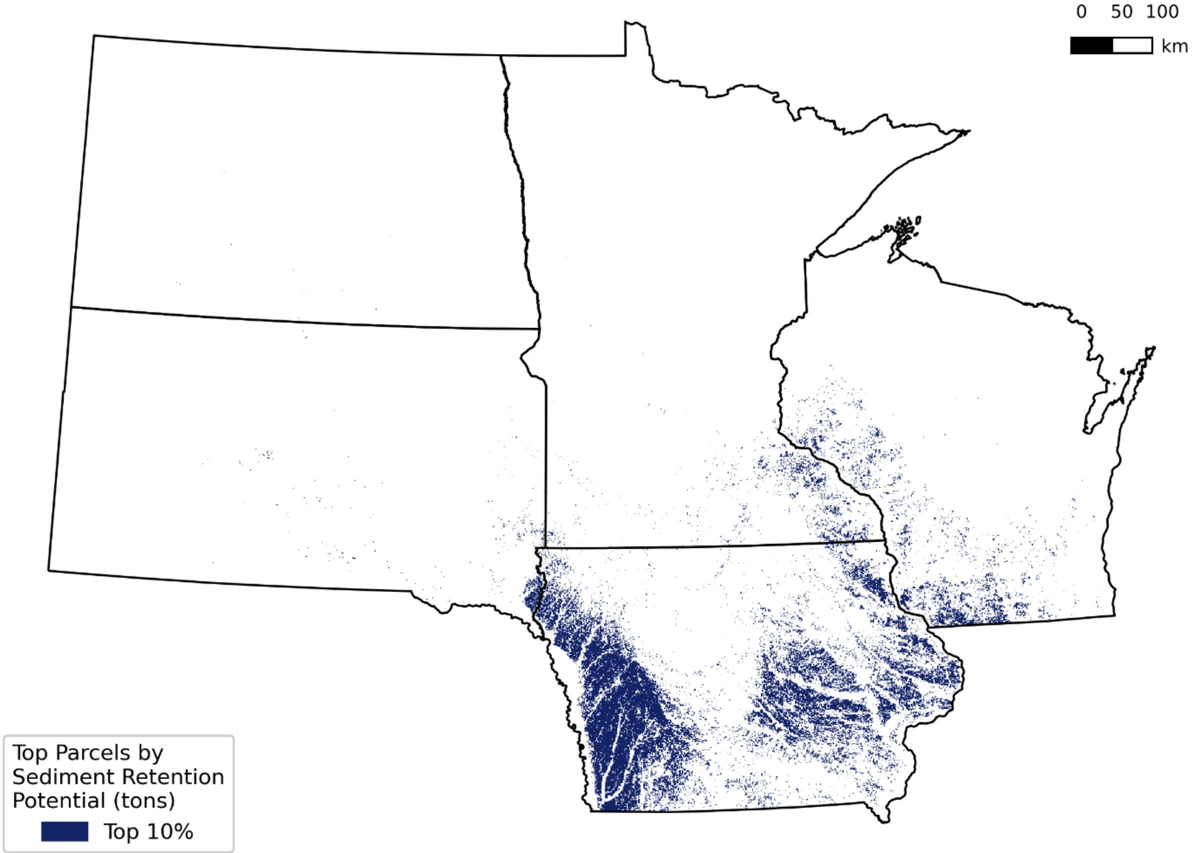

Figure 41. The top 10% of all 64-hectare parcels based on the sediment retention value of prairie restoration.

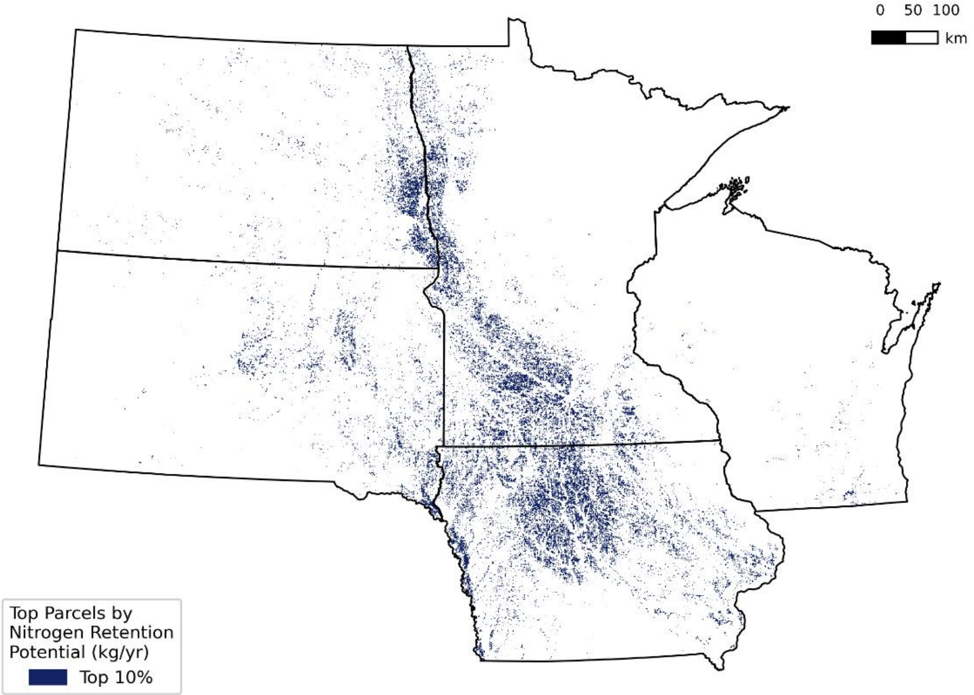

Figure 42. The top 10% of all 64-hectare parcels based on the nitrogen retention value of prairie restoration.

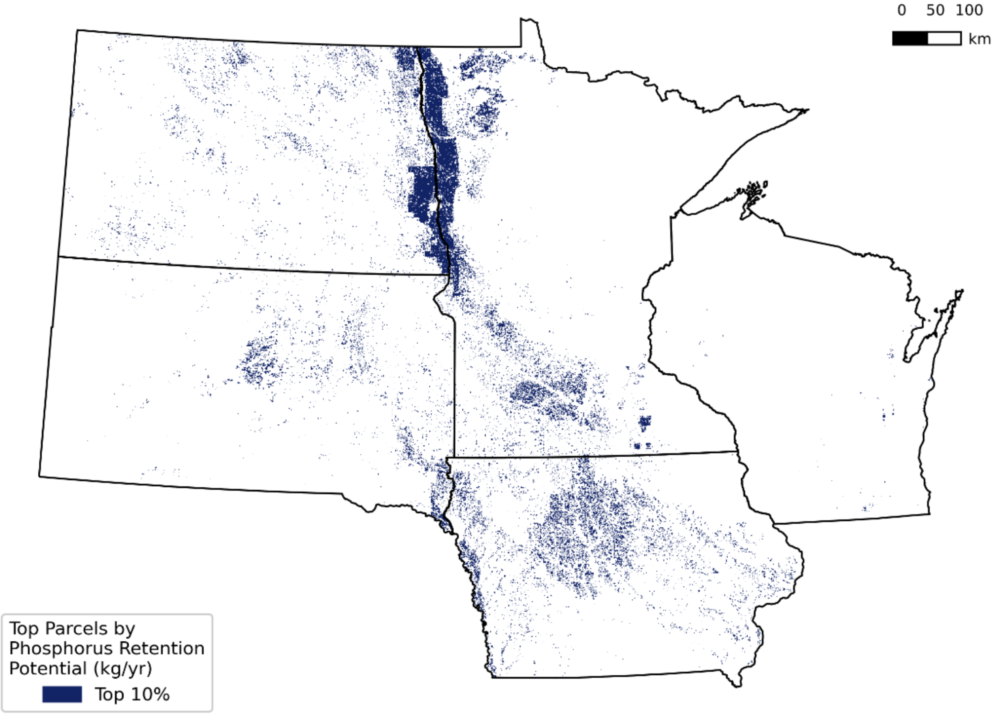

Figure 43. The top 10% of all 64-hectare parcels based on the phosphorus retention value of prairie restoration.

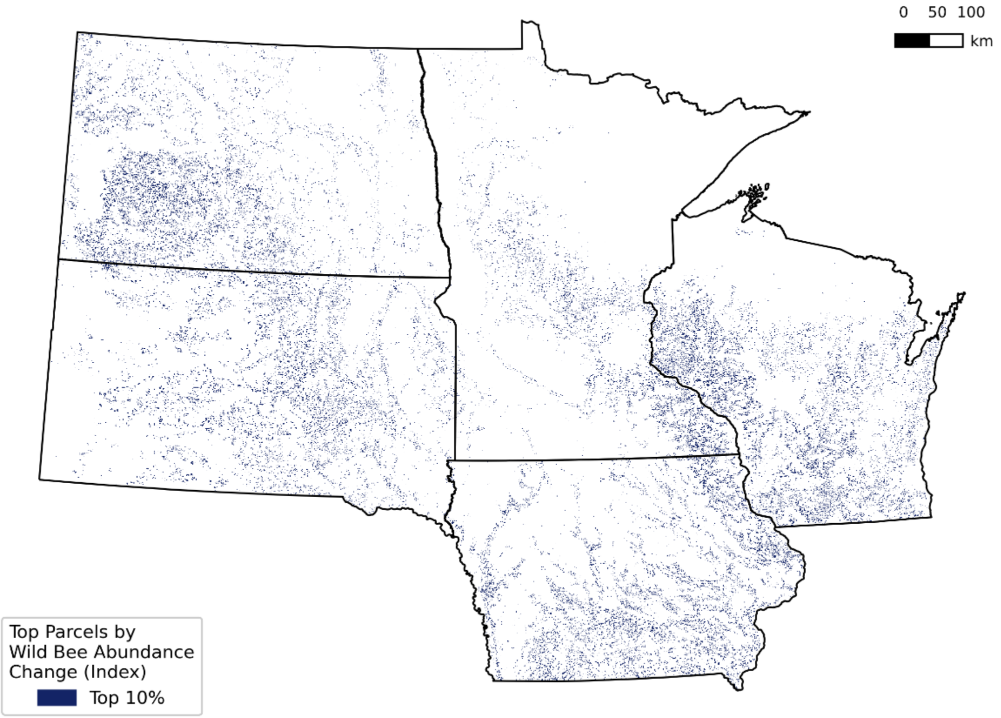

Figure 44. The top 10% of all 64-hectare parcels based on the wild bee abundance value of prairie restoration.

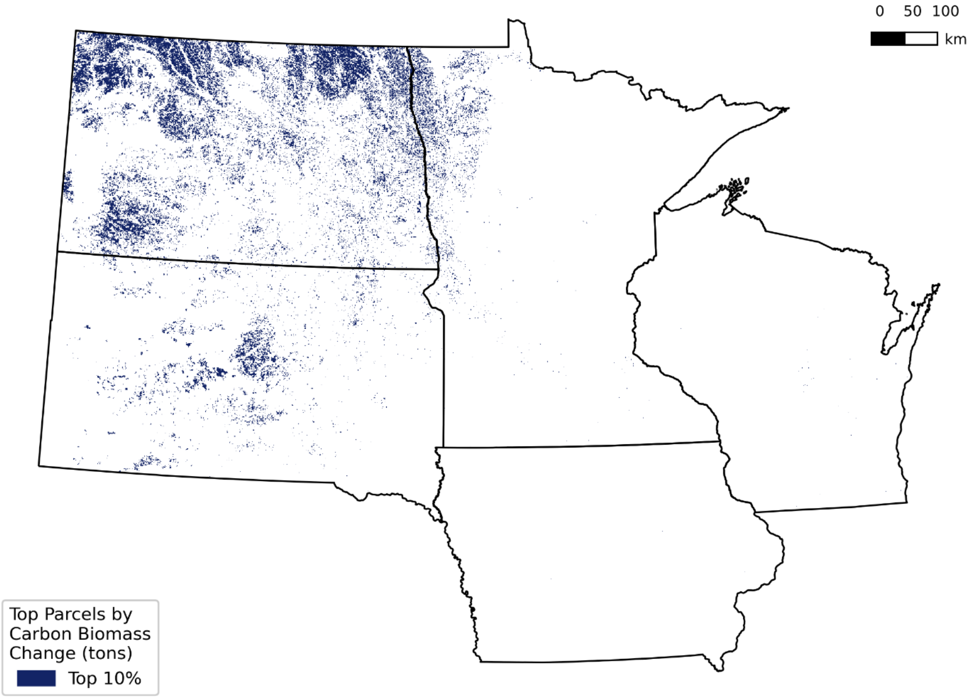

Figure 45. The top 10% of all 64-hectare parcels based on the carbon storage value of prairie restoration.

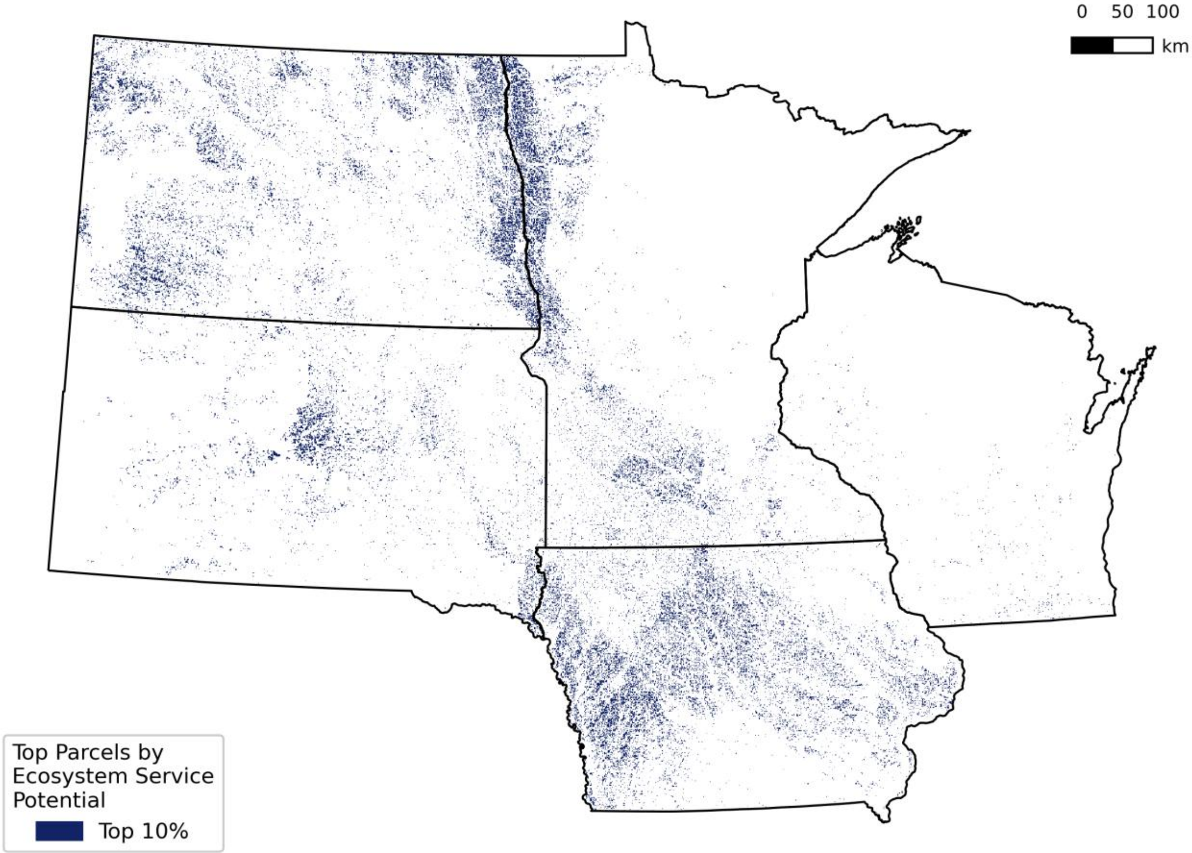

Figure 46. The top 10% of all 64-hectare parcels based on the combined ecosystem service benefits of prairie restoration.

Integration of Site-scale Connectivity and Ecosystem Services Results

Integrating connectivity and ecosystem services together in the Root River clearly demonstrates the tradeoffs that can exist among these factors. Below we show the results of the co-benefits optimization analysis for the prairie analysis for the Root River, including the main objective frontier, spatial patterns of high-priority parcels, and benefits to the individual sub-metrics (Fig. 47). The upper-left panel plots the mean ecosystem service score against the mean connectivity score of the selected parcels at each weight step with each point on this curve representing a different combination of weights. The endpoints of this curve demonstrate that there are notable tradeoffs between parcel choices that maximize connectivity and those that maximize ecosystem services. The range of outcomes for connectivity are between 0.35 and 0.82, while the range of outcomes for ecosystem services range between 2.12 and 2.72. It is not a strictly linear tradeoff, however, and the convexity of the curve demonstrates the potential to target parcels that score highly for both objectives.

One challenge with multi-objective optimization is in deciding the precise weights to use to compare different objectives against each other. This challenge is even more difficult with indices when there may not be a clear way to determine relative value. One approach to dealing with this is to create a "robust agreement map" that counts how many times a given parcel is selected across the frontier. Parcels that score highly in this analysis are good choices across a range of potential weighting choices and are therefore good choices for restoration regardless of the uncertainty in objective weighting.

Figure 47, shows the selection frequency map for the 15% prairie restoration analysis in the upper right panel, showing parcels selected consistently regardless of weighting representing robust priorities, and parcels appearing only at the extremes or not selected at all.

Each of these portfolio choices has consequences for the constituent sub-objectives. The lower panels show how individual connectivity and ecosystem service metrics respond to shifting weights, making it possible to see which specific services are gained or lost as priorities change. For connectivity, we see that there are saturating benefits around a connectivity weighting of 0.55 after which net benefits to connectivity are minimal. For ecosystem services, both carbon storage and the water quality services decline more or less linearly between connectivity weights 0.2 and 1, while the pollinator habitat metric increases together with connectivity to a maximum at connectivity weight 0.6, and then declines again. The graphs together suggest a sweet spot for maximizing both sets of benefits at connectivity weight 0.4 (Fig. 48).

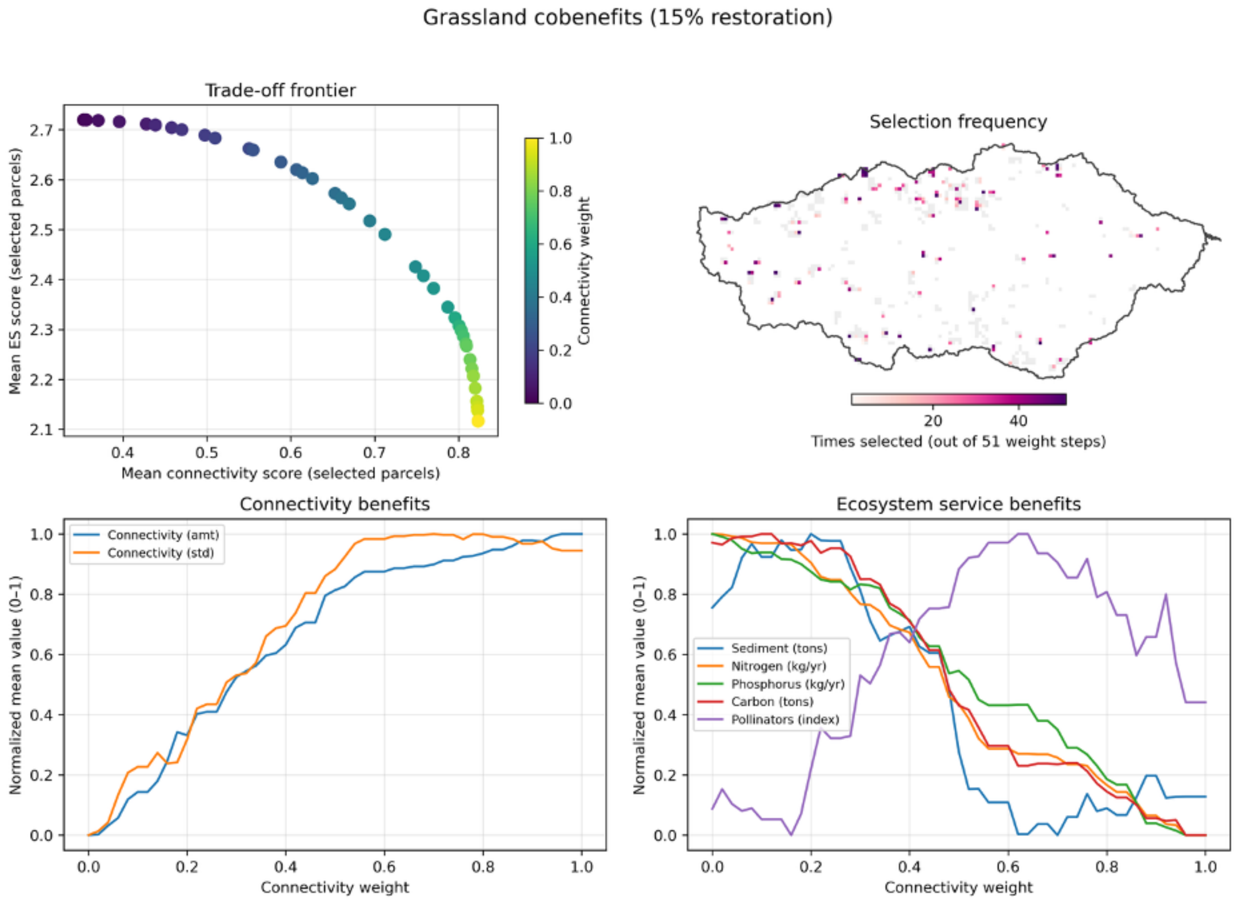

Figure 47. The upper-left panel plots the mean ecosystem service score against the mean connectivity score of the selected parcels at each weight step with each point on this curve representing a different combination of weights. The upper-right map shows how many weight steps each parcel was selected across: parcels selected consistently regardless of weighting represent robust priorities, while parcels appearing only at the extremes are more specialized. The lower panels show how individual connectivity and ecosystem service metrics respond to shifting weights, making it possible to see which specific services are gained or lost as priorities change.

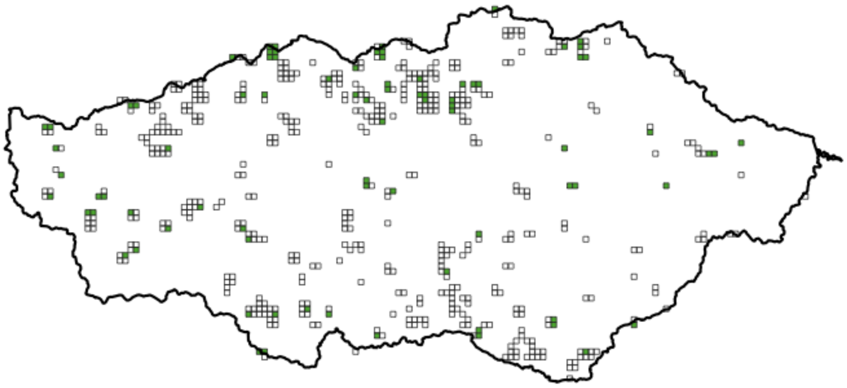

Figure 48. Parcel selection portfolio corresponding to connectivity weight 0.4, the “sweet spot” portfolio that balances connectivity and ecosystem service objectives. Parcels highlighted in green are part of this “sweet spot” portfolio of parcels that would optimize among connectivity and all ecosystem services.

Conclusions and Recommendations

As expected, ecosystem-based connectivity looked very different from ecosystem agnostic connectivity in the ecotone region between prairie and forest. In this project area, the forested ecosystem exhibited some areas of diffuse flow while the highly fragmented prairie ecosystem exhibited primarily concentrated and constrained flow interrupted by large areas of row crop agriculture with little to no connectivity. These maps suggested restoration opportunities existed for both ecosystems, and the magnitude of restoration opportunity for prairie was greater.

This project clearly demonstrates that restoration of prairie and forest has many benefits beyond connectivity for wildlife. While ecosystem service benefits from prairie or forest restoration were very similar to each other, these benefits varied widely across the project area and different services showed different patterns of benefit. Iowa and parts of southern Minnesota and Wisconsin stood out as important for sediment and nitrogen retention, while the Red River Valley of Minnesota and North Dakota was important for phosphorus retention. These results highlighted the tradeoffs in restoration benefits among ecosystem services that exist across the region.

The regional analyses demonstrated how connectivity data can be used alongside restoration priorities and climate exposure data to identify areas where restoration could benefit a climate adaptation strategy such as restoring habitat for climate refugia or where restoration could benefit a conservation strategy such as improving connectivity among existing high diversity prairie in a landscape. While these regional analyses focused on restoration for connectivity, with the data from this project, co-benefits of restoration could also be quantified in these areas using the ecosystem service benefits data. This could bring folks interested in water quality or pollination services in the same area into the conversation.

The connectivity for restoration at the parcel scale made the restoration opportunity results tangible and actionable for practitioners. The Glacial Lakes results highlighted 4,090 ha of sub-prime agricultural land that if restored would have the greatest benefit to improving connectivity for plants and animals in the landscape. The Root River results provided similar results for both prairie and forest restoration and identified places where restoration for one habitat could meaningfully disrupt connectivity for the other. Our results found that only ~3% of the top parcels were good restoration opportunities for both prairie and forest in this watershed. This is an issue that practitioners often wrestle with in these ecotone regions, and these results identified places where additional strategic thinking is warranted.

The primary take home message from this project is that restoration for prairie or forest results in multiple benefits and diversifying the reasons for doing restoration could improve our overall outcomes for nature and people. In this project, quantifying the ecosystem service benefits of restoration allowed multiple benefit analyses and will hopefully diversify the interested parties and outcomes of the work beyond climate adaptation for plants and animals. Specifically, multiple benefits analysis for the Root River showed that connectivity and pollinator benefits were correlated, but there were tradeoffs between connectivity and nutrients, sediment, and carbon. These results demonstrate it is possible to find win-wins even if you cannot maximize all benefits in the same place.

Engaging in outreach throughout the project definitely makes the outcomes and deliverables stronger and more widely applicable to practitioners, but meaningful engagement takes time. With many different participants, engagement is a time consuming and often slow process. This does create challenges with two-year project timelines. This was particularly challenging in our case because we were creating a large number of different types of data, which by themselves are complicated to understand and interpret, and our goal was to integrate these data into meaningful summaries for the partners. Integrating many different types of data is complicated with many different perspectives on which components are the most important. Flexibility is key with partners and entirely possible with these data. However, the time to create many different weighting or integration scenarios was too short. The integration vision was difficult for the Advisory Committee to imagine until all the datasets had been developed. This meant that identifying the most relevant questions to guide our integration process was difficult until near the end of the project. With little time left in the grant, we used some of the most straightforward ideas for integration to illustrate what can be done, but we are hopeful partners will find many other and new uses for these data in their conservation decisions. In the future, we would build in a longer time for data integration. Once people saw the data, they had more ideas for what to do with it than we had time for. These data and results are highly relevant for natural resource managers but hard to understand until they see it.

This project generated numerous exciting results and data products that provide a lot of insight into where to engage in restoration that will provide multiple benefits to people and nature, and these results also provide an amazing starting point to address many more in-depth and context specific questions. While we have shared the results in a data viewer, there is a huge opportunity here to build out more tools and use cases for the data for folks to see how to apply it to their work. Tools that visualize different prioritization scenarios and integrate more data sources would be beneficial to bring partners with different restoration goals together. In addition to tools to take the data integration further, another advancement from this project would be understanding how the temporal aspect of land use and climate change will interact to inform where restoration should be prioritized based on rate of changes in the landscape. These data significantly advance our ability to prioritize restoration actions across the region, and they provide a solid foundation from which to build some very useful decision support tools.

Outreach and Products

Outreach was a critical part of our work throughout the life of this project. We started the outreach with discussions with partners during proposal development and their letters of support continued that with the formation of an Advisory Committee in the beginning and their engagement throughout. In addition to regular communication and presentations to our 34 member Advisory Committee, we also presented and shared progress and results from the project with multiple audiences during the project period, and we will continue to share the results of this work with partners and practitioners moving forward.

Here is a list of the formal presentation and data sharing we accomplished during the project period.

- The ecosystem focused connectivity mapping results were shared with the Minnesota State Wildlife Plan working group, and incorporated into their plan update.
- Dr. Ahlering presented preliminary results at the International Society for Ecological Restoration meeting in Denver, Colorado in October 2025.
- Dr. Ahlering presented initial results and approaches for feedback at The Nature Conservancy's One Conservancy Science Gathering in Mexico City in November 2024.
- Dr. Ahlering presented initial results at the Midwest Climate Adaptation Science Center's Annual Gathering in Urbana, Illinois in August 2025.
- The full team presented final results to the Advisory Committee in February 2026.

In addition to the outreach we have been doing all along the way, we have numerous data products resulting from this project. These data products will be the center of outreach, communication and dissemination moving forward.

- **Data Viewer**: All the data presented in this report are accessible in a data viewer. The viewer allows folks to easily overlay the connectivity, ecosystem service, and climate results for project-wide, regional, and focal area analyses. The viewer helps folks visualize areas with multiple benefits and also allows folks to download the data to use in their own local contexts and decision making.
- **Report**: This report will be a key resource for understanding the methods behind these data and well as a guide to understanding and interpreting the results.
- **Publication**: This team is working on a publication from these data and results, and this report is a launching point for that product. This will be shared with the Midwest Climate Adaptation Science Center and the U.S. Geological Survey as soon as it is ready for submission. This is an important part of communicating the results of the project and peer-reviewing the methods.
- **Online Hosting**: The data viewer needs an online hosting location for people to access. This will be done on The Nature Conservancy's Center for Resilient Conservation Science's website. This site hosts many other publicly available datasets that TNC has created with parters, particularly around connectivity so is a natural place to house these data.

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Appendix A

Maps depicting the top 10% of prairie restoration benefit parcels for each state in the project area. Maps are presented in alphabetical order by state and then six ecosystem service maps: equal weighting all five services, carbon storage (biomass), nitrogen retention, phosphorus retention, wild bee habitat (pollination), and sediment retention.

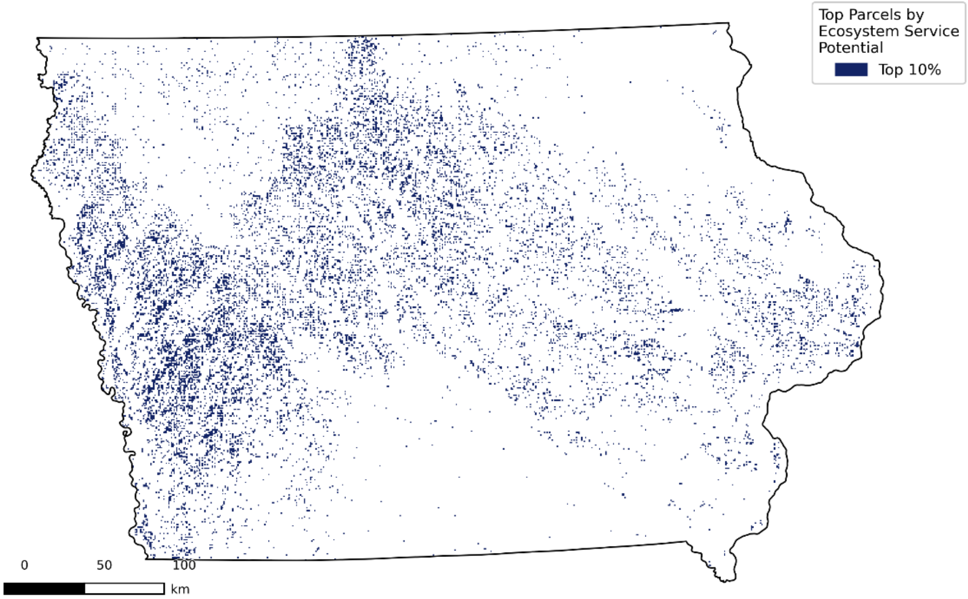


Figure A1. Top 10% of parcels by total ecosystem service potential with restoration of row crop agriculture to prairie.

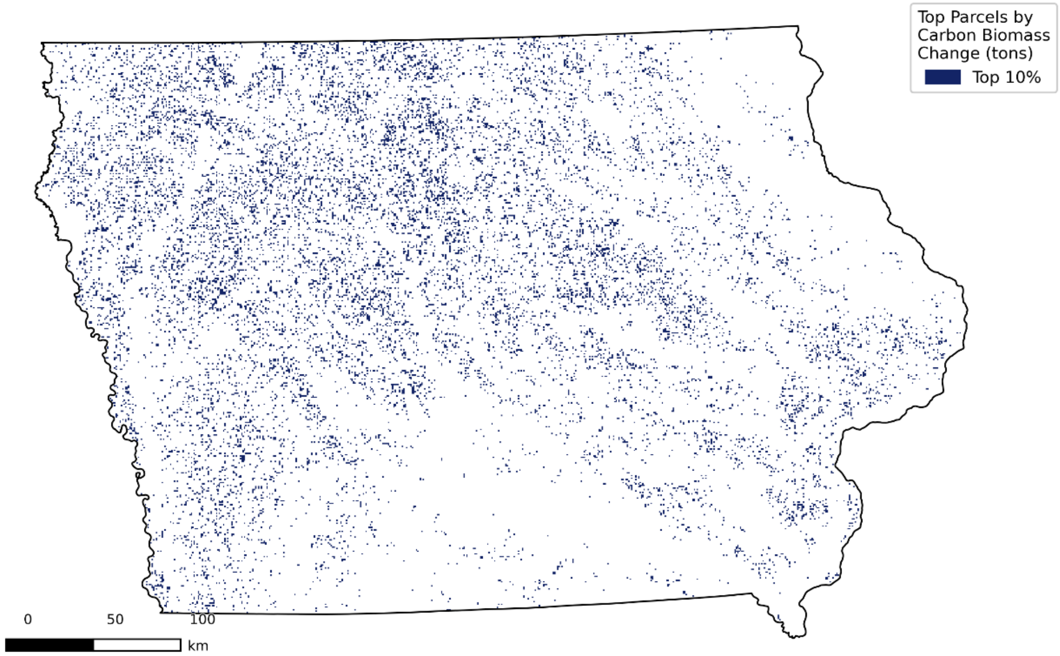


Figure A2. Top 10% of parcels by carbon storage potential with restoration of row crop agriculture to prairie.

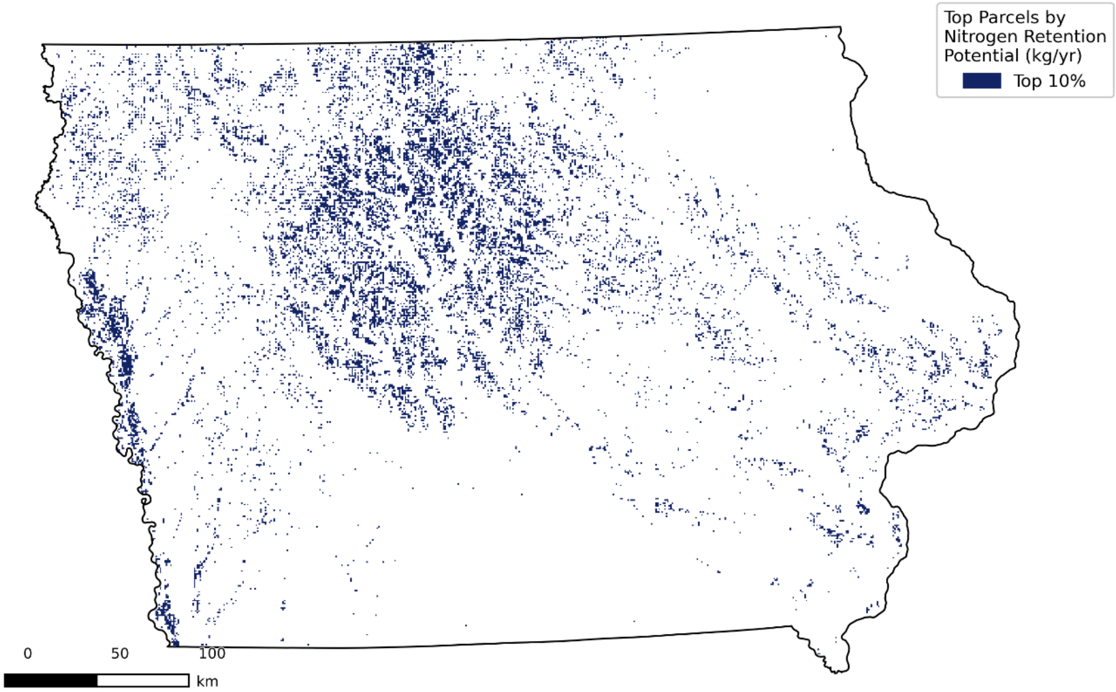


Figure A3. Top 10% of parcels by nitrogen retention with restoration of row crop agriculture to prairie.

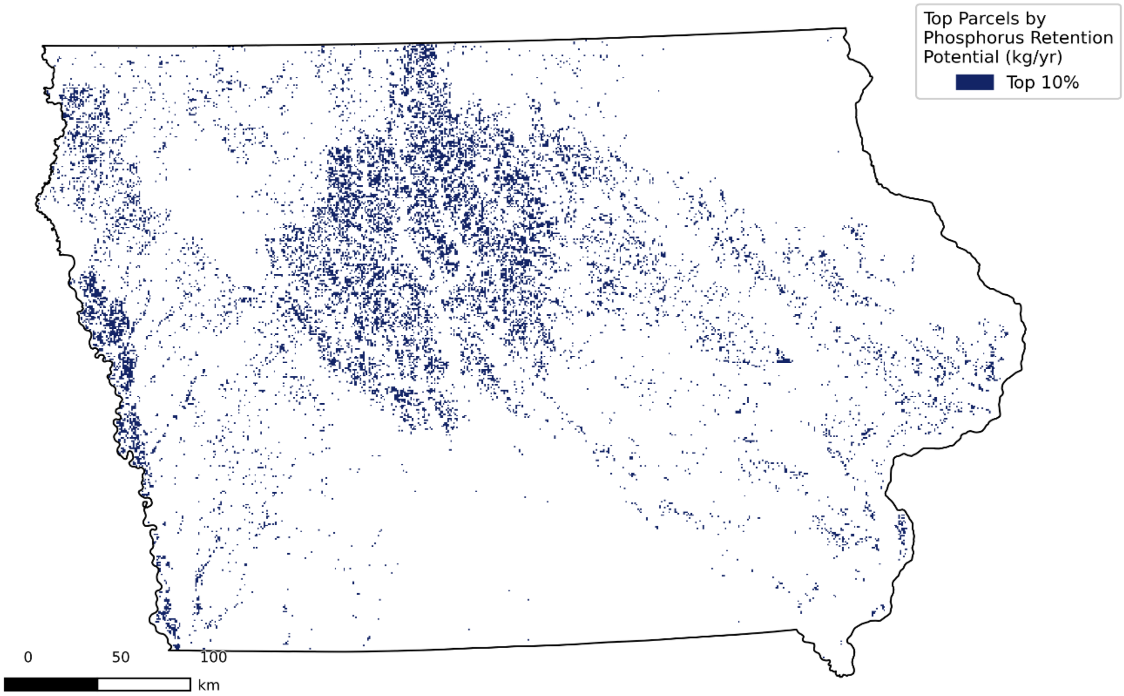


Figure A4. Top 10% of parcels by phosphorus retention with restoration of row crop agriculture to prairie.

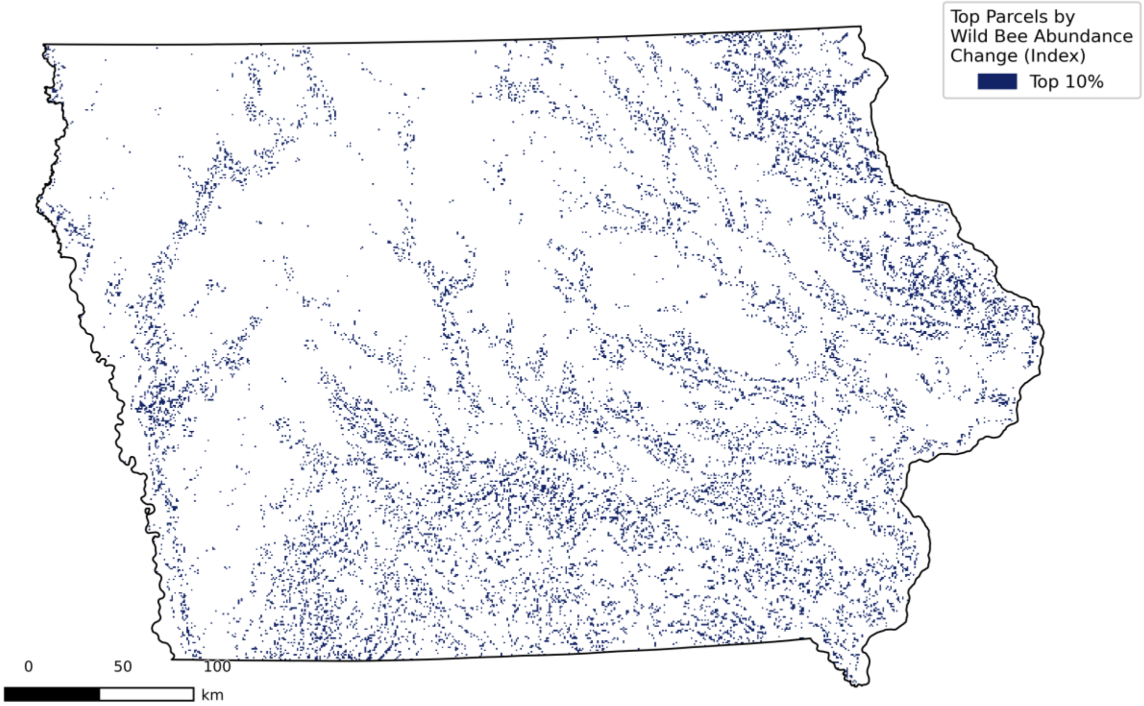


Figure A5. Top 10% of parcels by wild bee habitat (pollination) with restoration of row crop agriculture to prairie

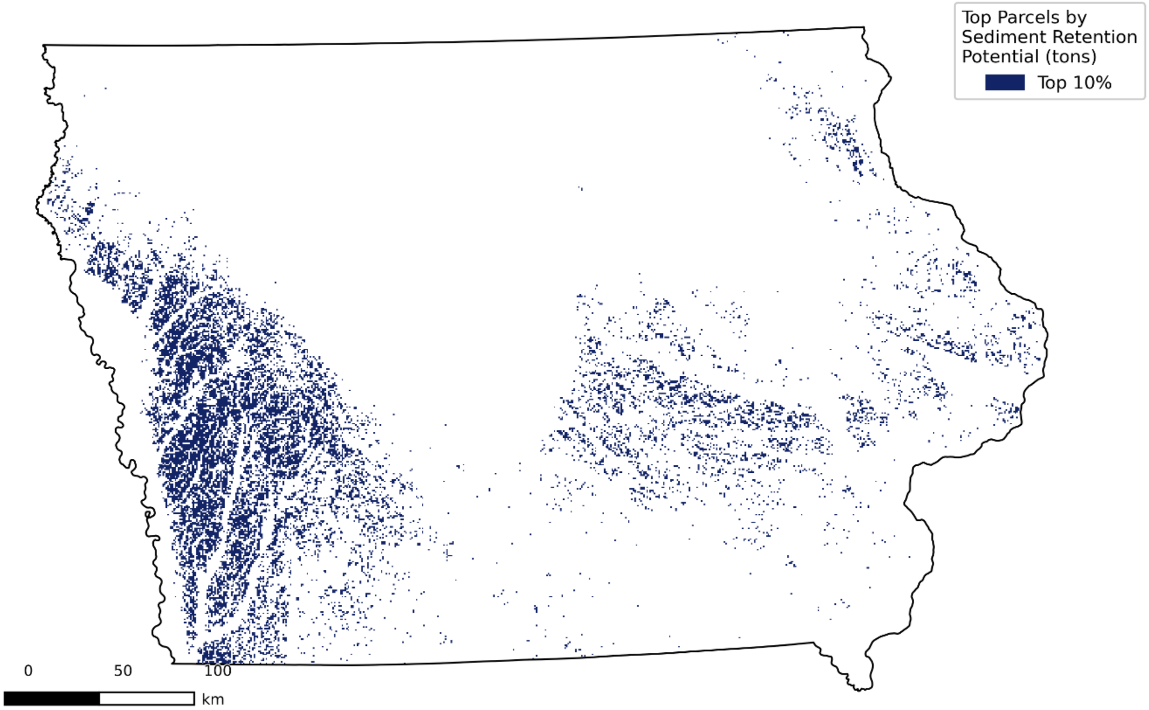


Figure A6. Top 10% of parcels by sediment retention with restoration of row crop agriculture to prairie.

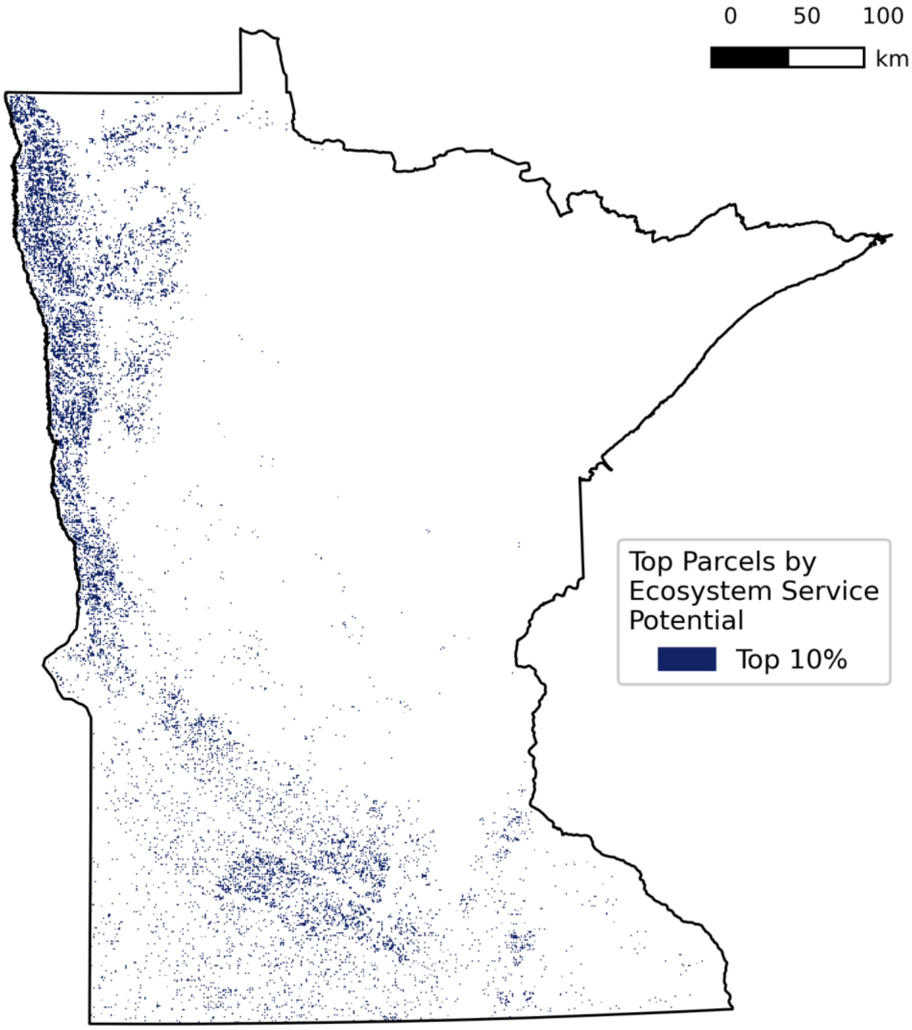


Figure A7. Top 10% of parcels by total ecosystem service potential with restoration of row crop agriculture to prairie.

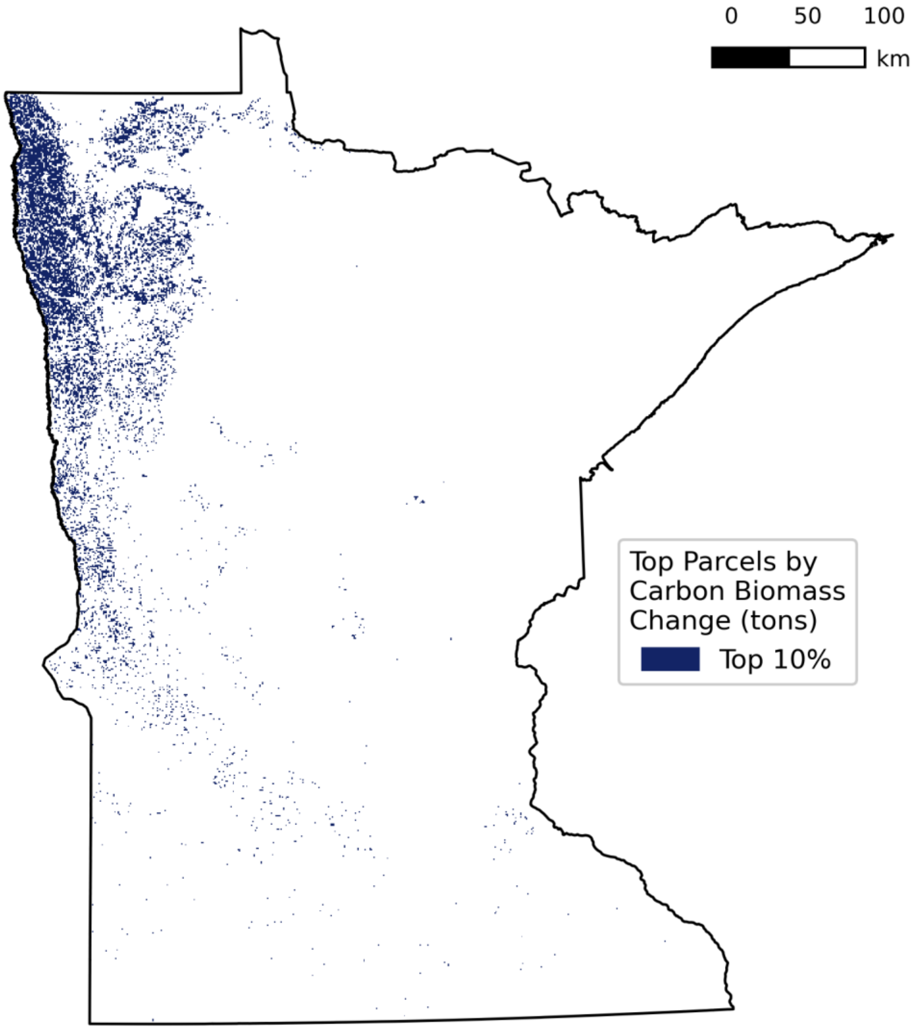


Figure A8. Top 10% of parcels by carbon storage potential with restoration of row crop agriculture to prairie.

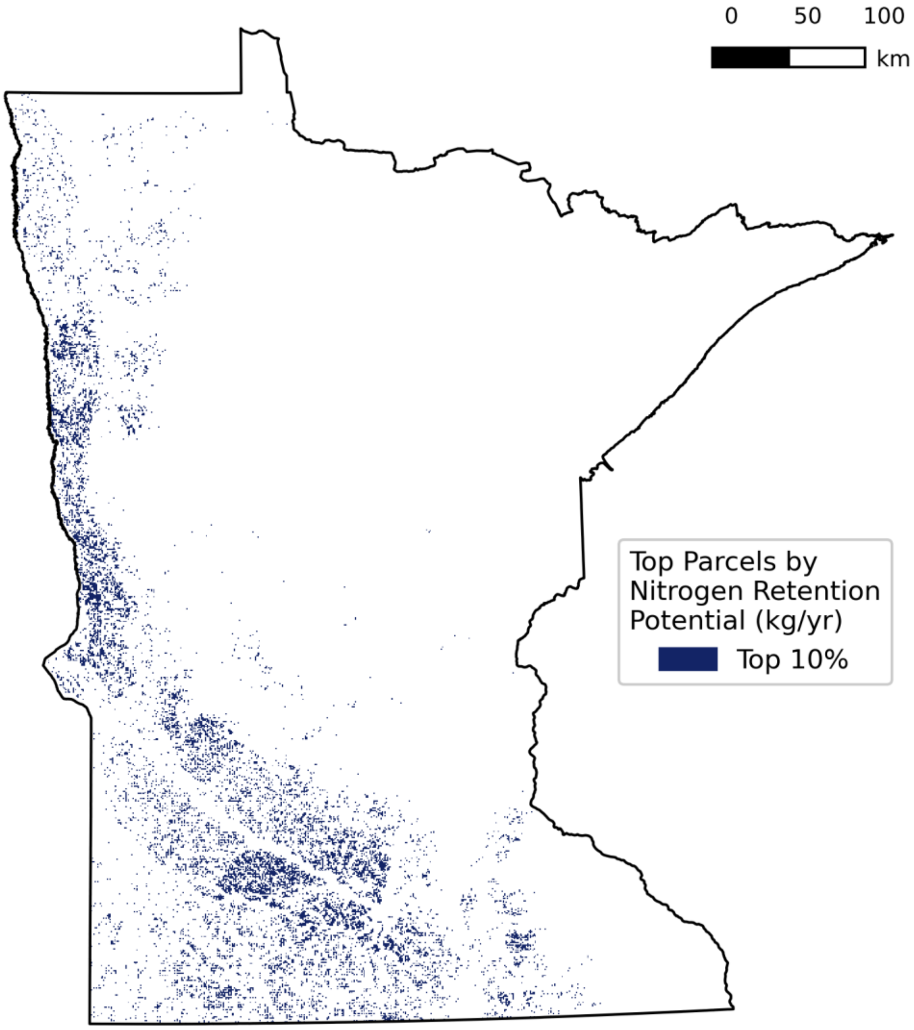


Figure A9. Top 10% of parcels by nitrogen retention with restoration of row crop agriculture to prairie.

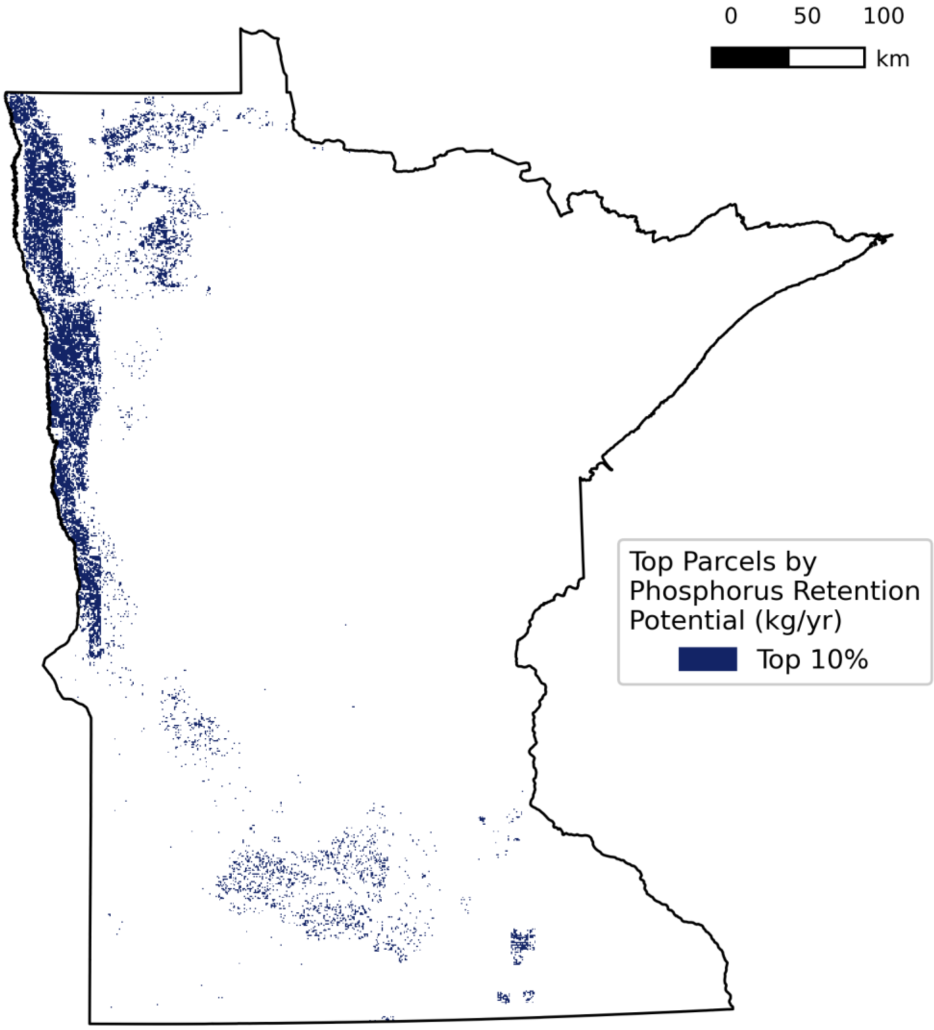


Figure A10. Top 10% of parcels by phosphorus retention with restoration of row crop agriculture to prairie.

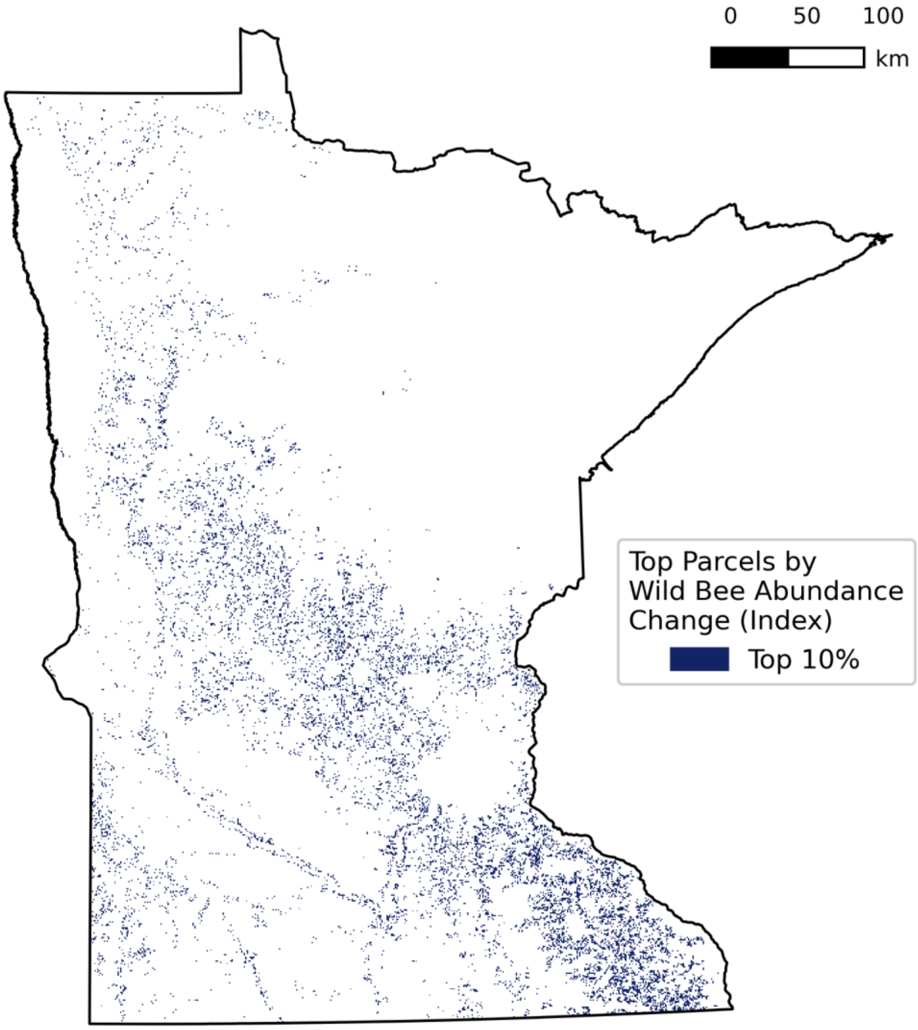


Figure A11. Top 10% of parcels by wild bee habitat (pollination) with restoration of row crop agriculture to prairie

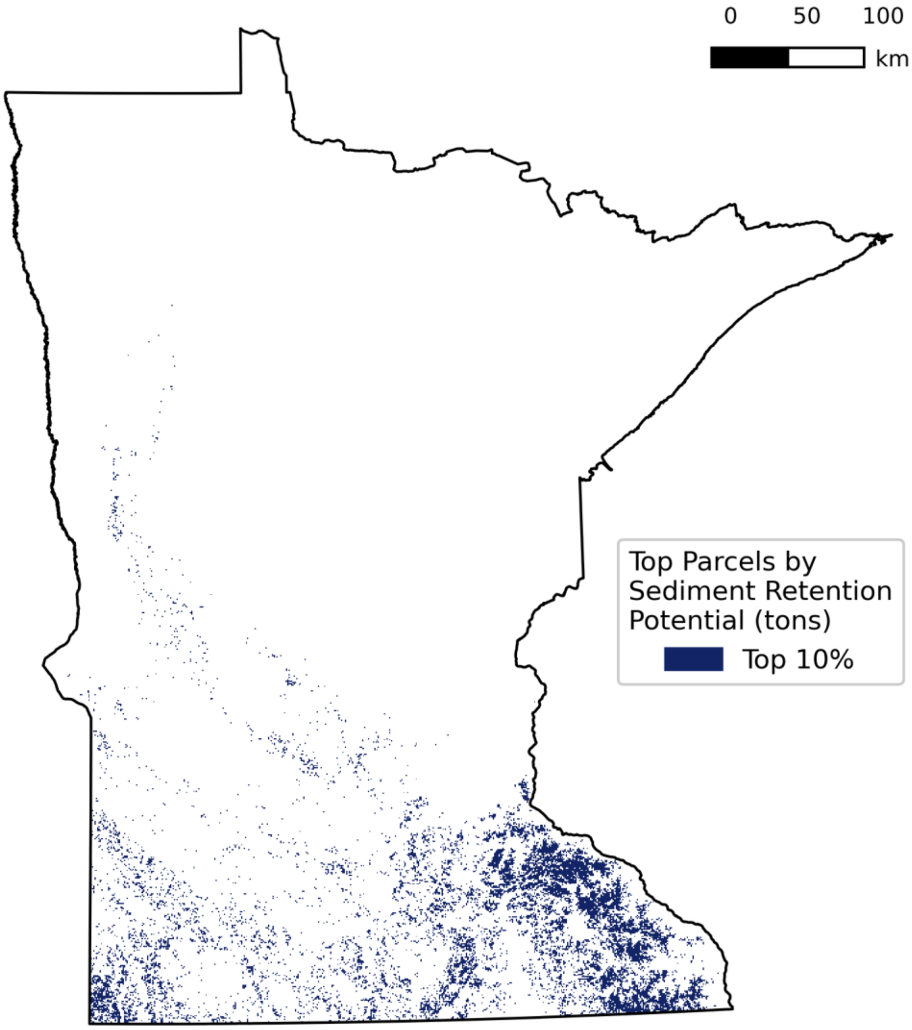


Figure A12. Top 10% of parcels by sediment retention with restoration of row crop agriculture to prairie.

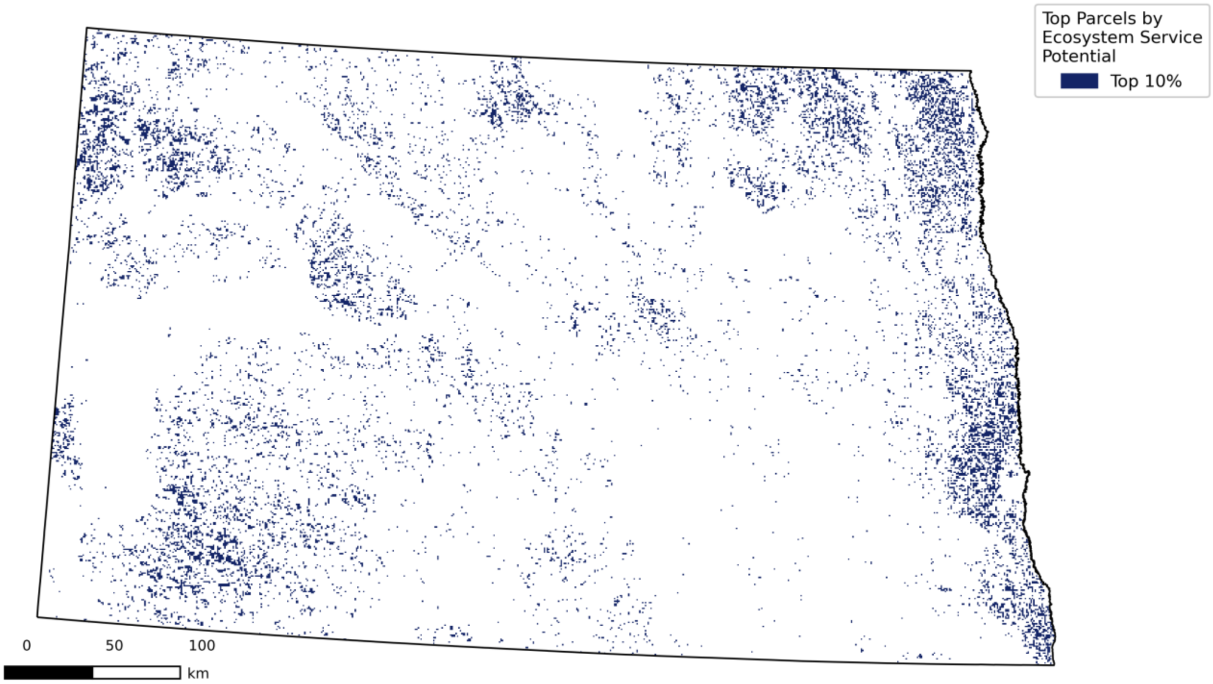


Figure A13. Top 10% of parcels by total ecosystem service potential with restoration of row crop agriculture to prairie.

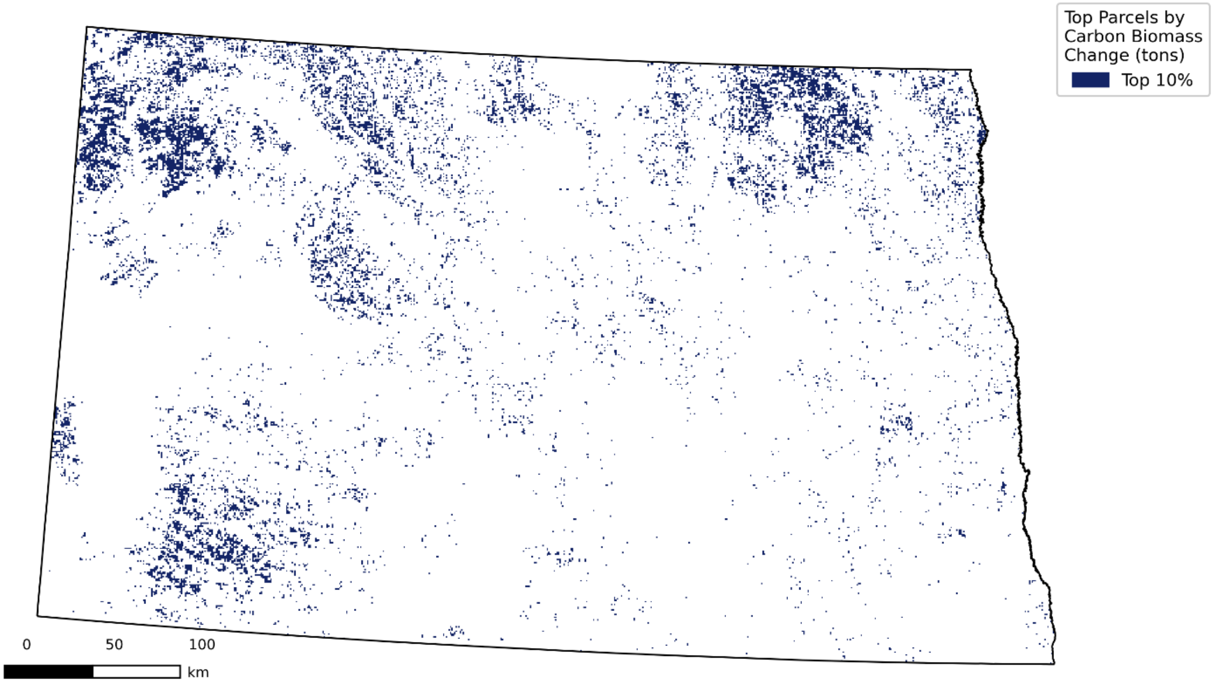


Figure A14. Top 10% of parcels by carbon storage potential with restoration of row crop agriculture to prairie.

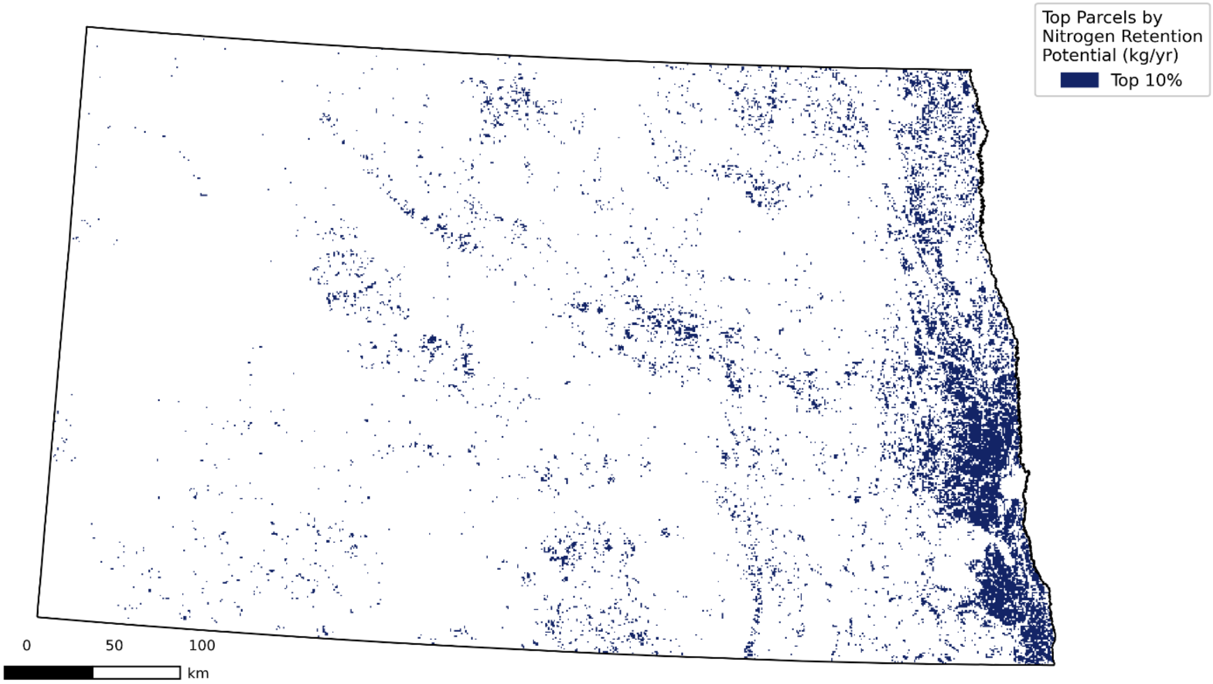


Figure A15. Top 10% of parcels by nitrogen retention with restoration of row crop agriculture to prairie.

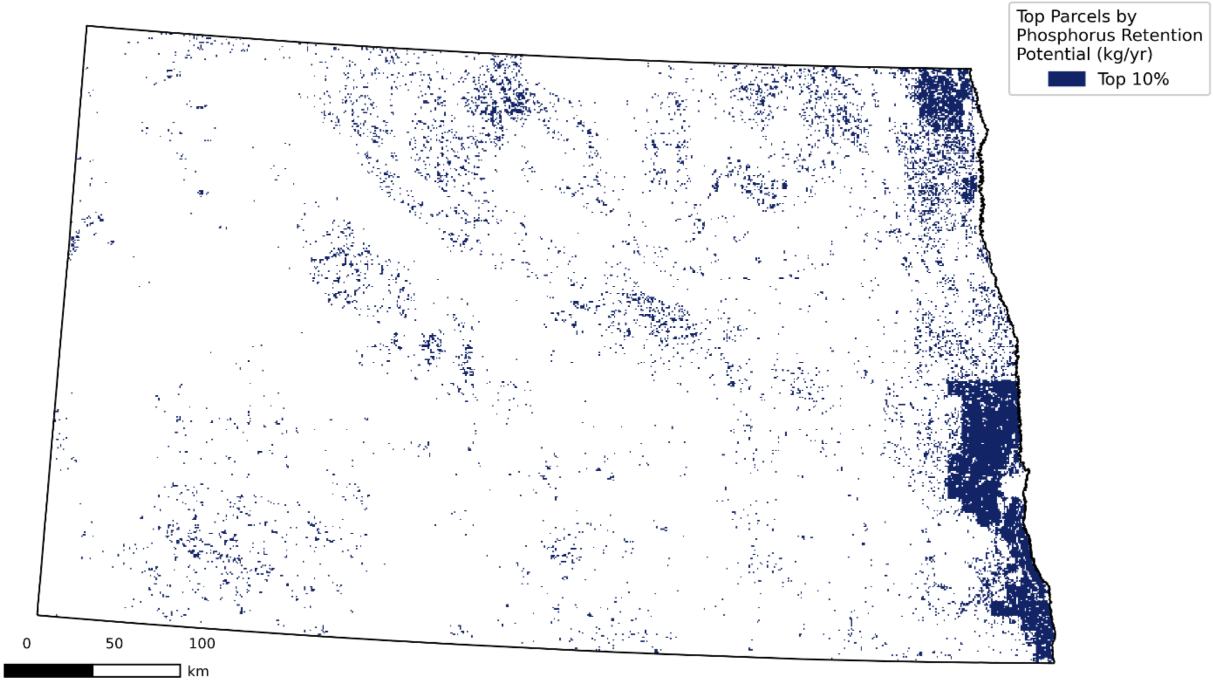


Figure A16. Top 10% of parcels by phosphorus retention with restoration of row crop agriculture to prairie.

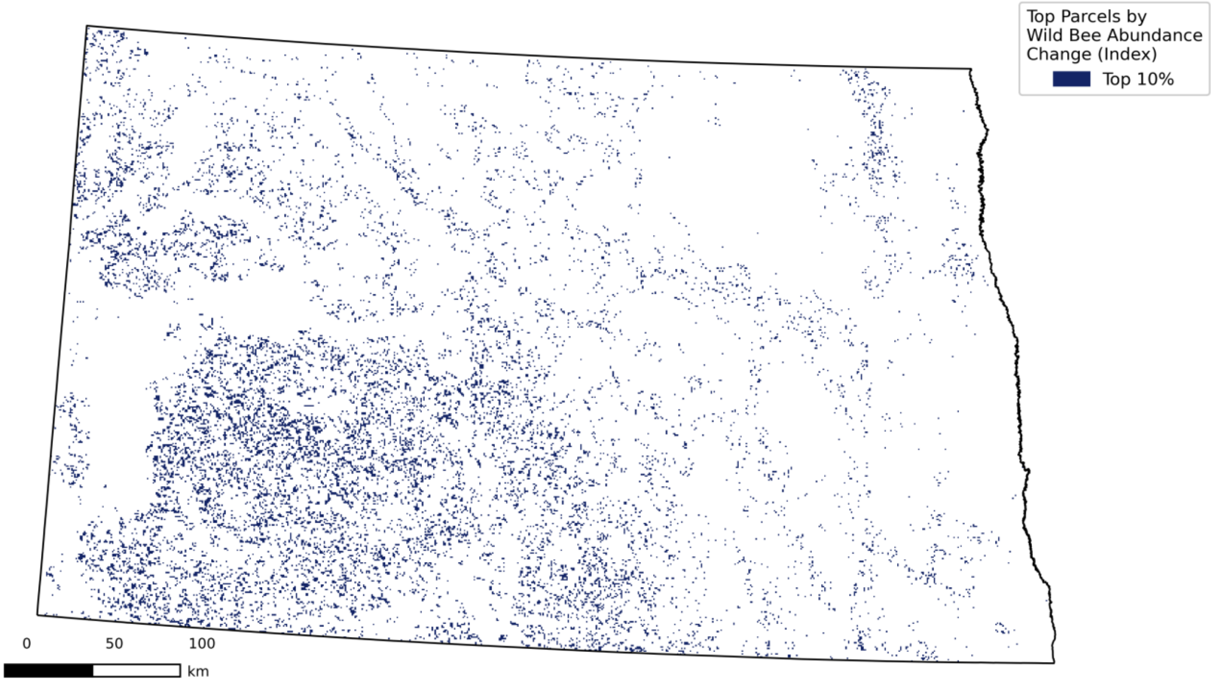


Figure A17. Top 10% of parcels by wild bee habitat (pollination) with restoration of row crop agriculture to prairie.

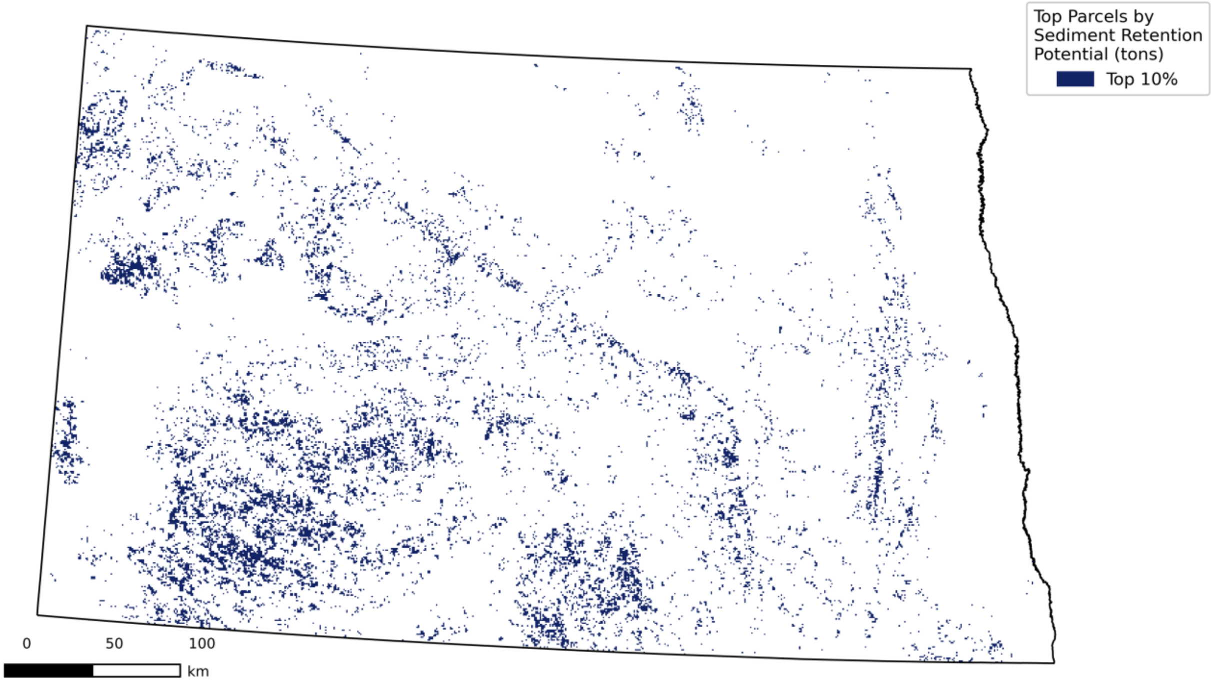


Figure A18. Top 10% of parcels by sediment retention with restoration of row crop agriculture to prairie.

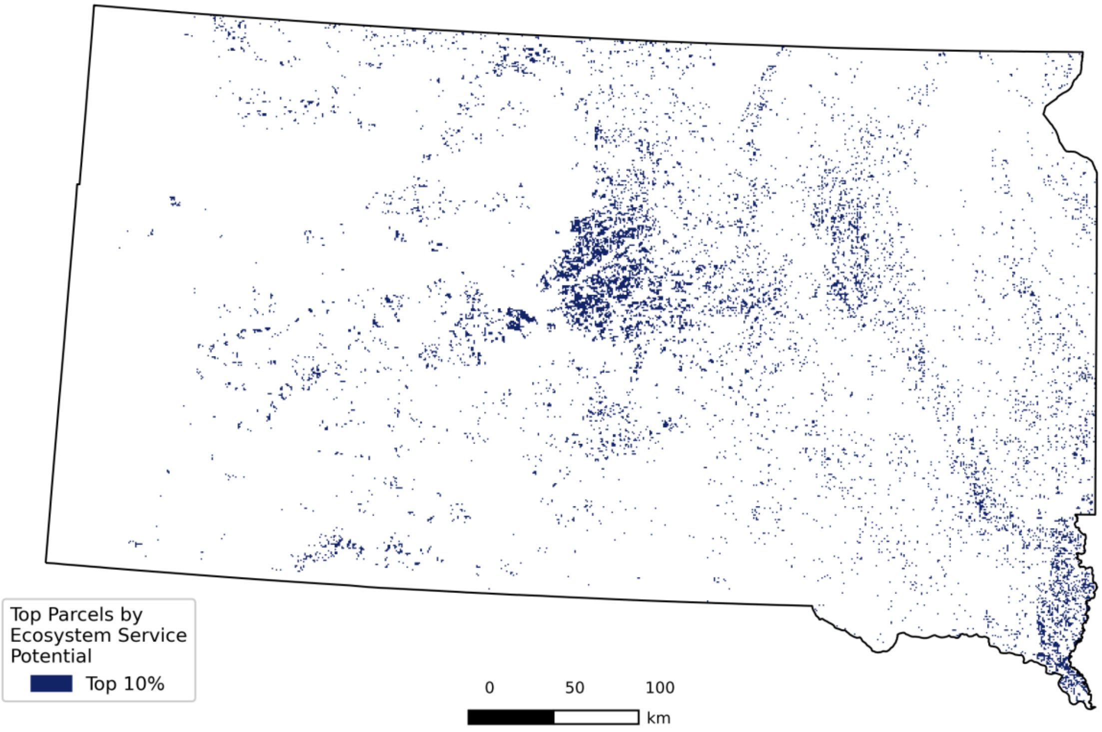


Figure A19. Top 10% of parcels by total ecosystem service potential with restoration of row crop agriculture to prairie.

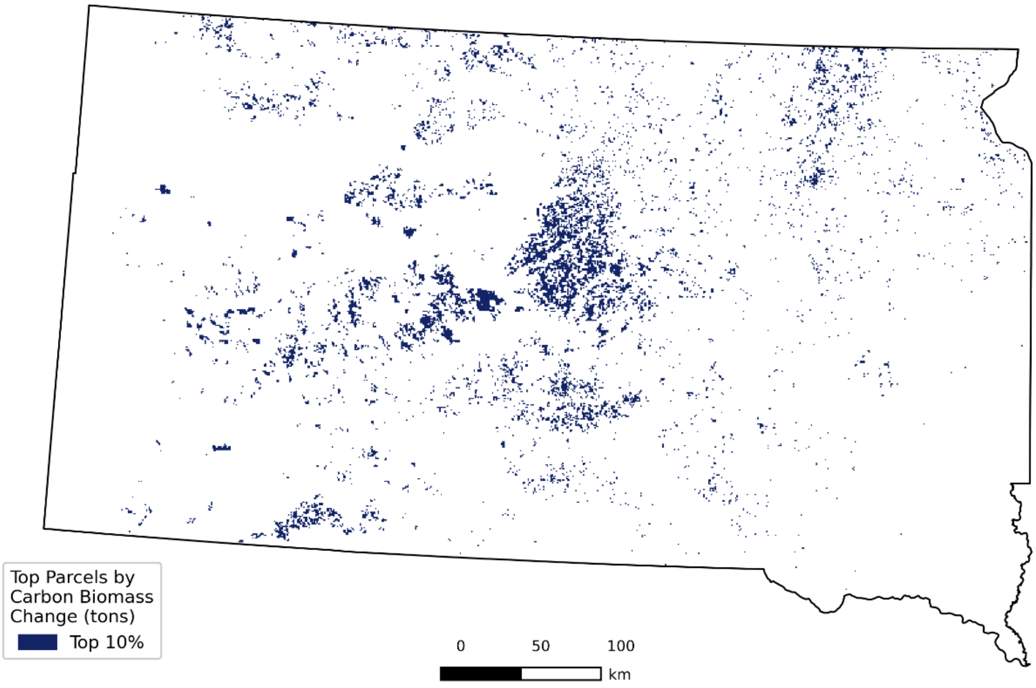


Figure A20. Top 10% of parcels by carbon storage potential with restoration of row crop agriculture to prairie.

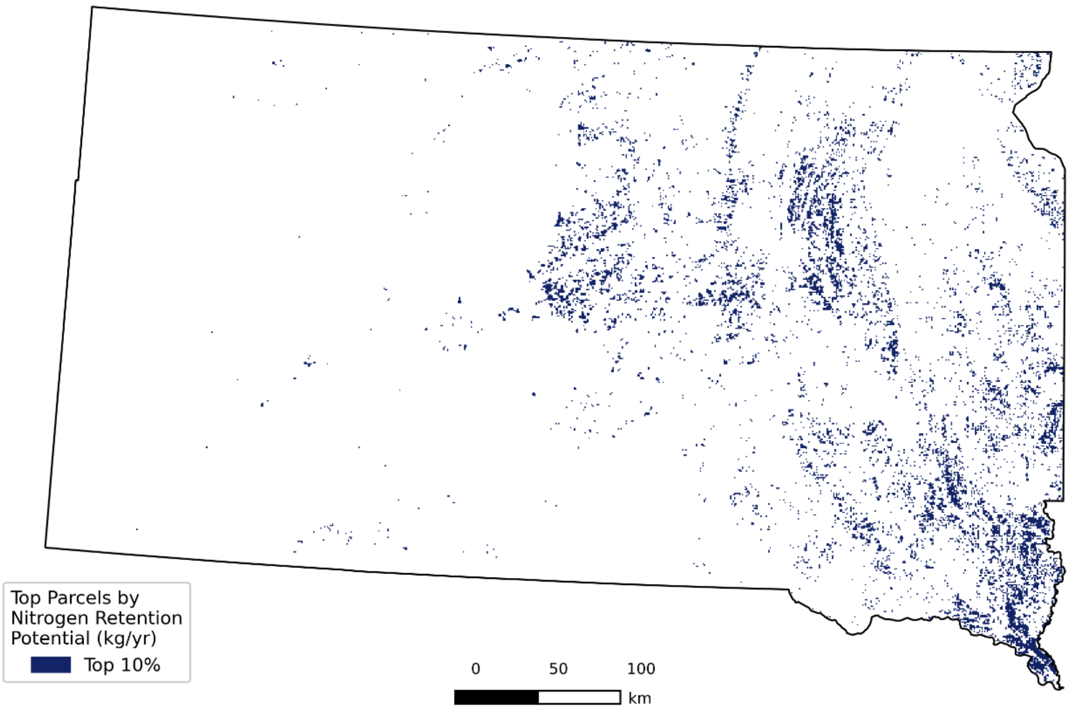


Figure A21. Top 10% of parcels by nitrogen retention with restoration of row crop agriculture to prairie.

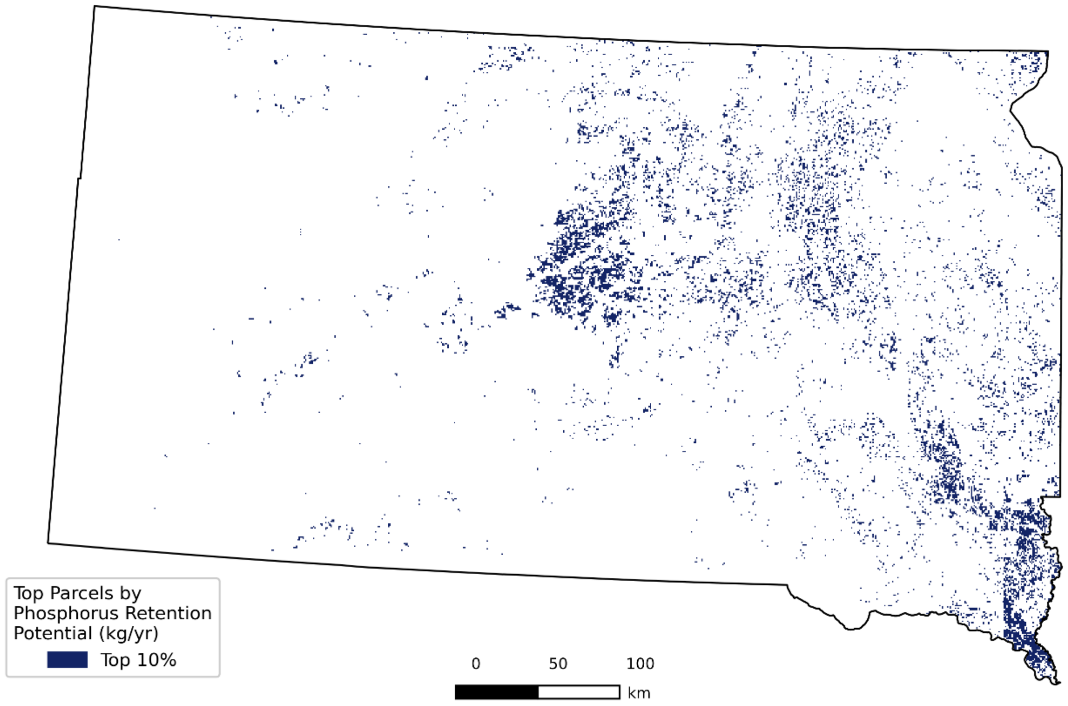


Figure A22. Top 10% of parcels by phosphorus retention with restoration of row crop agriculture to prairie.

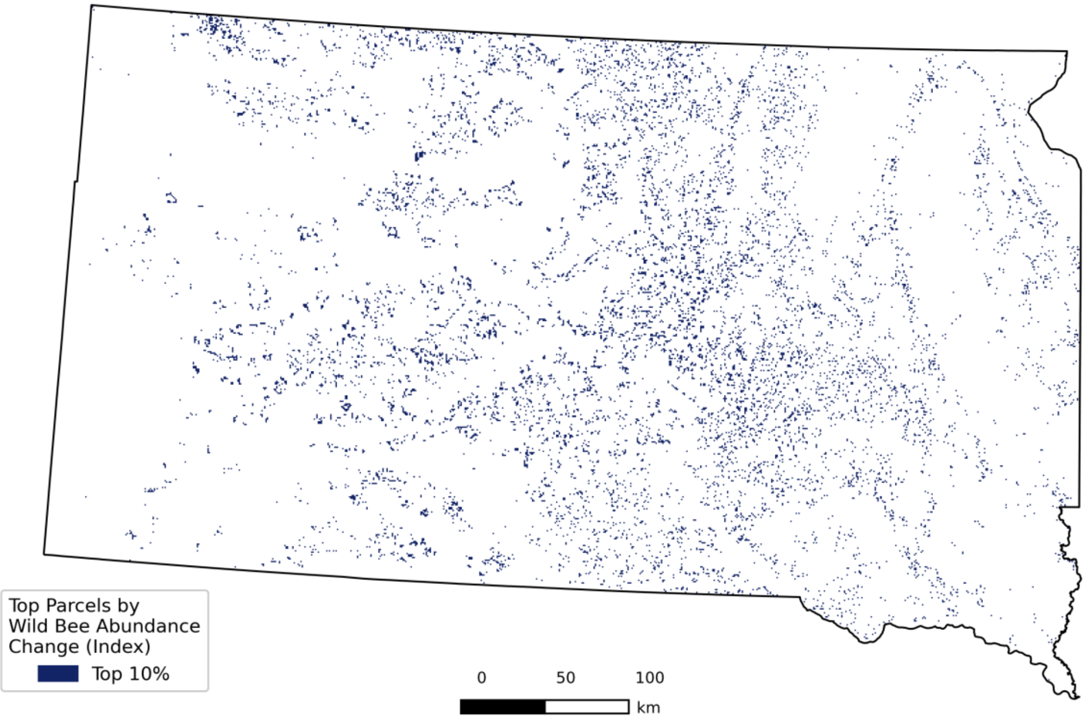


Figure A23. Top 10% of parcels by wild bee habitat (pollination) with restoration of row crop agriculture to prairie.

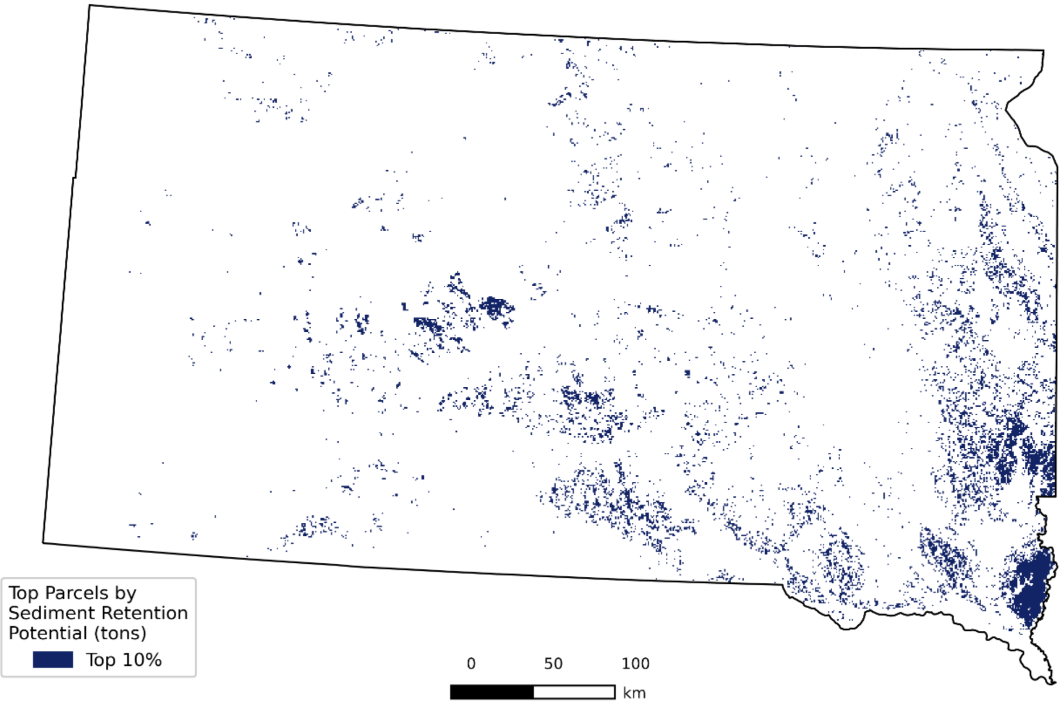


Figure A24. Top 10% of parcels by sediment retention with restoration of row crop agriculture to prairie.

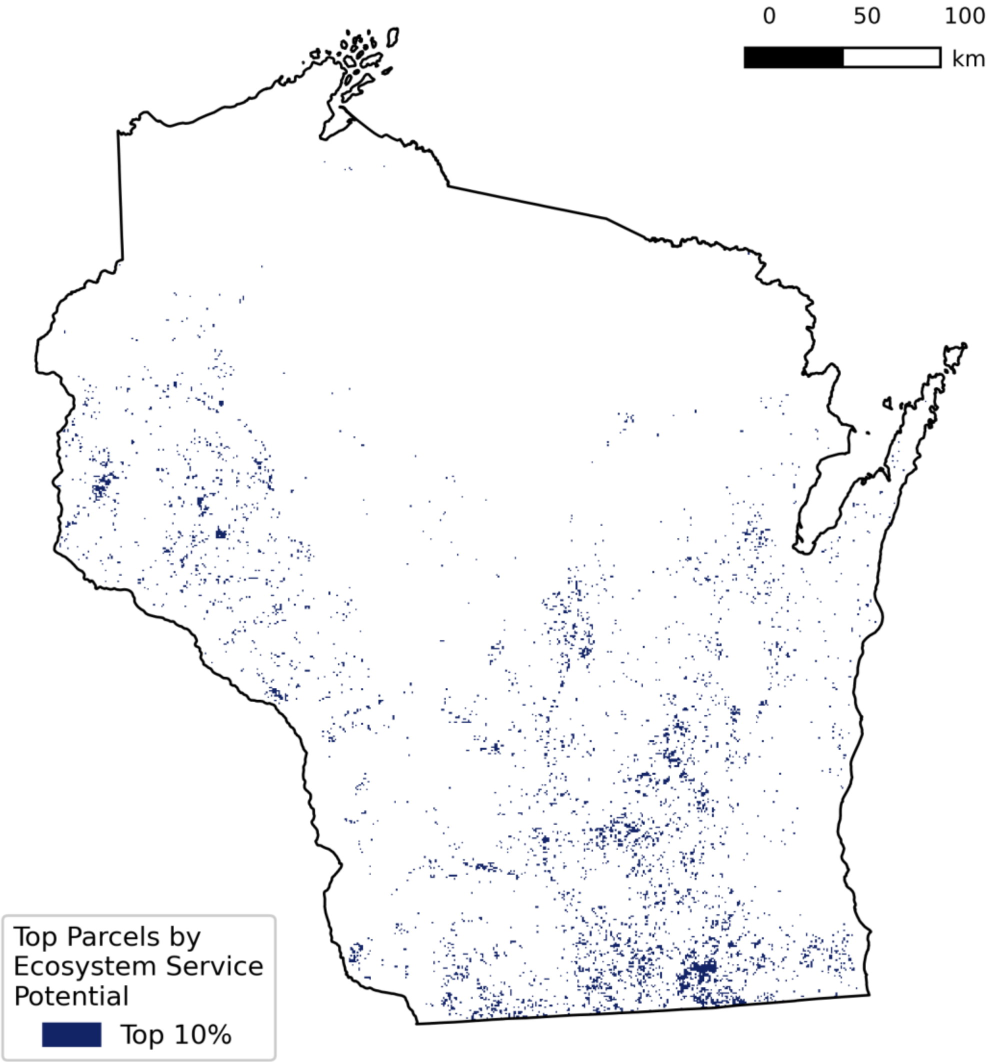


Figure A25. Top 10% of parcels by total ecosystem service potential with restoration of row crop agriculture to prairie.

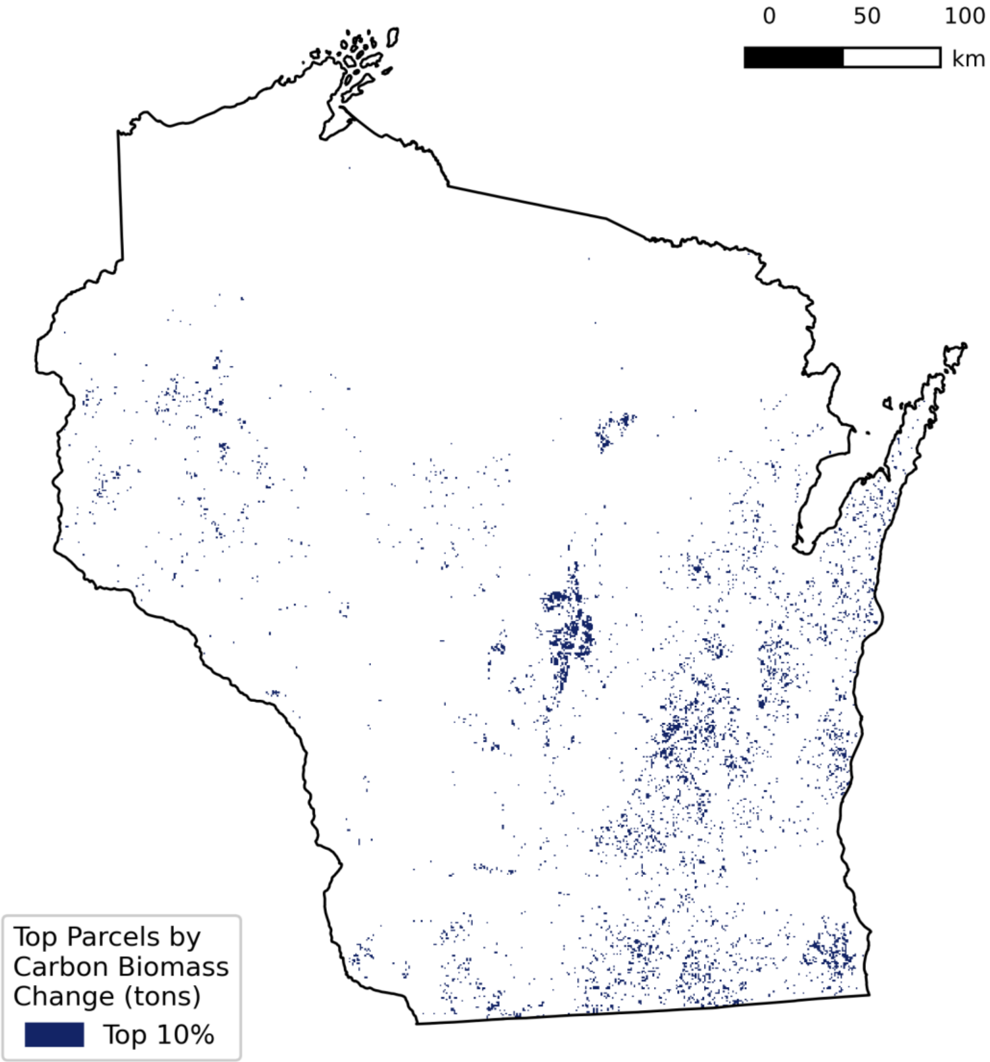
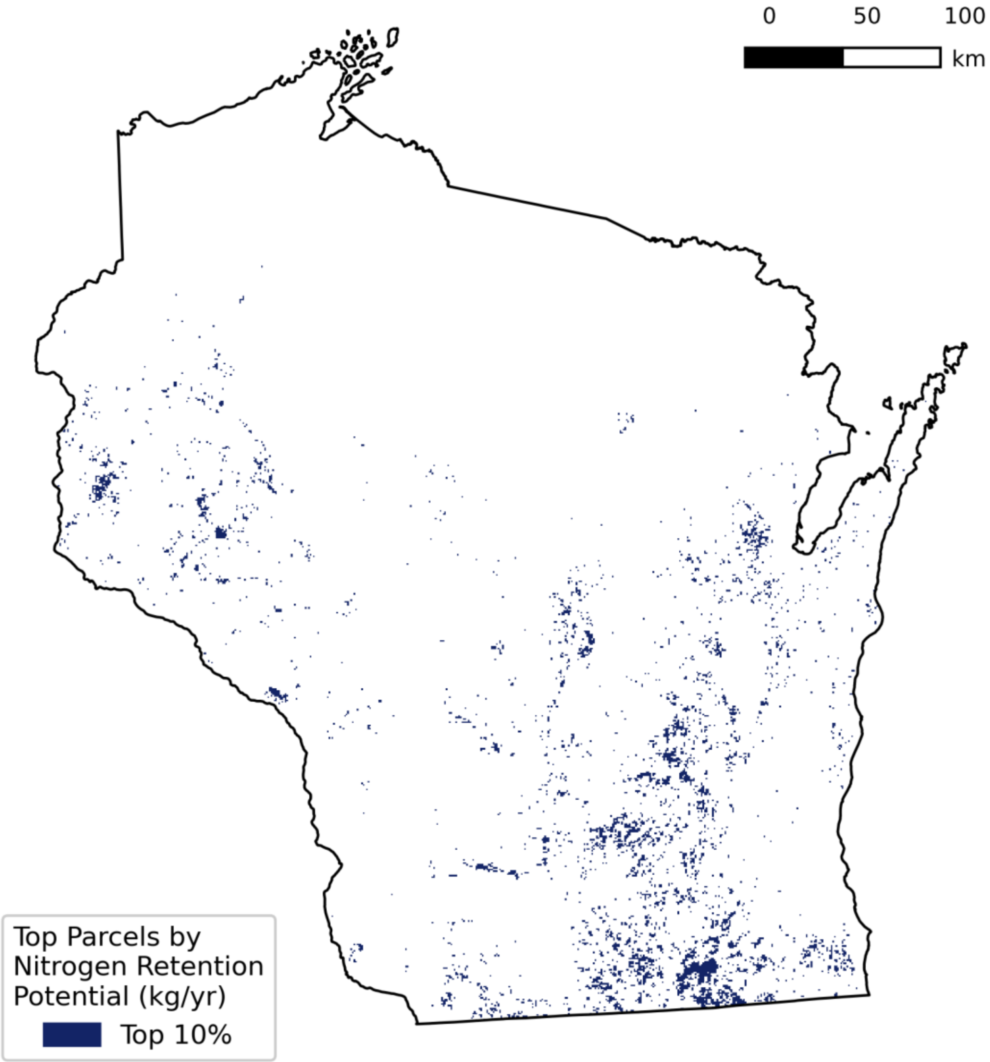


Figure A26. Top 10% of parcels by carbon storage potential with restoration of row crop agriculture to prairie.



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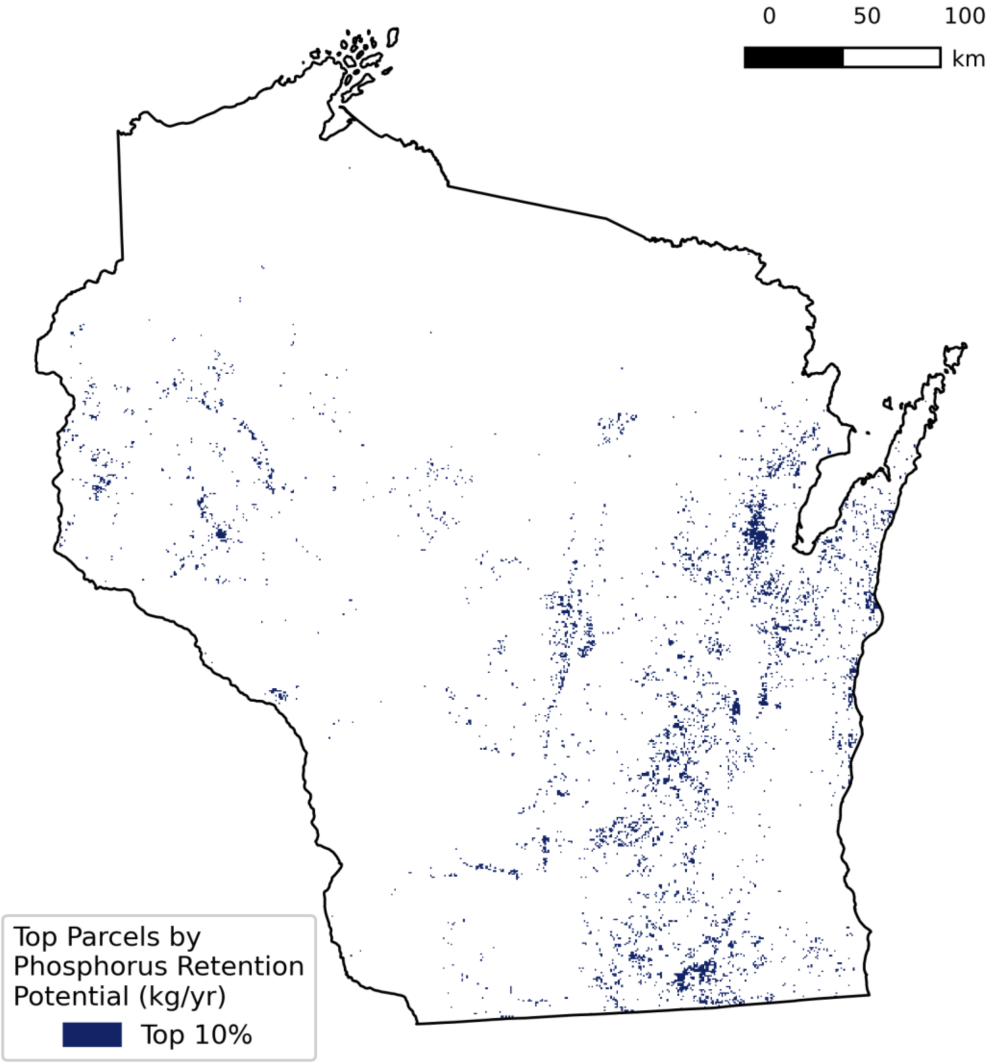

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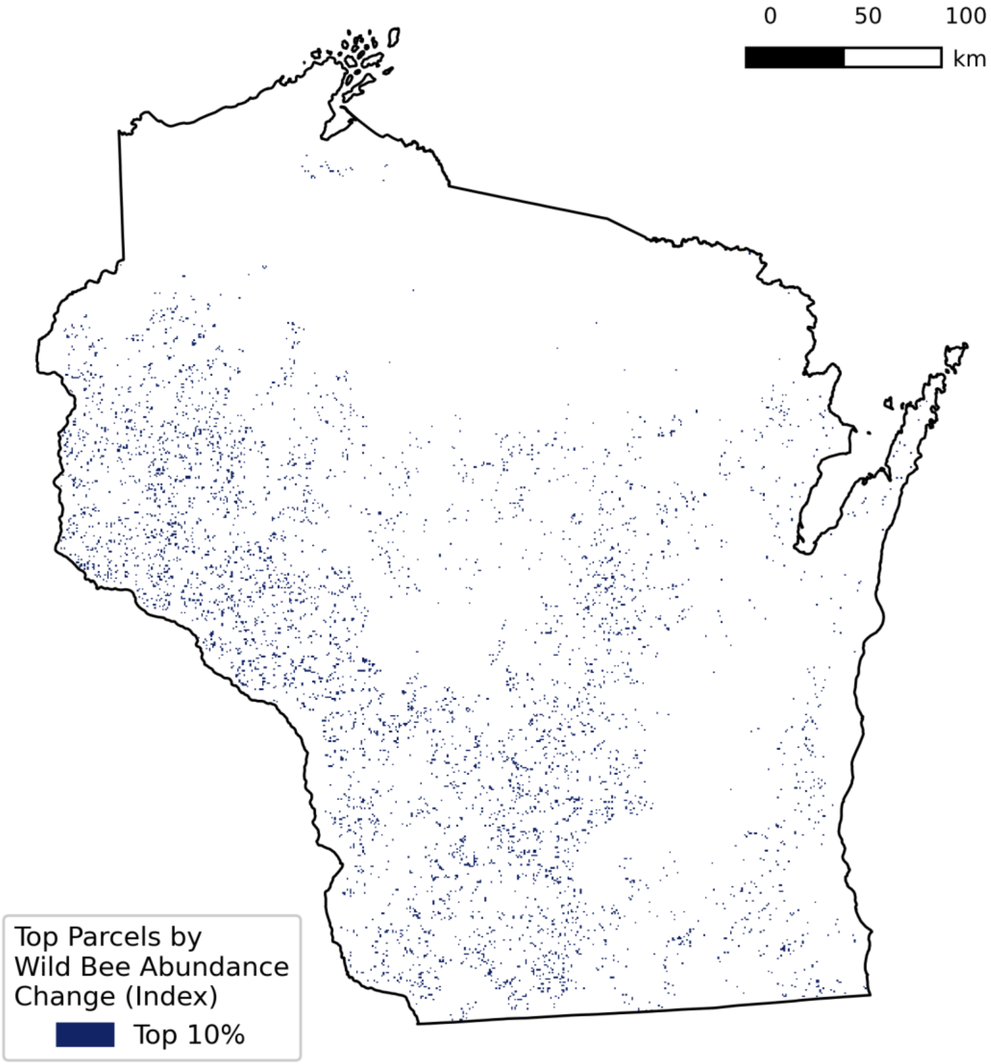

Figure A29. Top 10% of parcels by wild bee habitat (pollination) with restoration of row crop agriculture to prairie.

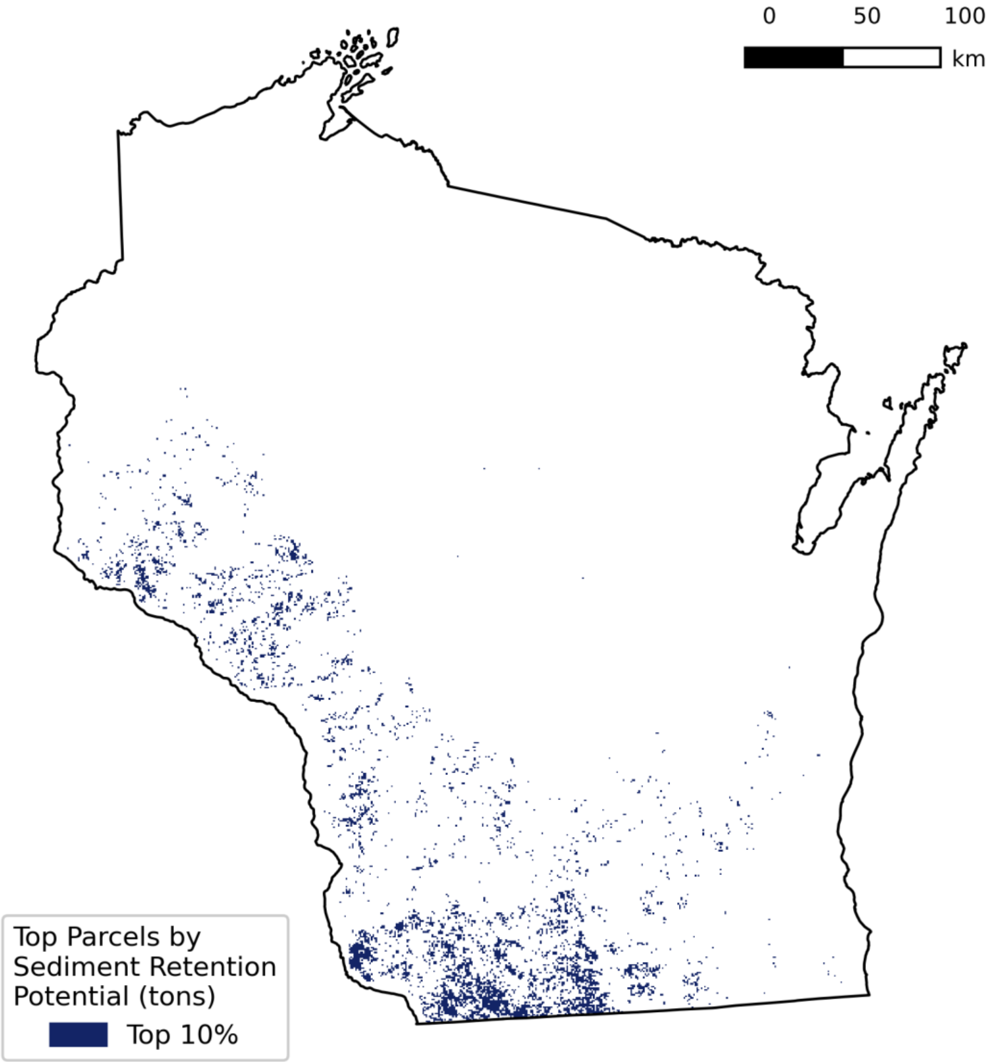

Figure A30. Top 10% of parcels by sediment retention with restoration of row crop agriculture to prairie.