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Landscape Change, Scale, and Human Response to Change in the Great Plains

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LANDSCAPE CHANGE, SCALE, AND HUMAN RESPONSE TO CHANGE IN THE GREAT PLAINS

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Great Plains landscapes are undergoing changes at multiple spatial and temporal scales due to processes ranging from woody encroachment to climate change. These changes may fundamentally alter the agroecosystems of the Great Plains such that the provisioning of ecosystem services including biodiversity and livestock production is affected. Improving our understanding of the effects of landscape change at multiple scales and how humans perceive and respond to these changes is important for facilitating research and management that enhances the resilience of these agroecosystems. As such, I first applied discontinuity theory and graph theory to evaluate the functional connectivity of the Central Platte River Valley (CPRV) for mammal species interacting with the landscape at multiple scales. I found that the CPRV was highly connected for mammal species at larger scales and less connected for those at smaller scales. I also found limited overlap in the patches of habitat most important for connectivity for mammals interacting with the landscape at smaller and larger scales. These results suggest that a multiscale approach to management in the CPRV will be most beneficial in supporting diverse species communities. Second, I interviewed ranchers in the Great Plains states of Nebraska and Colorado in order to examine their perceptions of landscape change and potential coping strategies. The ranchers interviewed identified numerous changes affecting Great Plains landscapes ranging from

shifting land ownership to woody encroachment, and they generally expressed a willingness to learn and adopt new practices. This willingness to adopt new practices, in combination with the management challenges and uncertainties presented by landscape change, indicates a need and opportunity for partnership between governmental and nonprofit entities and the ranching community in order to develop coping strategies. Cumulatively, by examining landscape change and the role of scale and human response to change, we gain insight into potential approaches to research and management in changing Great Plains agroecosystems, which is valuable in maintaining and building the resilience of these systems.

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CHAPTER 1. INTRODUCTION

The Great Plains of the United States (US) is a historically grassland-dominated region which today holds substantial ecological and agricultural significance (Joern & Keeler, 1995; Cunfer, 2005). The Plains is a leading national producer of crops including wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.), as well as livestock such as cattle (NASS, 2017). The state of Nebraska, for example, accounts for six percent of all US agricultural sales and ranks within the top five producing states of both crops and livestock and poultry (NASS, 2017). Roughly 95% of farms in the region are considered family farms, characterized by the majority of the farm being owned by the operator and their family members (NASS, 2017). The Great Plains also includes extensive grassland ecosystems, including tallgrass, mixed-grass, and shortgrass prairie, whose geographic distributions are bounded by the gradient of environmental conditions such as temperature and precipitation across the region (Joern & Keeler, 1995). These grasslands support agricultural production and a diversity of plant and animal species including livestock; provide recreational opportunities; and play an important role processes such as carbon sequestration, climate regulation, and erosion control (Joern & Keeler, 1995; Sala & Paruelo, 1997; Zhao et al., 2020). Notably, some types of grassland found in the Great Plains such as Sandhills mixed-grass prairie, which is located primarily in the state of Nebraska, are unique to the region (Joern & Keeler, 1995). At present, the Nebraska Sandhills are one of the largest and most intact grasslands in the world and the largest stabilized sand dune region in the Western Hemisphere (Scholtz & Twidwell, 2022). The persistence of Great Plains agroecosystems is critical in order to support the continued provisioning of ecosystem services and the existence of the diverse ecological communities found in the region.

Great Plains landscapes, however, are non-stationary systems that are characterized by constant change and ecological processes that vary across space and time (Rollinson et al., 2021). For example, the area of grassland in the region has decreased substantially in the last few hundred years, and only a small amount of the grassland cover present in the region pre-European settlement remains (Samson et al., 2004; Augustine et al., 2021). Beginning around 1850, the conversion of grassland to cropland has driven the fragmentation of the region’s grasslands (Vickery et al., 1999; Cunfer, 2005). Habitat fragmentation is characterized by a decrease in the size of habitat patches, which may force species to move across the landscape matrix between noncontiguous patches of habitat in order to gain access to sufficient resources (Noss, 1991; Taylor et al., 1993; Rudnick et al., 2012), and an increase of edge habitat, which may increase species interaction with the non-habitat landscape matrix and increase mortality and predation rates (Fagan et al., 1999; Fahrig, 2003; Ries et al., 2004). For example, decreasing grassland patch size and increasing edge habitat has been associated with the decline of avian species in the Great Plains (e.g., Sieg et al., 1999; Vickery et al., 1999; Fuhlendorf et al., 2002). Notably, although the rate of conversion of grassland to farmland slowed by the late 20th century (Waisanen & Bliss, 2002; Drummond et al., 2012), a recent increase in demand for biofuel based on corn ethanol has reaccelerated the conversion of grassland to cropland, including the conversion of grassland located in close proximity to wetlands, which has generated additional concerns related to the impact of these conversions on wetland-dependent species (Wright & Wimberley, 2013; Lark et al., 2015; Wright et al., 2017; Lark et al., 2020; Lark et al., 2022).

The grasslands remaining in the Great Plains region have also undergone substantial changes in plant species composition characterized by an increase in non-native grass species, in particular cool-season grasses such as smooth brome (*Bromus inermis*) (Cully et al., 2003; Miles & Knops, 2009; DeKeyser et al., 2013), and an increase in woody species such as juniper (*Juniperus* spp.) (Engle et al., 2008; Van Auken, 2009). Although junipers are native to the Great Plains, their distribution was historically limited to areas such as rocky outcrops due to the regular occurrence of wildfire (Engle et al., 2008). In the absence of fire following Euro-American settlement, juniper has spread across the Great Plains, presenting the greatest concern facing the region's grasslands today (Twidwell et al., 2013). The increase of juniper has caused a multiplicity of impacts on the ecosystem including shifting carbon storage from soil carbon to above-ground storage in woody vegetation (Briggs et al., 2002; Briggs et al., 2005; Pinno & Wilson, 2011), increasing the risk of large wildfires due to the accumulation of above-ground woody biomass (Donovan et al., 2020), changing herbaceous species composition (Gehring & Bragg, 1992; Van Auken, 2009; Alofs & Fowler, 2013), and reducing the ability of the grasslands to support the grazing of cattle and other large ungulates (Van Auken, 2009).

Other factors directly and indirectly affecting the landscape of the Great Plains range from climate change to land ownership change. For instance, in the Northern Great Plains, decreased snowpack in the Rocky Mountains and warmer temperature associated with climate change are expected to decrease water availability in the region, while the

Southern Great Plains is expected to experience drier summers associated with increased evapotranspiration due to warming temperatures (USGCRP, 2018). The projected increase in the frequency of extreme weather events such as heavy rainfall in both the Northern and Southern Great Plains is anticipated to cause flooding, erosion, and damage to infrastructure (USGCRP, 2018). These changes will likely influence species distributions and behavior (Peterson, 2003; Travers et al., 2015), as well as impact agricultural productivity both directly (e.g., increased temperature) and indirectly (e.g., increased weed pressure) (Wienhold et al., 2018). Furthermore, changes in land ownership may lead to different land uses and different approaches to rangeland management, subsequently affecting the landscape of the Great Plains itself (e.g., Leonard & Gutmann, 2006; Sorice et al., 2014; Haggerty et al., 2018). The use of land for energy production, for example, is increasing in the Great Plains through oil and gas and renewable energy development (Allred et al., 2015; Diffendorfer et al., 2017; Ott et al., 2021). These historical, ongoing, and predicted changes in the landscape, coupled with the ecological and agricultural importance of the Great Plains, make understanding the effects of landscape changes in the region important.

Extensive changes to the landscapes of the Great Plains, including those previously described, have the potential to fundamentally alter the region's agroecosystems, such that they are unable in some cases to support the current form and level of agricultural production (e.g., Kukal & Irmak, 2018; USGCRP, 2018) and the existing ecological communities in the region (e.g., Morford et al., 2021). Ecological resilience describes amount of change a system can undergo without fundamentally changing from the current state of the system to an alternative stable state characterized by a new set of structuring processes (Holling, 1973; Angeler & Allen, 2016). For example, as previously mentioned, rangeland systems can transition from a grassland state into a woodland state due to the encroachment of woody species, altering the structure and processes of the system, as well as the services it provides (Holling, 1986; Engle et al., 2008). Uncertainties exist related to (1) the amount of change the Great Plains can undergo before its agroecosystems are compromised in such a way that they do not provide their current desirable functions and (2) the best approaches to management given the non-stationarity of these systems (e.g., Steiner et al., 2018; Maestas et al., 2022). Looking forward, management aimed at retaining these desirable ecosystem functions must identify and reduce the uncertainties associated with landscape change to ensure that the intended goals of management are achieved (Allen et al., 2013). Accordingly, better understanding the resilience of Great Plains agroecosystems and the impacts of landscape change in this region is needed to inform research and ecosystem management that will enhance the resilience of agroecosystems and prevent them from further shifting towards undesirable alternative states.

In addition to being agroecosystems, Great Plains landscapes are complex socioecological systems in which the presence of multiple spatial and temporal scales and diverse stakeholders, among other factors, are substantial sources of complexity (Walker et al., 2002). For example, different social (e.g., management and governance) and ecological processes (e.g., disturbance) act at and elicit different responses at the different scales present in Great Plains systems (Holling, 1992; Walker et al., 2002). Trade-offs in ecosystem services across spatial and temporal scales may also exist, in which management for an ecosystem service at one scale may negatively impact the provisioning of an ecosystem service at a larger or smaller scale (e.g., Birgé et al., 2016). As such, explicitly examining the impact of landscape change at multiple scales in the Great Plains and improving understanding of approaches to management at these scales will be critical in ensuring the resilience of the region's landscapes. Furthermore, understanding human responses to landscape change in the region and the adaptive capacity of different communities to respond to these changes is critical to the systems' resilience (Walker et al., 2002; Angeler & Allen, 2016). The ability of agricultural producers, for instance, to adapt to changes in the landscape may vary based on factors such as their financial capacity and scientific awareness (Briske et al., 2015) and, in some cases, can be constrained by governmental regulation on practices such as prescribed burning (e.g., Twidwell et al., 2013). In the context of climate change, for instance, individuals' perceptions of climate-related changes and associated risk may be a determining factor in their adaptive capacity (Williamson et al., 2012). As such, improving understanding of human perceptions of landscape change in the Great Plains and their resulting responses will be crucial to informing engagement with stakeholders related to the development of coping strategies to address to these changes.

This Master of Science thesis examines landscape change in the agroecosystems of the Great Plains, explicitly exploring the ecological and social components of landscape change with quantitative and qualitative methods. The second chapter of this thesis applies discontinuity theory and graph theory to examine the relationship between scale and landscape connectivity in the Central Platte River Valley of Nebraska, U.S.A. The third chapter applies discontinuity theory and graph theory to evaluate the functional connectivity of the Central Platte River Valley, U.S.A. for multiple mammal species interacting with the landscape at different scales and assesses the merit of an umbrella species approach to management. The fourth chapter utilizes a qualitative approach to explore ranchers' perceptions of landscape change in the Great Plains. The fifth chapter describes how these projects cumulatively enhance understanding of landscape change in the Great Plains and both the ecological consequences and human responses to these changes, with the goal of informing research and management in support of the resilience of Great Plains agroecosystems.

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CHAPTER 2. FUNCTIONAL CONNECTIVITY VARIES ACROSS SCALES IN A FRAGMENTED LANDSCAPE

Abstract

Species of different sizes interact with the landscape differently because ecological structure varies with scale, as do species movement capabilities and habitat requirements. As such, landscape connectivity is dependent upon the scale at which an animal interacts with its environment, and analyses of landscape connectivity must incorporate ecologically relevant scales in order to address scale-specific differences. Many evaluations of landscape connectivity utilize incrementally increasing buffer distances or other arbitrary spatial delineations as scales of analysis. Instead, I used a mammalian body mass discontinuity analysis to objectively identify scales in the Central Platte River Valley (CPRV) of Nebraska, U.S.A. I implemented a graph-theoretic network analysis to evaluate the connectivity of two wetland landcover types in the CPRV, wet meadow and emergent marsh, at multiple scales represented by groupings of species with similar body mass. Body mass is allometric with multiple traits of species, including dispersal distances. The landscape was highly connected at larger scales but relatively unconnected at smaller scales, and I identified a threshold at which the landscape becomes highly connected between 500 m and 6,500 m dispersal distances. The presence of a connectivity threshold suggests that species with dispersal distances close to the threshold may be most vulnerable to habitat loss or reconfiguration and that management should account for the connectivity threshold. Furthermore, I propose that a multiscale approach to management will be necessary to ensure landscape connectivity for diverse species communities.

Introduction

Human-driven disturbances such as land use change produce scale-specific impacts and responses in ecosystems (Nash et al., 2014a). At each spatiotemporal scale, different biotic and abiotic processes structure ecosystems, creating a scale-dependent suite of responses (Urban et al., 1987; Peterson et al., 1998; Nash et al., 2014a). These processes and the resulting ecosystem structure also entrain attributes of animals, including how animals perceive and exploit the landscape (Holling, 1992). Species may exist in the same geographic area but experience and move through the landscape differently because scale of interaction determines resource availability, habitat requirements, and species movement capabilities (Wiens, 1989; Holling, 1992; Nash et al., 2014a). An understanding of how species at different scales perceive and interact with a given landscape will help anticipate the effects of future disturbances and inform ecosystem management and conservation efforts (Wiens et al., 1989; Keitt et al., 1997; Nash et al., 2014a). Multiscale approaches to management and conservation that incorporate a range of species are necessary for preventing the loss of biodiversity and maintaining resilient ecosystems (Peterson et al., 1998). Investigating patterns of connectivity for ecological communities, and how these patterns change with scale, will increase the likelihood of successful ecosystem management.

Landscape connectivity is species-dependent and scale-dependent. Connectivity may describe (1) structural connectivity, or the spatial arrangement of habitat patches, and (2) functional connectivity, or how species move through the landscape (Taylor et al., 1993; With et al., 1997; Tischendorf & Fahrig, 2000). For instance, in a fragmented landscape, species that interact with their environment at a larger scale will experience a more connected landscape than species at smaller scales because they possess a greater capability to move between distant habitat patches (Keitt et al., 1997; Bunn et al., 2000; Fahrig, 2003). Previous studies have examined the influence of scale on connectivity and, for example, identified thresholds of connectivity that represent the minimum species dispersal distance at which the landscape is connected (Keitt et al., 1997). Knowledge of how scale affects landscape connectivity is critical for ensuring that management efforts such as habitat conservation and restoration benefit the intended species in an ecosystem.

Scales are frequently assigned arbitrarily or are applicable to only a single species or subset of species, limiting the utility of any results and raising the possibility that the selected scales are irrelevant for the processes or species of focus (Wheatley & Johnson, 2009; Nash et al., 2014a; Angeler et al., 2016). Scales of management must align with or transcend multiple ecologically relevant scales to maximize beneficial outcomes for ecological communities, given that communities consist of multiple species interacting with the landscape at different scales (Wiens, 1989; Noss, 1991; Cumming et al., 2006; Nash et al., 2014a). Discontinuity theory presents a method to objectively identify scales in a variety of systems, including ecological systems (Allen & Holling, 2008; Nash et al., 2014a; Sundstrom et al., 2014; Angeler et al., 2016). Discontinuity theory emerged from Holling's (1992) conception of ecosystems, in which the organization of ecosystems sets a template for the structure of their animal communities, specifically body mass distributions. This approach identifies aggregations of species, which represent the species at a given scale of the ecosystem. Breaks between aggregations of species in the body mass distribution separate scales, indicating discontinuities in the ecological processes that structure the system (Holling, 1992). Body mass discontinuity analyses have previously been applied to identify scales in studies of biological invasion and extinction (Allen et al., 1999; Allen, 2006) and population variability (Wardwell & Allen, 2009), among others (e.g., Allen & Saunders, 2002; Angeler et al., 2014).

In this study, I apply both discontinuity theory and graph theory to determine how the connectivity of the Central Platte River Valley (CPRV) in Nebraska, U.S.A. varies across objectively defined scales for mammals. Body mass is allometric with multiple traits of species, including mammalian dispersal distances (Sutherland et al., 2000). I utilize a mammalian body mass discontinuity analysis to identify scales in the ecosystem represented by groupings of species with similar body mass. To serve as an example of multiscale analysis of connectivity, I implement a graph-theoretic network analysis to evaluate the connectivity of two wetland landcover types, wet meadow and emergent marsh, at the identified scales. I evaluate how node-level and landscape-level connectivity metrics vary across scales and identify thresholds of connectivity in the landscape.

Methods

Study area and data

The Big Bend Reach is a 145 km stretch of the Central Platte River extending between Lexington, NE and Chapman, NE. The area surrounding the Central Platte River is dominated by agriculture, specifically corn and soybean production (Bishop et al., 2020). This system is of substantial management interest because of tensions between providing habitat for endangered and other species and meeting human demands for irrigation and other water uses (Smith, 2011; USBOR, 2018). For example, the Big Bend Reach encompasses important habitat for mammal species of concern including the plains pocket mouse (*Perognathus flavescens*) and long-tailed weasel (*Mustela frenata*) (Schneider et al., 2018). Furthermore, wetland landcover types such as wet meadow and emergent marsh are threatened by hydrological changes caused by the construction of the Kingsley Dam in 1941 and the extensive diversion of water from the Central Platte River (National Research Council, 2005; USBOR & USFWS, 2006). My study area (5,868 km^2) encompassed the Platte River Basin, extending east and west to the bounds of the Big Bend Reach (Fig. 2.1). Landcover data for the study area in raster format at 30 m resolution were provided by the Rainwater Basin Join Venture (Bishop et al., 2020).

Mammalian focal species

In accordance with previous applications of discontinuity theory seeking to examine ecosystem structure (e.g., Holling, 1992; Allen et al., 1999; Wardwell & Allen, 2009), I compiled a list of all species of a single taxonomic group, mammals, in the CPRV. I used *Mammals of Nebraska* (Genoways et al., 2008) and additional published sources to determine species ranges (Appendix A). Extirpated and extinct species (e.g., black bear [*Ursus americanus*]) previously present in the ecosystem were also included. Peripheral species, including species with ranges that have recently expanded into the study area but are still rare or transient (e.g., nine-banded armadillo [*Dasypus novemcinctus*]) and transient species, such as native species that have been recorded in the study area but are not known to have a breeding population, were not included. Body mass data were collected from published sources, primarily the *CRC Handbook of Mammalian Body Masses* (Silva & Downing, 1995; Appendix A). From the available body mass data, data with the geographic proximity closest to the study area were selected for each species. Male and female body mass data were averaged when both were available for a given species. If only male or female data were available, the data for the available sex were used.

Discontinuity analysis

Applying discontinuity analysis to body mass distributions involves examining the differences between rank-ordered species body masses. Accordingly, I first ranked all mammalian focal species (n=49) in ascending order of body mass. I analyzed the body mass distribution by comparing the distribution of the actual body mass data to a null distribution developed using a continuous unimodal kernel distribution of the log-transformed body mass data (Barichievy et al., 2018). Discontinuities were identified as any gaps between successive species body masses that significantly exceeded the gaps created by the null distribution using a consistent statistical power. Species aggregations, or groups of species representing each scale in the system, were identified as any group of three or more successive species that were not separated by a discontinuity. I disregarded discontinuities that resulted in aggregations of fewer than three species (Holling, 1992).

Mammal dispersal

Mammal species body mass is allometric to dispersal distance (Sutherland et al., 2000; Jenkins et al., 2007). I obtained dispersal data for the mammal species included in the body mass discontinuity analysis (Appendix A). For each mammal species, I selected natal or adult dispersal data from published sources using the following order of preference: 1) measured as the mean distance from the center or edge of the natal range to the center or edge of the adult home range; 2) measured as the mean distance between recaptures, capture and death, or capture and loss of tracking; 3) measured as the maximum distance from the center or edge of the natal range to the center or edge of the adult home range; 4) measured as the maximum distance between recaptures, capture and death, or capture and loss of tracking; 5) measured based on home range size; 6) measured as the cumulative distance moved over a given number of days; and 7) other dispersal measurements. If multiple sources with similar methods were available for a given species, I preferentially selected the data with the closest geographic proximity to the study area, with the largest sample size, or natal dispersal measurements. I selected dispersal measurements that were either for male and female individuals combined or, if unavailable, only for female individuals. Dispersal data were not available for some species. Although I utilized multiple types of dispersal measurements due to the limited availability of mammal dispersal data, the expected pattern of increasing dispersal distance with greater body mass size is present in the selected data (Sutherland et al., 2000; Jenkins et al., 2007). I converted all available dispersal distances to meters, then calculated the mean dispersal distance, rounded to the nearest hundredth, for the species in each aggregation in order to obtain a dispersal distance in meters representing every scale identified in discontinuity analysis.

Evaluating connectivity

I applied a graph-theoretic network analysis approach to evaluate the connectivity of the Central Platte River Valley at multiple objectively identified scales (Bunn et al., 2000; Urban & Keitt, 2001; Calabrese & Fagan, 2004; Minor & Urban, 2008). Using ArcGIS Pro 2.8.3 (ESRI, 2021), I converted the 30 m resolution raster landcover data provided by the Rainwater Basin Joint Venture Nebraska Land Cover Development (2016 Edition) dataset to vector format and identified all patches of wet meadow and emergent marsh landcover in the study area (Bishop et al., 2020). To ensure that polygons sharing a common boundary at a vertex point were considered to be a single patch of habitat, I added a 0.01-m buffer to all polygons before using the Dissolve Boundaries tool to combine all patches sharing a common boundary. This small buffer ensured that the Dissolve Boundaries tool ran correctly but did not influence the connectivity analysis. I then used the Generate Near Table function to calculate the Euclidean edge-to-edge distances between all wet meadow and emergent marsh patches respectively at each scale. In other words, I identified all the patches of each landcover type within the scale-specific dispersal distance from each other. Notably, I selected these wetland landcover types to serve as an example application of my approach, and my focus is not on the connectivity of these landcover types for specific species but instead on the relationship between scale and connectivity.

Using R 4.0.5 (R Core Team, 2021), I separately developed and analyzed networks for the wet meadow and emergent marsh landcover types respectively at each scale using functions included the packages tidyverse (Wickham et al., 2019), igraph (Csardi & Nepusz, 2006), and rgdal (Bivand et al., 2021). For each scale, the network was composed of nodes, which were patches of wet meadow or emergent marsh, and edges, which were the edge-to-edge connections between nodes within the given dispersal distance. I measured patch (i.e., node-level) connectivity using degree centrality, or the number of direct connections between a node and other adjacent nodes (Minor & Urban, 2007; Uden et al., 2014). A node with a high degree centrality represents a habitat patch that is within the given distance to many other patches of habitat, indicating that species can move from this patch to many other patches of habitat

(Minor & Urban, 2008). I evaluated landscape (i.e., network-level) connectivity using mean degree centrality, characteristics of network components, and modularity. Mean degree centrality is the mean number of edges adjoining each node in the network, and it describes the degree to which nodes in the network are connected to other neighboring nodes (Minor & Urban, 2008; Uden et al., 2014). A higher number of connections between neighboring nodes on average suggests a greater potential for species movement between patches of habitat in the network. I evaluated the characteristics of the components, or clusters of connected nodes, in each network by calculating the number of components in the network, the mean number of nodes in the largest component, and the percent of nodes in the largest component (Minor & Urban, 2008; Uden et al., 2014). Patches of habitat are more disconnected for species moving through the landscape in a network consisting of many small, separate clusters of nodes, whereas a network consisting of fewer, larger clusters of nodes begets a more connected landscape for those species (Uden et al., 2014). A highly connected network may consist of a single cluster of nodes, indicating that every habitat patch can be accessed directly or indirectly from all other patches in the network (Uden et al., 2014). Modularity measures the extent to which there are highly connected subgroups of nodes with few connections between subgroups in the network (Newman, 2006; Uden et al., 2014). Although a high degree of modularity in a network may impede the movement of species between habitat patches, a moderate degree of both modularity and connectivity may facilitate movement while also limiting the negative effects of disturbances such as disease spread through the habitat network (Walker & Salt, 2006; Webb & Bodin, 2008; Cumming, 2011).

Results

Species and scale identification

I identified 49 mammal species present or historically present in the CPRV study area (Appendix A). The body mass distribution of the mammal species was discontinuous. I identified eight aggregations of mammals in the data separated by seven discontinuities (Fig. 2.2). The number of mammal species in each aggregation ranged from three species to eleven species. The average dispersal distance of mammal species in each aggregation increased with scale (Table 2.1). The longest mean dispersal distance was 67,500 m for mammal species at the largest scale, more than 300 times longer than the mean dispersal distance of 200 m for species at the smallest scale in the ecosystem.

Network analysis

My examination revealed that the spatial characteristics of the two landcover types selected for my example analysis differed. The wet meadow landcover type presented a greater total area, greater mean patch size, and greater number of patches than the emergent marsh landcover type in the CPRV (Fig. 2.3). The total area of wet meadow landcover in the study area was 208 km^2, roughly 15 times larger than the area of emergent marsh landcover (14 km^2). Similarly, the mean patch size for the wet meadow landcover type was 32,913 m^2, approximately 4.5 times larger than the mean patch size of emergent marsh landcover (7,446 m^2).

Landscape connectivity varied substantially by both landcover type and scale. For example, the mean degree centrality of the wet meadow network was greater than the mean degree centrality of the emergent marsh network at all scales (Fig. 2.4). However, the wet meadow and emergent marsh networks demonstrated similar patterns of connectivity across scales in the landscape. As scale increased, mean degree centrality increased, modularity decreased, the number of components decreased, the mean component size increased, and the percent of nodes in the largest component increased (Fig. 2.4).

For both wetland landcover types, a threshold of connectivity at which most nodes in the network were directly or indirectly connected to each other existed between the 500 m and 6,500 m dispersal distances of analysis. Between these dispersal distances, modularity decreased from 0.91 to zero in the wet meadow network and from 0.95 to zero in the emergent marsh network (Fig. 2.4). Similarly, between the 500 m and 6,500 m distances, the percent of habitat nodes in the largest component increased from below 25% to over 95% for both wetland landcover types (Fig. 2.4). For example, in the wet meadow network, 95% of nodes became present in the largest component at a dispersal distance of 2,250 m, whereas in the emergent marsh network, 95% of nodes became present in the largest component at a dispersal distance of 4,257 m.

Node-level connectivity followed the same pattern as the connectivity of the broader landscape. As scale increased, the number of isolated wetland patches, or patches with no connections to other wetland patches, decreased for both landcover types. For example, at the 200 m dispersal distance, there were 622 and 637 isolated patches and a maximum node degree of 12 and 31 in the emergent marsh and wet meadow networks, respectively (Table 2.2; Fig. 2.5; Fig. 2.6). At the 6,500 m dispersal distance, there were no isolated nodes in either network and the maximum node degree was 232 for the emergent marsh network and 459 for the wet meadow network, demonstrating that node-level connectivity increases with scale and supporting the connectivity threshold previously identified at the landscape level (Table 2.2; Fig. 2.5; Fig. 2.6).

Discussion

My results demonstrate the utility of body mass discontinuity analysis as a method to objectively identify scales in ecosystems for the evaluation of landscape connectivity at the level of ecological communities. In the CPRV, the body mass distribution of mammal species was discontinuous, indicating the presence of approximately eight scales in the ecosystem as utilized by mammals, each comprised of a unique set of mammal species, similar only in that they interact with their environment at a similar scale. Discontinuous body mass distributions have similarly been identified in animal communities in multiple ecosystems and for multiple taxa (Holling, 1992; Restrepo et al., 1997; Lambert & Holling, 1998; Allen et al., 1999; Allen & Holling, 2008; Nash et al., 2014b). The presence of aggregations of mammal species suggests that these groups of mammals interact with the landscape differently due to (1) movement capabilities that vary by species and especially by species size, represented in this analysis by dispersal distance; and (2) a scale-specific suite of structuring processes, disturbance responses, and habitat requirements (Wiens, 1989; Nash et al., 2014a). This analysis also demonstrates how the limited data requirements of body mass discontinuity analysis make this approach well-suited to identify ecosystem scales in situations with limited data availability or data collection capability (Angeler et al., 2016). Notably, I found that the availability of dispersal data for some mammal species, particularly small mammals, was limited. Additional research and data on animal movement would be valuable in improving our general understanding of animal responses to non-stationarity, as species with different dispersal capability and interacting with the landscape at different scales will respond differently to changes to the ecosystem and its structuring processes (Nash et al., 2014a).

Historically, the CPRV was a non-stationary ecological system in which the Central Platte River, a braided prairie stream, was shaped by periodic scouring flows (Birgé et al., 2014; Uden et al., 2021). Following European settlement, the CRPV became more stationary due to the regulation of the river's flow regime through damming and diversion and the management of the waters for purposes including irrigation and endangered species (Birgé et al., 2014). Today, management in this more stationary system is challenged with maintaining habitat for endangered and other species while meeting human demands for water (Smith, 2011; Nemec et al., 2014). In order to better understand the ability of the CPRV to support diverse ecological communities, I examined the general pattern of connectivity across scales in this highly altered system. Overall, I found that connectivity varies substantially across scales in the CPRV. As scale increased, represented in this analysis by dispersal distance, the connectivity of the landscape increased non-linearly. A threshold of connectivity existed between the 500 m and 6,500 m scales, and the landscape became highly connected at a dispersal distance of 2,250 m in the wet meadow network and 4,257 m in the emergent marsh network. At the threshold distance for both wetland types, the landscape shifted from being relatively unconnected with many isolated habitat patches to almost all habitat patches being directly or indirectly connected to each other. The presence of this threshold of connectivity suggests that human fragmentation of the landscape may primarily occur between the 500 m and 6,500 m scales in the CPRV, causing differing effects on landscape connectivity because species interact with the landscape at different scales (Lord & Norton, 1990). For instance, a mammal species with a dispersal distance equal to or greater than the threshold dispersal distance can access almost all patches of wet meadow or emergent marsh landcover, respectively, in the landscape from a given patch of either wetland type. In contrast, those species with dispersal distances below the threshold lack the ability to move easily between patches of wetland habitat in the fragmented landscape of the CPRV.

This analysis of wet meadow and emergent marsh landcover types reveals patterns of landscape connectivity across scales in the CPRV that can be used to inform research and management efforts. The aggregations of mammal species identified in the discontinuity analysis will likely demonstrate scale-specific responses to habitat loss and habitat restoration, illustrating the importance of incorporating scale in management decisions. For example, mammal species with dispersal distances close to the connectivity threshold may be highly impacted by changes in habitat configuration because they rely on specific patches as stepping stones (Keitt et al., 1997). In contrast, mammals with relatively short or long dispersal capability may be less affected by changes in habitat configuration because the landscape remains largely unconnected or connected (Keitt et al., 1997). In this study area, species with dispersal distances above the connectivity threshold could likely directly or indirectly access many patches of wetland landcover in the landscape despite changes in habitat configuration.

Management intended to enhance landscape connectivity must incorporate scale in order to ensure benefit to specific species or suites of species in the CPRV. If management is intended to increase or maintain the connectivity of the landscape for all species, management for connectivity must occur at multiple scales, in particular at the scales around or below the connectivity threshold located between the 500 m and 6,500 m dispersal distances. Identification of a critical connectivity threshold suggests that in the absence of complete information, maintaining connectivity at a distance below the threshold will likely have the broadest benefit to species. Management for species interacting with the landscape at greater scales and with longer dispersal distances may not benefit species at smaller scales due to their more limited ability to move between habitat patches. The lack of a multiscale, multispecies approach to management will likely restrict the benefits of management to a subset of species that are present at the selected scale of management and neglect species at other scales, potentially eroding the resilience of the ecosystem (Peterson et al., 1998).

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Tables and Figures

Table 2.1. Mean dispersal distances for mammal body mass aggregations.

Species aggregation	Mean dispersal (m)
1-2	200
3	500
4	6500
5	8200
6	22700
7	27000
8	67500

Mean dispersal distances were rounded to the nearest hundredth. Due to the limited availability of mammal dispersal data and the similarity of the mean dispersal distances for aggregations numbers one and two, those aggregations were combined as one scale for analysis.

Table 2.2. Maximum node degree and number of isolated nodes at seven dispersal distances.

	Maximum node degree		Number of isolated nodes	
Dispersal (m)	Wet meadow	Emergent marsh	Wet meadow	Emergent marsh
200	31	12	637	622
500	50	22	195	370
6500	459	232	0	0
8200	564	278	0	0
22700	1974	888	0	0
27000	2392	965	0	0
67500	5910	1713	0	0

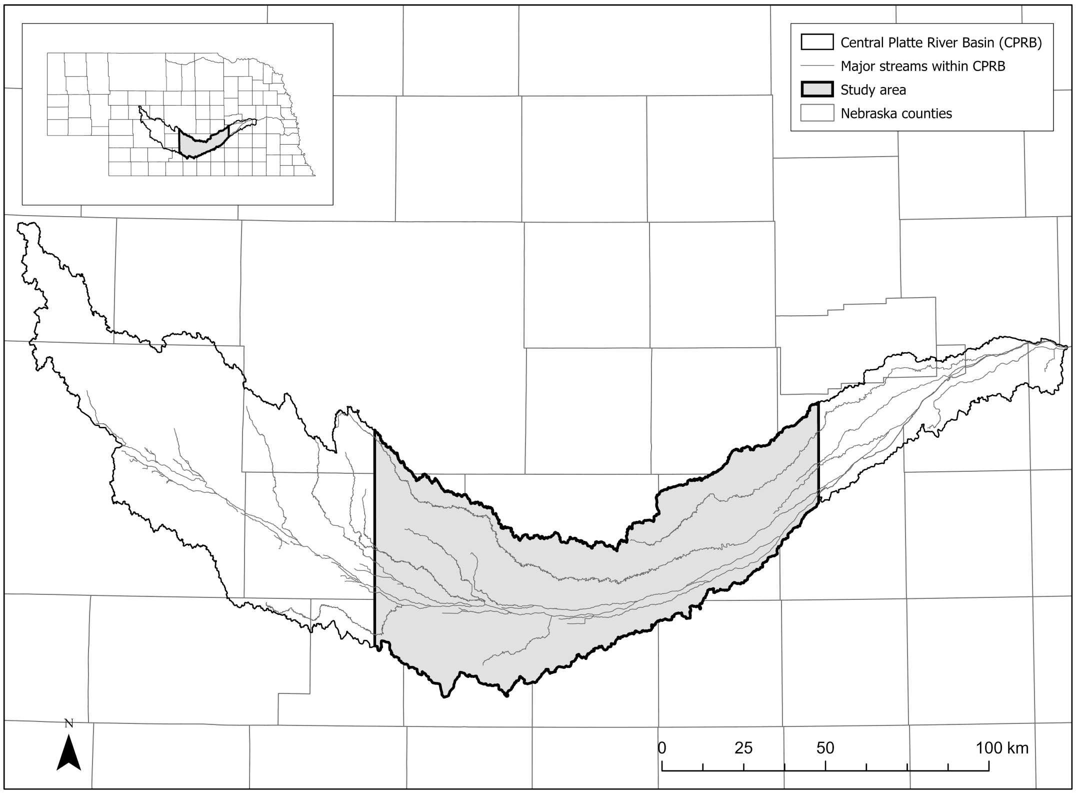

Figure 2.1. Study area encompassing the Big Bend Reach of the Central Platte River in central Nebraska, U.S.A. Figure developed using spatial data from NebraskaMAP County Boundaries, HUC 8, and Major Streams datasets (State of Nebraska, 2020a; 2020b; 2020c).

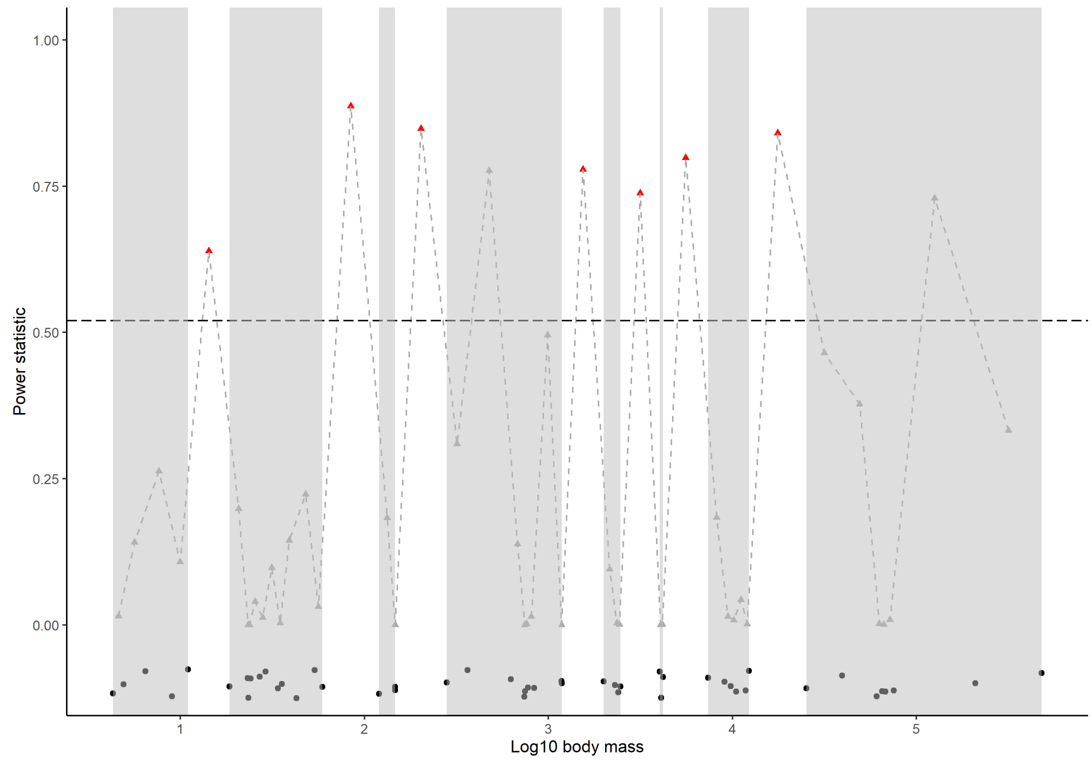

Figure 2.2. Discontinuities and mammal species aggregations in the Central Platte River Valley. The $\log_{10}$ body masses of all mammal species are represented by points (black) along the x-axis. The points are jittered for illustrative purposes. The power statistic (~0.50, n = 49) is shown by the slashed horizontal line (black). All gaps between species are represented by triangles; red triangles indicate discontinuities between species aggregations. Species aggregations (defined as groups of three or more species) are shaded (gray).

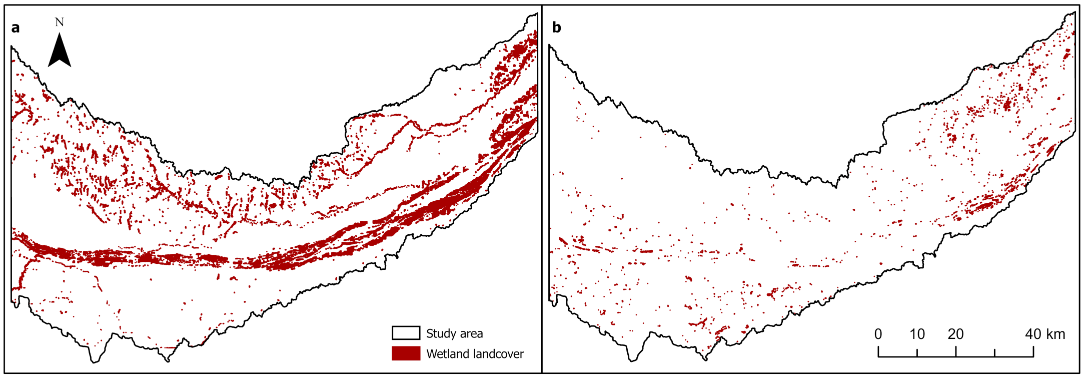

Figure 2.3. Map of (a) wet meadow and (b) emergent marsh landcover in the Central Platte River Valley study area. The study area included 6,330 patches of wet meadow landcover and 1,847 patches of emergent marsh landcover. Figure developed using spatial data from the NebraskaMAP HUC 8 (State of Nebraska, 2020b) and Rainwater Basin Joint Venture Nebraska Land Cover Development (2016 Edition) (Bishop et al., 2020) datasets.

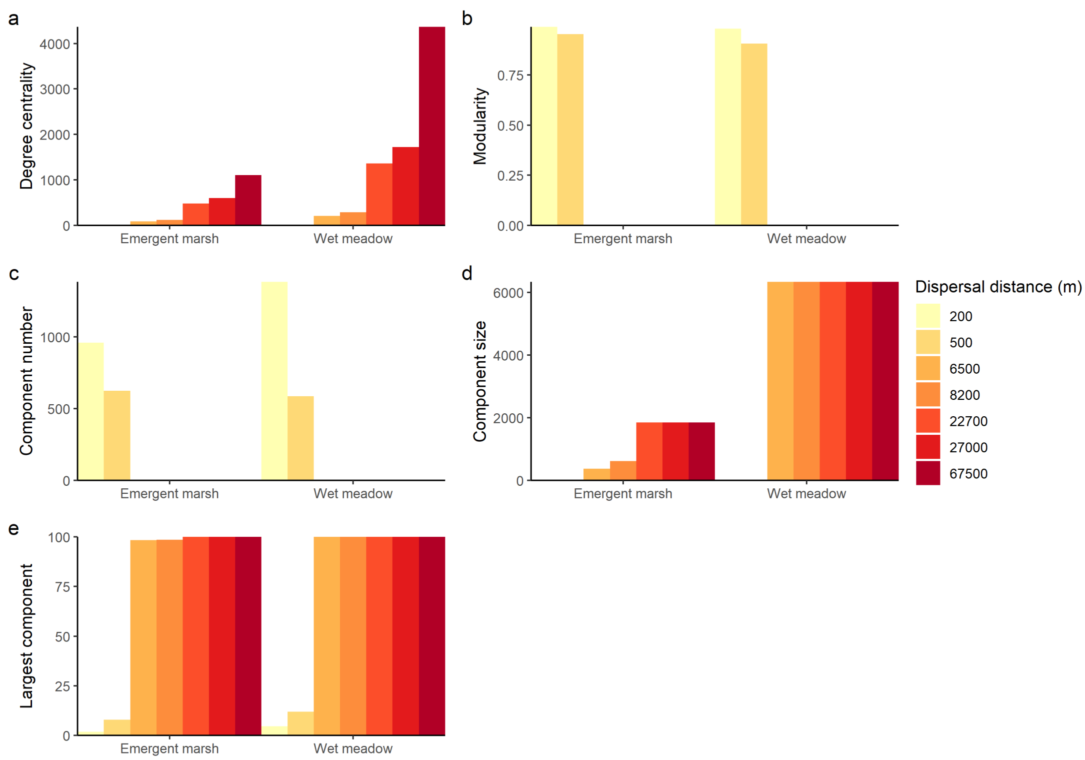

Figure 2.4. Evaluation of wetland connectivity in the Central Platte River Valley using seven dispersal distances. (a) Mean degree centrality, the mean number of direct connections each wetland patch has to other wetland patches. (b) Modularity, the strength of division in the wetland network. (c) Component number, the number of components of wetland patches. Components are groups of connected wetland patches. (d) Component size, the number of wetland patches in the largest component. (e) Largest component, the percentage of wetland patches in the largest component.

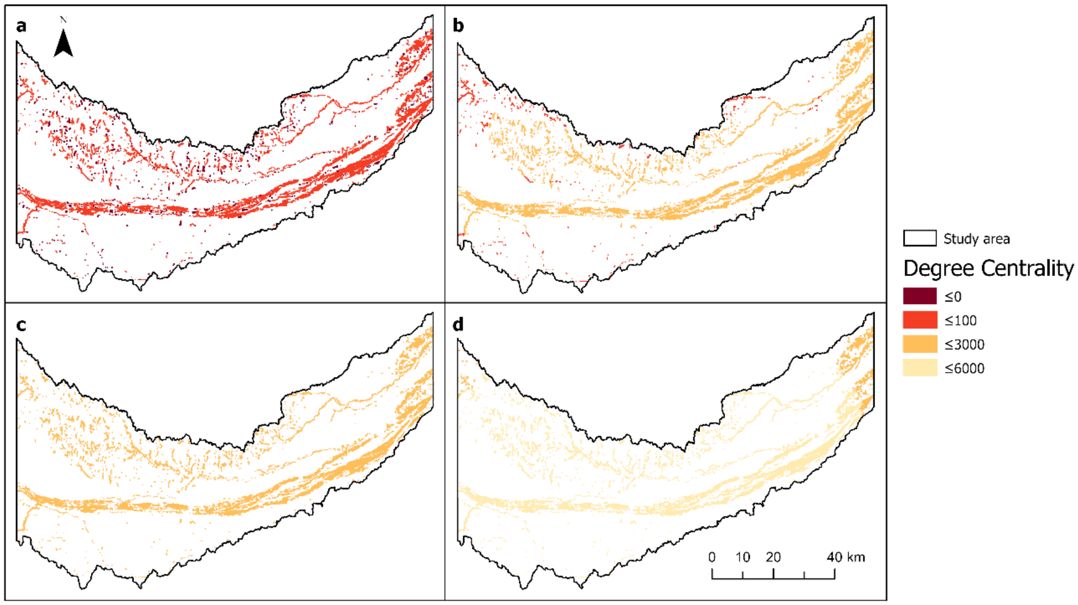

Figure 2.5. Node-level degree centrality of wet meadow patches at (a) 200 m, (b) 6,500 m, (c) 22,700 m, and (d) 67,500 m dispersal distances. Degree centrality describes the number of direct connections each wet meadow node has to other wet meadow nodes at the given dispersal distance. Figure developed using spatial data from the NebraskaMAP HUC 8 (State of Nebraska, 2020b) and Rainwater Basin Joint Venture Nebraska Land Cover Development (2016 Edition) (Bishop et al., 2020) datasets.

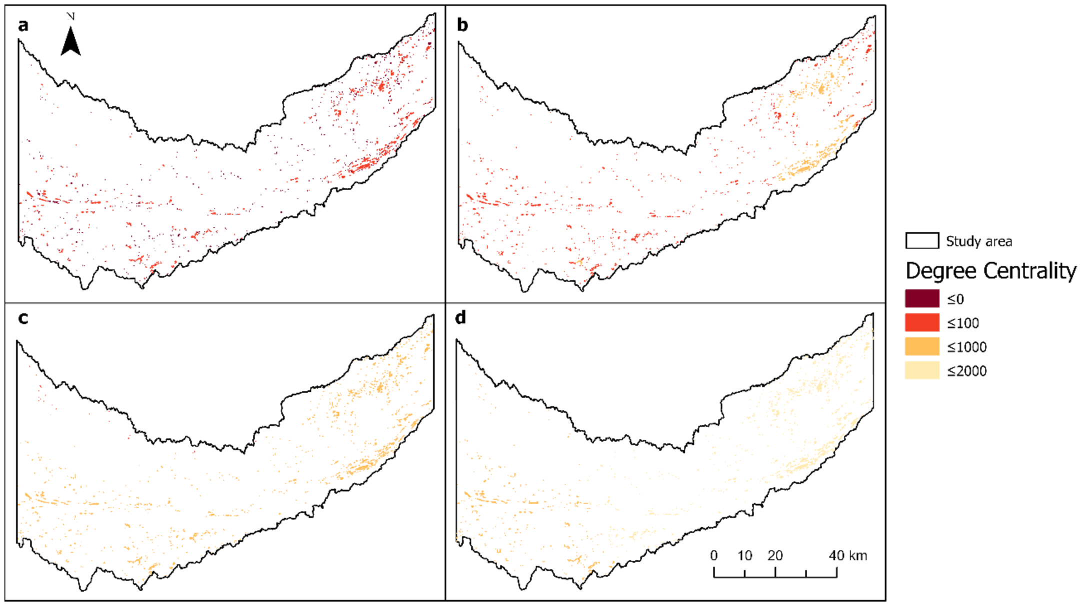

Figure 2.6. Node-level degree centrality of emergent marsh patches at (a) 200 m, (b) 6,500 m, (c) 22,700 m, and (d) 67,500 m scales. Degree centrality describes the number of direct connections each emergent marsh node has to other emergent marsh nodes at the given dispersal distance. Figure developed using spatial data from the NebraskaMAP HUC 8 (State of Nebraska, 2020b) and Rainwater Basin Joint Venture Nebraska Land Cover Development (2016 Edition) (Bishop et al., 2020) datasets.

CHAPTER 3. CROSS-SCALE COMPARISON OF FUNCTIONAL CONNECTIVITY FOR MAMMALS IN AN AGRICULTURALLY DOMINATED LANDSCAPE

Abstract

Functional connectivity is necessary to facilitate species movement between noncontiguous patches of habitat. The use of umbrella species has been examined as a strategy of management for connectivity, premised on the assumption that management for a single species, usually a mammal with large area or specific habitat requirements, will enhance connectivity for co-occurring species. Results of previous examinations of umbrella species in management for connectivity have varied by species, trophic level, and taxa. Few studies have explicitly incorporated scale in examining the use of the umbrella species concept in the context of landscape connectivity. I employed a graph-theoretic network analysis to evaluate the functional connectivity of the Central Platte River Valley (CPRV) of the North American Great Plains for eight species that interact with the landscape at different scales, which I objectively identified using discontinuity analysis. I also examined the overlap in habitat patch importance for connectivity among species with shared habitat usage but interacting with the landscape at different scales. I found that the CPRV is connected for species interacting with the landscape at larger scales and less connected for species interacting with the landscape at smaller scales. However, the spatial distribution and characteristics of the habitat patches most important for connectivity for small and large mammal species differed. The lack of cross-scale overlap in connectivity indicates that the effects of management for connectivity are unlikely to flow up or down across scales and that successful management for

connectivity must be scale-specific, suggesting that the efficacy of umbrella species management for connectivity may be limited.

Introduction

Habitat fragmentation, describing both the loss and reconfiguration of habitat in the landscape (Fahrig, 2003), presents a substantial threat to global biodiversity (Noss, 1991; Haddad et al., 2015). Landscape connectivity, which describes (1) the spatial arrangement of habitat patches and (2) how species move through the landscape (Taylor et al., 1993; With et al., 1997; Tischendorf & Fahrig, 2000), is vital in order for species to be able to move between noncontiguous patches of habitat; access necessary resources such as food, habitat, and refuge; and for migration and dispersal (Noss, 1991; Taylor et al., 1993; Rudnick et al., 2012). In addition, an intermediate degree of connectivity is associated with greater spatial resilience of a landscape, as it theoretically balances the benefits (e.g., rescue effect) and risks (e.g., disease spread) of connectivity (Walker & Salt, 2006; Cumming, 2011). However, species interacting with the landscape at different scales may experience different levels of connectivity. For example, species with greater dispersal capability may be better able to move between spatially distant habitat patches in the landscape, whereas dispersal-limited species can be restricted to certain sets of well-connected patches that may have insufficient resources to support them (Keitt et al., 1997; Bunn et al., 2000; Fahrig, 2003; Haddad et al., 2015).

To confront the rapid decline of species populations on a global scale with limited time and resources (Cardinale et al., 2012; Brondizio et al., 2019), surrogate-species approaches to management that utilize a single species to represent a broader group of species in the ecosystem have garnered interest as a method to efficiently maintain biodiversity (Simberloff, 1998; Wiens et al., 2008), including in the context of managing for landscape connectivity (Meurant et al., 2018). One such strategy is the use of umbrella species, which are frequently but not always (e.g., Fleury et al., 1998) mammal species with large area or specific habitat requirements (Noss, 1990; Caro, 2003; Roberge & Angelstam, 2004; Branton & Richardson, 2010). This approach is premised on the assumption that conservation of the umbrella species will indirectly benefit many other co-occurring species due to the unique set of characteristics of the umbrella species (Noss, 1990; Caro, 2003; Roberge & Angelstem, 2004; Caro, 2010). For example, using a common umbrella species such as a large mammal in management for landscape connectivity assumes that a landscape that is connected for the umbrella species will also be connected for other co-occurring species (Roberge & Angelstam, 2004) because connectivity for smaller species is nested within connectivity for larger species. However, uncertainty remains regarding the efficacy of umbrella species management in this context, especially regarding the benefits provided by umbrella species to species across taxa and for species interacting with the landscape at different scales (Roberge & Angelstam, 2004; Branton & Richardson, 2010).

Several studies have identified overlap in the movement corridors of umbrella species and co-occurring species (Epps et al., 2011; Brodie et al., 2015; Wang et al., 2018; Brennan et al., 2020), suggesting the potential value of an umbrella species approach to conservation. However, the level of benefit to connectivity conferred by umbrella species has been found to vary depending on species characteristics such as trophic level and taxa (Breckheimer et al., 2014; Brodie et al., 2015). For example, multiple studies suggest that the traditional umbrella species, or large mammals with large area requirements, are unreliable umbrellas for guiding management for connectivity for co-occurring species (Beier et al., 2009; Cushman & Landguth, 2012; Brodie et al., 2015; Meurant et al., 2018; Brennan et al., 2020). Furthermore, few studies have explicitly examined the use of umbrella species conservation to confer benefit to species of smaller body size and that interact with the landscape at smaller scales, and those that have suggest that the efficacy of large mammals as umbrella species for small mammals is limited. For example, Minor and Lookingbill (2010) found substantial differences in the connectivity of protected area networks for small and large mammal species and that the relationship between connectivity for large mammal species and small mammal species was insignificant, suggesting that management for connectivity for large mammal species will not reliably confer benefit to small mammal species. Similarly, Beier et al. (2009) suggested that large carnivorous mammals are ineffective umbrella species for smaller mammal species in the connectivity of wildlife corridors. Additionally, little information exists regarding the utility of small mammal species as connectivity umbrellas for large mammal species, although data suggest that in some cases small or intermediate mammals may be more effective connectivity umbrellas than large mammal species (Cushman & Landguth, 2010). Further research is necessary to better understand the utility of umbrella species approaches for managing species that interact with their environment at different scales than the umbrella species. If there is evidence that connectivity for larger species is predictive of connectivity for smaller species, or the reverse, then management might expect the effects of management for connectivity to flow up or down across scales. However, if there is no discernable cross-scale pattern, then successful assessment of and management for connectivity for species at each scale domain will differ.

In this study, I evaluate the functional connectivity of the Central Platte River Valley (CPRV) of Nebraska, U.S.A., a highly altered and agriculturally dominated landscape, for mammal species interacting with the landscape at different scales. I first utilize a mammalian body mass discontinuity analysis to objectively identify aggregations of mammal species representing different scale domains in the CPRV, including species that interact with the landscape at smaller scales and species that interact with the landscape at larger scales. I next apply a graph-theoretic network analysis approach to evaluate connectivity for mammal species interacting with the landscape at different scales and utilizing different habitat networks, including identifying the habitat patches of greatest importance for connectivity in the network. Finally, I apply the results to (1) examination of the efficacy of umbrella species management for connectivity across ecological scales, (2) discussion of the factors contributing to scale-specific differences in landscape connectivity for mammal species in the CPRV, and (3) recommendations for multispecies and multiscale management in the CPRV.

Methods

Study area and landcover data

Located in the grassland-dominated North American Great Plains, the Central Platte River was historically a braided river characterized by multiple channels, shifting sandbars, and little woodland vegetation and structured by a disturbance regime of grazing, fire, and scouring river flows (Johnson, 1994; National Research Council, 2005;

Uden et al., 2021). However, the once non-stationary Central Platte has undergone substantial hydrological and geomorphological change during the 20th century, largely due to the construction of the Kingsley Dam on the North Platte River in 1941, which controls water flows in the downstream Central Platte River, and decades of extensive water diversion for irrigation purposes (National Research Council, 2005; USBOR & USFWS, 2006; Birgé et al., 2014). These hydrological changes have created a more stationary system, and in combination with the conversion of land to agricultural production, have resulted in dramatic changes to riparian vegetation in the CPRV (National Research Council, 2005). Notably, the reduction in frequency of scouring flows in the Central Platte has facilitated the expansion of woodland vegetation along the river channel, reducing the habitat available for species such as the interior least tern (*Sterna antillarum athalassos*), piping plover (*Charadrius melodus*), Sandhill crane (*Antigone canadensis*), and whooping crane (*Grus americana*) that rely on open, sparsely vegetated riparian areas for roosting and nesting (Faanes, 1983; Faanes et al., 1992; Kirsch, 1996; Currier, 1997; National Research Council, 2005). Furthermore, the extensive conversion of native grasslands and wetlands to cropland in the CPRV has resulted in the reduction and fragmentation of habitat for grassland species in the region (USFWS, 1981; Wright & Wimberly, 2013). For example, the area encompasses important but highly fragmented habitat for several mammal species of concern in Nebraska including the plains pocket mouse (*Perognathus flavescens*) and long-tailed weasel (*Mustela frenata*) (Schneider et al., 2018). Management efforts by governmental agencies and conservation organizations have worked to maintain and restore wet meadow and sparsely vegetated habitats to support the aforementioned species (e.g., National Research Council, 2005). Today, the management of the CPRV involves balancing tradeoffs between providing habitat for endangered and other species and meeting human demands for irrigation and other water uses (National Research Council, 2005; Smith, 2011; USBOR, 2018).

The 1997 Federal Energy Regulatory Commission (FERC) relicensing of the Kingsley Dam located upriver from the CPRV spurred negotiations focused on addressing concerns related to the conservation of threatened and endangered species on the Central Platte River while preserving other water uses such as irrigation (Freeman, 2003; Birgé et al., 2014). This process led to the development of the Platte River Recovery Implementation Program (PRRIP) in 2007 (Smith, 2011). The PRRIP focuses on the management of a 145 km stretch of the Central Platte River called the Big Bend Reach located between Lexington, NE and Chapman, NE with dual objectives focused on increased streamflow and habitat restoration and protection (Smith, 2011). My study area (5,868 km^2) encompassed the Platte River Basin, extending east and west to the bounds of the Big Bend Reach such that my analysis encompassed the PRRIP associated habitat area and surrounding cropland, grassland, and developed areas (Fig. 3.1). Landcover data for the study area in raster format at 30 m resolution were provided by the Rainwater Basin Join Venture (Bishop et al., 2020).

Identifying mammal species

Discontinuity theory is a method to objectively identify scales in both ecological and non-ecological systems (Allen & Holling 2008; Nash et al. 2014; Sundstrom et al. 2014; Angeler et al. 2016). In accordance with previous applications of discontinuity theory seeking to examine ecosystem structure (e.g., Holling, 1992; Allen et al., 1999; Wardwell & Allen, 2009), I compiled a list of all species of a single taxonomic group, mammals, in the CPRV. I used *Mammals of Nebraska* (Genoways et al., 2008) and additional published sources to determine species ranges (Appendix A). Extirpated and extinct species (e.g., black bear [*Ursus americanus*]) previously present in the ecosystem were also included. Peripheral species, including species with ranges that have recently expanded into the study area but are still rare or transient (e.g., nine-banded armadillo [*Dasypus novemcinctus*]) and transient species, such as native species that have been recorded in the study area but are not known to have a breeding population, were not included. Body mass data were collected from published sources, primarily the *CRC Handbook of Mammalian Body Masses* (Silva & Downing, 1995; Appendix A). From the available body mass data, data with the geographic proximity closest to the study area were selected for each species. Male and female body mass data were averaged when both were available for a given species. If only male or female data were available, the data for the available sex were used.

Discontinuity analysis

Applying discontinuity analysis to body mass distributions involves examining the differences between rank-ordered species body masses. Accordingly, I ranked all mammalian focal species (n=49) in ascending order of body mass. I analyzed the body mass distribution by comparing the distribution of the actual body mass data to a null distribution developed using a continuous unimodal kernel distribution of the log-transformed body mass data (Barichievy et al., 2018). Discontinuities were identified as any gaps between successive species body masses that significantly exceeded the gaps created by the null distribution using a consistent level of statistical power. Species aggregations, or groups of species representing the scale domains identified in the system, were identified as any group of three or more successive species that were not separated by a discontinuity. I disregarded discontinuities that resulted in aggregations of fewer than three species (Holling, 1992).

Mammal dispersal

Mammal species body mass is allometric to dispersal distance (Sutherland et al., 2000; Jenkins et al., 2007). I obtained dispersal data for the mammal species included in the body mass discontinuity analysis (Appendix A). For each mammal species, I selected natal or adult dispersal data from published sources using the following order of preference: 1) measured as the mean distance from the center or edge of the natal range to the center or edge of the adult home range; 2) measured as the mean distance between recaptures, capture and death, or capture and loss of tracking; 3) measured as the maximum distance from the center or edge of the natal range to the center or edge of the adult home range; 4) measured as the maximum distance between recaptures, capture and death, or capture and loss of tracking; 5) measured based on home range size; 6) measured as the cumulative distance moved over a given number of days; 7) other dispersal measurements. If multiple sources with similar methods were available for a given species, I preferentially selected the data with the closest geographic proximity to the study area, with the largest sample size, or natal dispersal measurements. I selected dispersal measurements that were either for male and female individuals combined or, if unavailable, only for female individuals. Although I utilized multiple types of dispersal measurements due to the limited availability of mammal dispersal data, the expected trend of increasing dispersal distance with greater body mass size is present in the selected data (Sutherland et al., 2000; Jenkins et al., 2007).

Selecting focal species and identifying habitat

I selected one omnivorous mammal species from each species aggregation for a network analysis of connectivity. As such, the species I selected represent species that interact with the landscape at both larger scales, or traditional umbrella species, and smaller scales. I only selected species with a dispersal distance greater than the grain size of landcover data, i.e., 30 m. If multiple eligible omnivorous species were present in a given aggregation, I preferentially selected species with dispersal data collected in the closest geographic proximity to the study area, with the largest sample size, or using natal dispersal measurements. I then identified the habitat for each selected species using published sources, primarily *Mammals of the Northern Great Plains* (Jones et al., 1983) and the *National Audubon Society Field Guide of North American Mammals* (Whitaker, 1997), and then identified corresponding landcover types in the Nebraska Land Cover Development (2016 Edition) dataset (Appendix B; Bishop et al., 2020).

Evaluating connectivity

I applied a graph-theoretic network analysis approach to evaluate the connectivity of the CPRV for omnivorous mammal species at multiple objectively identified scales (Bunn et al., 2000; Urban & Keitt, 2001; Calabrese & Fagan, 2004; Minor & Urban, 2008). Using ArcGIS Pro 2.8.3 (ESRI, 2021), I converted the 30 m resolution raster landcover data to vector format. I identified all patches (polygons) of habitat in the study area for each selected species and used the Dissolve Boundaries function to combine all habitat patches of different landcover types but sharing common boundaries. To ensure that polygons sharing a common boundary at a vertex point alone were combined, I added a 0.01-m buffer to all polygons. This small buffer ensured that the Dissolve

Boundaries tool ran correctly but did not influence the connectivity analysis. For example, for a species whose habitat corresponds with the mixedgrass prairie and wet meadow landcover types, any patches of mixedgrass prairie and wet meadow that shared a common boundary were merged to create a larger contiguous habitat patch (Table 3.1). I then used the Generate Near Table function to calculate the Euclidian edge-to-edge distances between all habitat patches within the selected species dispersal distance.

Using R 4.0.5 (R Core Team, 2021), I developed and analyzed the habitat network for each selected species using functions in the packages tidyverse (Wickham et al., 2019), igraph (Csardi & Nepusz, 2006), and rgdal (Bivand et al., 2021). Each network was composed of nodes, which were patches of habitat, and edges, which were the edge-to-edge connections between nodes within the species' dispersal distance from each other. For each network, I evaluated landscape (i.e., network-level) connectivity using mean degree centrality, characteristics of network components, and modularity. Mean degree centrality provides the mean number of edges adjoining each node in the network, and it describes the degree to which nodes in the network are connected to other neighboring nodes (Minor & Urban, 2008; Uden et al., 2014). A greater number of connections among nodes in the network suggests a greater potential for species to move between patches of habitat. I evaluated characteristics of the components, or clusters of connected nodes, in each network by calculating the number of components in the network, the mean number of nodes in each component, the number of nodes in the largest component, and the percent of nodes in the largest component (Minor & Urban, 2008; Uden et al., 2014). In general, a network comprised of many small, separate clusters of nodes indicates that patches of habitat are more disconnected for species moving across the landscape, whereas a network with fewer, larger clusters of nodes suggests that the landscape is more connected because species can move among a greater portion of the habitat patches present (Uden et al., 2014). A highly connected network may consist of a single cluster of nodes, indicating that any habitat patch can be accessed directly or indirectly from any other patch in the network (Uden et al., 2014). Modularity measures the extent to which there are highly connected subgroups of nodes with few connections between subgroups in the network (Newman, 2006; Uden et al., 2014). For example, a landscape with an intermediate degree of both modularity and connectivity may be more resilient because it receives the benefits of connectivity while minimizing its risks such as by facilitating species movement while also limiting the spread of disturbances such as disease (Walker & Salt, 2006; Webb & Bodin, 2008; Cumming, 2011).

In order to evaluate cross-scale overlap in functional connectivity, I identified two groups of species from among the previously selected species: (1) red fox and masked shrew and (2) North American deer mouse, thirteen-lined ground squirrel, and swift fox (Table 3.1). I utilized these species groupings because the species in each group use the same habitat in the study area but interact with the landscape at different scales. The other three species in the initial analysis (Table 3.1) did not share habitat usage with any other selected species and were thus omitted from the cross-scale analysis. For the selected species, I calculated the importance of each node in the respective network by sequentially removing each node, recalculating the mean degree centrality of the network, and replacing the node before repeating the process for the next node (Keitt et al., 1997; Urban & Keitt, 2001; Uden et al., 2014). A node with a relatively high importance score represents a patch of habitat that is more important for network-level connectivity and plays a greater role in facilitating species movement through the landscape. I normalized the importance scores to a 0-1 range and compared the spatial distribution of patch importance and other characteristics of the most important patches for species using the same habitat network but interacting with the landscape at different scales.

Results

Species and scale identification

In accordance with previous applications of discontinuity theory seeking to examine ecosystem structure (e.g., Holling, 1992; Allen et al. 1999; Wardwell & Allen, 2009), I compiled a list of all species of a single taxonomic group, mammals, in the CPRV (Appendix A). The body mass distribution of the mammal species was discontinuous. I identified eight aggregations of mammals in the data separated by seven discontinuities (Fig. 3.2). The number of mammal species in each aggregation ranged from three species to eleven species. Dispersal data were not available for some species, primarily small mammals (Appendix A). For the omnivorous mammal species selected from each aggregation (Fig. 3.2), dispersal distances ranged from a minimum of 53.1 m to a maximum of 53,200 m (Table 3.1).

Functional connectivity

Differences in the habitat networks for species that utilize different landcover types were evident from a comparison of the number of habitat patches and the total habitat area of the networks (Table 3.1). The two species that exclusively utilize forest landcover, black bear, which is presently extirpated from Nebraska but historically utilized riparian woodland vegetation in the CPRV, and eastern fox squirrel, presented notably lower total habitat area within the study area (Table 3.1). For example, the habitat network for black bear included roughly a tenth of the habitat area of the other species analyzed, excluding the eastern fox squirrel, and its habitat network contained only 7,152 patches of habitat versus more than 13,000 patches for the other species (Table 3.1). The habitat networks for all other species included at least 1,000 km^2 of habitat area (Table 3.1).

Furthermore, I identified differences in functional connectivity for species that interact with the landscape at different scales in the CPRV through a comparison of network connectivity metrics (Fig. 3.3). Connectivity tended to be greater for species at larger scales and with greater dispersal distances. For example, the mean degree centralities of the habitat networks belonging to the mammal species at the four smallest scales (i.e., masked shrew, North American deer mouse, thirteen-lined ground squirrel, eastern fox squirrel) were notably lower than those belonging to the species at the four largest scales (i.e., swift fox, red fox, coyote, black bear) (Fig. 3.3). Similarly, the habitat networks for the species at the three smallest scales were highly clustered with modularity scores around or above 0.75 and containing many small components, in contrast to the species at larger scales that all presented modularity scares of zero, indicating that all nodes in the networks belonged to one large component (Fig. 3.3). However, notable exceptions to the broader pattern of increasing connectivity with scale existed within the set of mammal species I analyzed. For example, the habitat network for the eastern fox squirrel, which interacts with the landscape at an intermediate scale, presented a low mean degree centrality, along with a low modularity score and a small number of relatively large components (Fig. 3.3). Although the habitat network for the black bear consisted of a single large component, it similarly presented a relatively low mean degree centrality score and a relatively low number of habitat patches in the network (Fig. 3.3).

Multiscale connectivity

I also examined the spatial distribution and characteristics of patches important for connectivity using two subsets of the species previously selected for analysis that use the same habitat network, respectively: (1) masked shrew and red fox, and (2) North American deer mouse, thirteen-lined ground squirrel, and swift fox. For both subsets of species, the spatial distribution of important patches in the habitat network differed among species that interact with the landscape at larger scales, representing traditional umbrella species, and smaller scales. For example, the most important patches in the masked shrew network were located in the riparian areas following the Central Platte River horizontally across the study area, whereas there was no clear pattern in the spatial distribution of the most important habitat patches for the red fox (Fig. 3.4). Furthermore, an examination of patch importance identified a small number of relatively important patches and many relatively unimportant patches for the masked shrew, contrasting with the habitat network for the red fox which included many habitat patches of relatively intermediate importance (Fig. 3.5). Similar patterns were evident in the distribution of patches important for connectivity for the three-species subset. The habitat networks for the North American deer mouse and thirteen-lined ground squirrel included many relatively unimportant patches and a smaller number of patches of relatively high importance, primarily located in one area in the northwest of the study area (Fig. 3.6; Fig.

3.7). In contrast, patch importance was more evenly distributed across patches in the swift fox habitat network, although there were two groups of higher importance patches evident in the northern half of the study area (Fig. 3.6; Fig. 3.7).

I examined the relationship between patch importance for connectivity and patch size for the mammal species interacting with the landscape at smaller and larger scales. For the three shorter dispersing species, the mean area for habitat patches in the top 10% (i.e., 10^{th} decile) of importance was at least eight times larger than the mean area for patches in any other decile of importance (Fig. 3.8). In contrast, for the two species interacting with the landscape at larger scales, red fox and swift fox, I found that the mean area for habitat patches in the top 10% (i.e., 10^{th} decile) of importance was between 1.5 and 2.5 times larger than the mean area for patches in any of the lower deciles of importance (Fig. 3.8). A Spearman's rank correlation showed weak but significant positive correlations between patch area and patch importance for connectivity for the three shorter dispersing species (masked shrew: $r(13416) = .110$, $p < .001$; North American deer mouse: $r(14915) = .109$, $p < .001$; thirteen-lined ground squirrel: $r(14915) = .189$, $p < .001$). For the two longer dispersing species, a Spearman's rank correlation similarly showed a weak positive or weak negative, yet significant relationship between patch area and patch importance for connectivity (red fox: $r(13416) = -.034$, $p < .001$; swift fox: $r(14915) = .053$, $p < .001$).

I found little overlap in the most important patches for connectivity for mammal species using the same habitat network but interacting with the landscape at different scales. Examining the masked shrew and red fox, only 191, or 14% of habitat patches in the top decile of importance for each species, overlapped (Fig. 3.9). In other words, the probability of a given habitat patch being located in the top 10% of importance for both species was 0.142. Similarly, for the subset of species including North American deer mouse, thirteen-lined ground squirrel, and swift fox, only 178 habitat patches, or 12% of patches, were in the top decile of importance for all three species (Fig. 3.9). The probability of a patch being present in the top decile of patch importance for North American deer mouse and swift fox was 0.199 and for thirteen-lined ground squirrel and swift fox was 0.236. The probability of patch being in the top decile of patch importance for all three species was 0.119. For both species sets, the most important patches for species interacting with the landscape at smaller and larger scales did not reach maximum possible overlap, or 100% overlap, until all patches were included in the comparison (Fig. 3.9). The set of species containing only two species maintained a greater degree of overlap across all node importance percentages than the set of species containing three species (Fig. 3.9).

Discussion

Using a graph-theoretic network analysis approach, I found limited evidence of cross-scale overlap of functional connectivity in the landscape of the CPRV, a highly altered and, in many ways, increasingly stationary system that is confronting management challenges associated with supporting diverse ecological communities while also meeting human demands on the system (Smith, 2011; Nemec et al., 2014). Ultimately, my results suggest that an umbrella species approach to management for connectivity would have limited efficacy in enhancing the connectivity of the CPRV for co-occurring species at different scales. In my analysis, functional connectivity of the landscape for species interacting with the landscape at larger scales, i.e., traditional umbrella species, did not predict connectivity for small mammals using the same habitat network (Fig. 3.2). These findings align with previous examinations of umbrella species management for connectivity that included species with differing dispersal capability, including Minor and Lookingbill (2010) and Beier et al. (2009), who both found that connectivity for traditional umbrella species, large mammals or large carnivores, did not accurately predict connectivity for small mammals. The landscape of the CPRV was relatively unconnected for the small mammals examined (Fig. 3.2), so it remains unclear if a relatively high degree of connectivity for small mammals is associated with a similarly high degree of connectivity for large mammals. To further understand the aforementioned relationship, examining connectivity for small and large mammals in a landscape where connectivity for small mammals is high would be a valuable. Furthermore, in a cross-scale comparison of connectivity for species utilizing the same habitat network, the habitat patches most important for connectivity for mammal species interacting with the landscape at small and large scales exhibited little overlap (Fig. 3.9). These results suggest that the protection of the most important habitat patches for large mammals would not confer substantial benefit across scales to smaller mammal species, or vice versa, because species interacting with the landscape at different scales rely on a different set of habitat patches to move across the landscape.

Multiple factors contribute to the functional connectivity of a landscape for a species, including the distances between patches of noncontiguous habitat, the presence of physical barriers in the landscape, other physical characteristics of the landscape such as hydrology and topography, and the biology and behavior of the species related to dispersal and habitat preference (Henein & Merriam, 1990; Taylor et al., 1993; With &

Crist, 1995; Rudnick et al., 2012). I examined the influence of species dispersal capability, habitat configuration, and habitat availability on connectivity and identified differences in the habitat networks and the functional connectivity of the landscape for mammal species at all objectively defined scale domains of the CPRV landscape. I found that the CPRV was relatively connected for omnivorous mammal species with greater dispersal capabilities and substantial habitat availabilities such as the swift fox, red fox, and coyote (Table 3.1; Fig. 3.2). For these species, all habitat patches in the networks I developed were part of one large component, or group of interconnected nodes (Fig. 3.2), indicating that from any given patch of habitat in the landscape, the species could access all other habitat patches. Accordingly, management should be aware that landscape connectivity for these species is not limited by dispersal or habitat availability under the current distribution of habitat patches in the CPRV. However, the connectivity of the landscape for other species with substantial dispersal capability but specific habitat requirements such as the black bear, which is extirpated from the study area, was limited by the lack of available habitat in the CPRV (Table 3.1; Fig. 3.2). My results suggest that although connectivity for some species is not dispersal-limited, it may be limited by other factors such as habitat availability, which should be accounted for in management objectives.

For species interacting with the landscape at smaller scales, I found that each habitat patch had relatively few adjacent patches (i.e., patches connected by a network edge; indicated by the low mean degree centrality), a relatively large number of components, and relatively high modularity scores compared to larger-scale species (Fig. 3.2). Although the habitat networks for species such as the masked shrew and North

American deer mouse contained a comparable number of habitat patches as the habitat networks for species with greater dispersal capability (e.g., red fox, swift fox), fewer of these habitat patches were functionally connected for these short-dispersing species, suggesting that these species are more restricted in their movements across the CPRV landscape. As such, these smaller mammal species would benefit most from management to increase the connectivity of the landscape within the CPRV, in order to support population viability within the study area. For example, management could have a conservation of connectivity objective for the linear corridor of relatively high-importance patches along the Central Platte, whereas in other areas, management could focus on building connections between patches at a smaller scale. Interestingly, species with limited available habitat but intermediate dispersal capability experience a relatively connected landscape. The habitat network for the eastern fox squirrel, a species with roughly a tenth of the habitat area as the other species examined (excluding black bear), consisted of only three components of interconnected nodes including one large component that encompassed 99% of habitat patches, suggesting a 3,300 m dispersal distance is sufficient for moving amongst nonadjacent habitat patches in the landscape (Table 3.1; Fig. 3.2). Cumulatively, my analysis applied a multiscale assessment of functional connectivity that accounted for all scales at which mammals interact with the landscape in the present and historically, highlighting the differences in connectivity for mammal species interacting with a landscape at different scales and that are differently constrained by habitat use and availability, findings that provide additional support for the species-specific nature of functional connectivity (Tischendorf & Fahrig, 2000).

I also identified differences in the spatial distribution and characteristics of the habitat patches most important for connectivity among the species habitat networks in the CPRV. Only about 10% of the habitat patches in the top 10% of importance overlapped for the two subsets of species I examined (Fig. 3.9), which can be partially attributed to the greater reliance of shorter dispersing species than longer dispersing species on large, contiguous patches of habitat. The relatively large size and spatial clustering of the most important patches for the shorter dispersing species I examined suggests that it may be valuable for management to focus on maintaining corridors of relatively high-importance habitat patches that facilitate the movement of those species across the landscape. For example, the most important patches for the connectivity of the masked shrew habitat network were notably grouped along the Central Platte River, indicating that these spatially proximate patches may act as a corridor for the movement of the masked shrew across the landscape and that management for connectivity focused on conserving these patches may be beneficial (Fig. 3.3).

In contrast, I did not identify clear patterns in the spatial distribution of important patches for connectivity for species with greater dispersal capability such as the red fox, suggesting that they likely rely less on clusters of high-importance habitat patches and more on their ability to move across the landscape matrix between spatially distant patches of habitat. These results are consistent with existing studies of connectivity for species with different movement capabilities suggesting that the physical contiguity or close proximity is more important for the abundance of small species with limited movement capability (Mortelliti et al., 2010) and that shorter-dispersing species are primarily confined to large, contiguous patches of habitat and may not benefit from stepping stone patches to the same degree as farther dispersing species (Herrera et al., 2017). The absence of habitat patches with relatively high importance in the habitat networks for species with greater dispersal capability (Fig. 3.6; Fig. 3.7) also suggests that the removal of any given patch is unlikely to substantially decrease the connectivity of the landscape for these species. For larger and longer dispersing species that experience relatively high connectivity within the CPRV, management focused on maintaining the connectivity of the CPRV with other more expansive habitat areas may be most beneficial because the CPRV in isolation would not provide sufficient area to support a viable population. Given the reliance of dispersal-limited species on a small number of patches for connectivity, in addition to the relatively low level of connectivity of their habitat networks, I assert that management for connectivity for species interacting with the landscape at smaller scales, specifically species with concerns about population viability or species metapopulations, should be prioritized within the CPRV.

In sum, I demonstrate how functional connectivity varies for species interacting with the landscape of the CPRV at different scales. Connectivity for longer dispersing species did not predict connectivity for shorter dispersers, and the habitat patches most important for connectivity for species interacting with the landscape at different scales presented little overlap, suggesting that the effects of management for connectivity are unlikely to flow up or down across scales. As such, management intended to enhance connectivity should be scale-specific in order to maximize benefit to the intended species, and an umbrella species approach to managing for connectivity in the CPRV would provide limited benefit for species across scales. However, landscape connectivity can have benefits and costs. A high degree of connectivity may have negative consequences such as the greater spread of disturbances such as disease in species populations, yet it may also have positive effects such as facilitating species' access to resources and the rescue effect (Holt, 1992; Cumming, 2011). If increasing the degree of landscape connectivity is a management goal, the relatively high level of functional connectivity and the absence of relatively highly important patches for mammals interacting with the landscape at a large scale suggest that conservation efforts within the CPRV should focus on increasing connectivity for the species at smaller scales experiencing a less connected landscape. More specifically, the results of my analysis point to the importance of prioritizing adjacent or contiguous areas of habitat for species interacting with the landscape at smaller scales, including the corridor of patches with relatively high importance for connectivity for smaller species currently located along the Central Platte River. Notably, the aforementioned approach to management differs from the current management regime of the CPRV under PRRIP, which focuses on habitat conservation for volant species with substantial dispersal capabilities (Smith, 2011). To ensure the future functional connectivity of the CPRV for species interacting with the landscape at multiple scales, I recommend further prioritizing habitat conservation for species interacting with the landscape at smaller scales.

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Tables and Figures

Table 3.1. Omnivorous mammal species and associated habitat network information. Total habitat area was rounded to the nearest hundredth. Number of habitat patches represents the number of patches after habitat patches of different landcover types that shared common boundaries were merged.

Scale	Species	Dispersal distance (m)	Source	Total habitat area (km^2)	Number of habitat patches
1	Masked shrew (*Sorex cinereus*)	260.5	Oleinichenko et al. (2020)	1,528	13,418
2	North American deer mouse (*Peromyscus maniculatus*)	306.3	Rehmeier et al (2004)	1,054	14,917
3	Thirteen-lined ground squirrel (*Ictidomys tridecemlineatus*)	53.1	Rongstad (1965)	1,054	14,917
4	Eastern fox squirrel (*Sciurus niger*)	3,300	Wooding (1997)	171	10,041
5	Swift fox (*Vulpes velox*)	13,100	Nicholson et al (2007)	1,054	14,917
6	Red fox (*Vulpes vulpes*)	44,800	Gosselink et al. (2010)	1,528	13,418
7	Coyote (*Canis latrans*)	53,200	Hibler (1977)	1,536	13,390
8	Black bear (*Ursus americanus*)	40,000	Costello (2010)	131	7,152

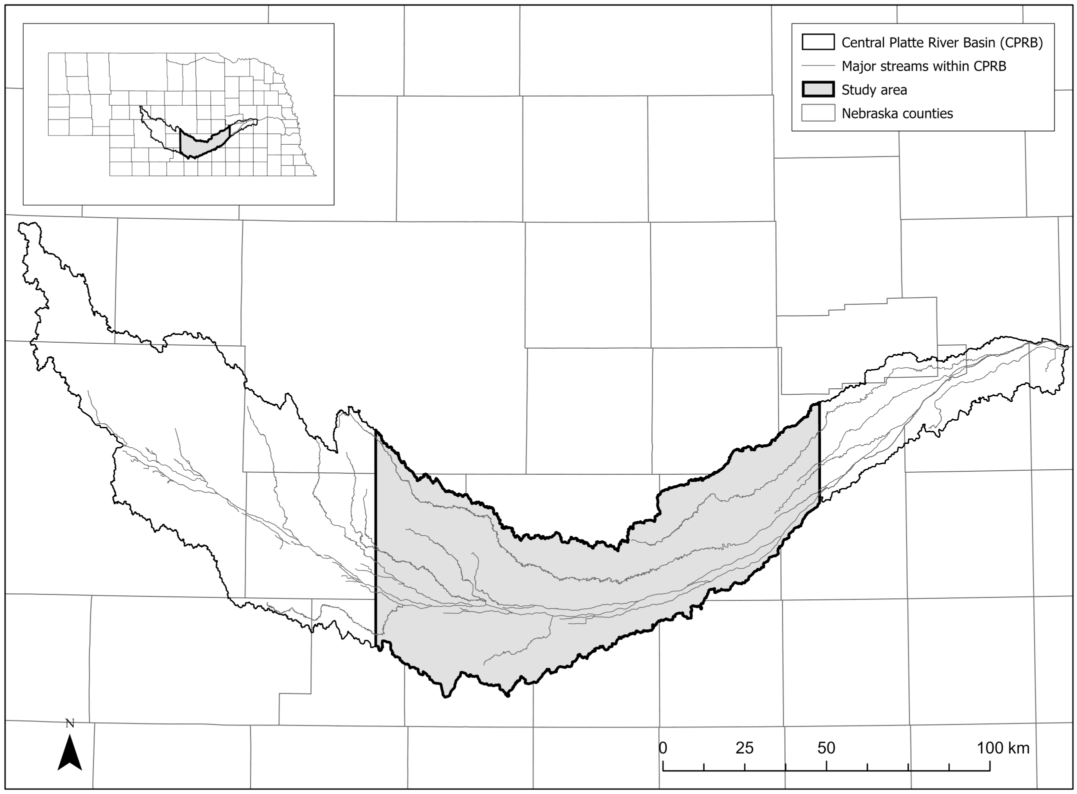

Figure 3.1. Study area encompassing the Big Bend Reach of the Central Platte River in Nebraska, U.S.A. Figure developed using spatial data from NebraskaMAP County Boundaries, HUC 8, and Major Streams datasets (State of Nebraska, 2020a; 2020b; 2020c).

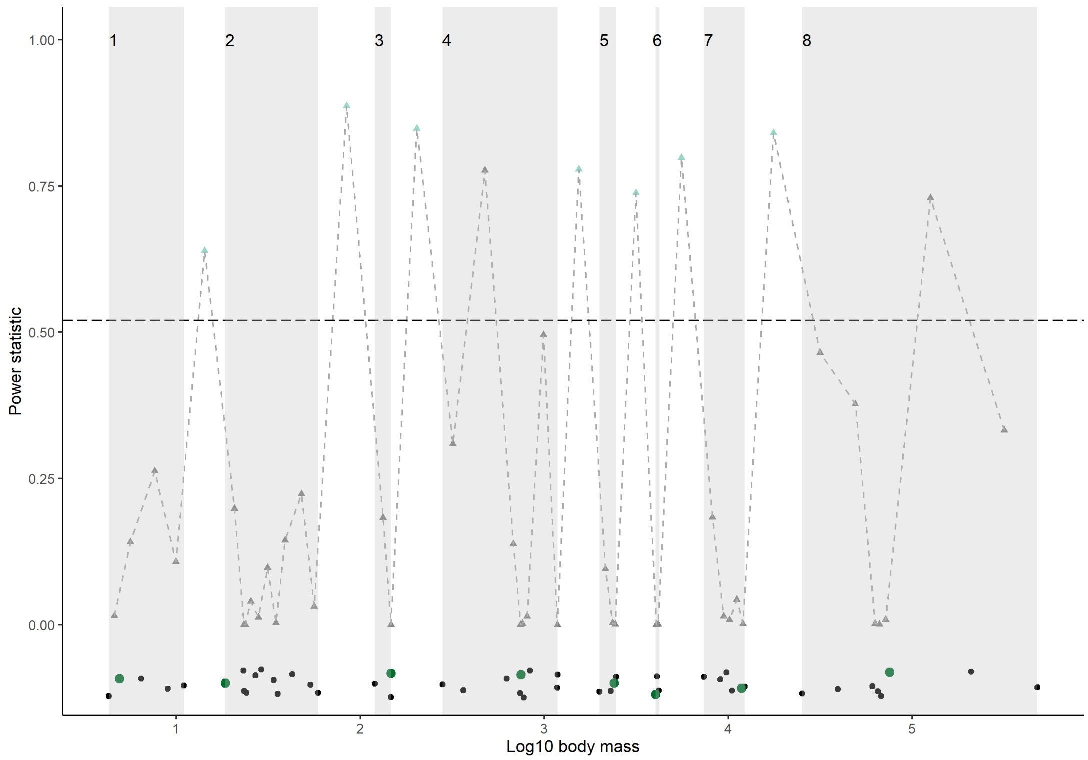

Figure 3.2. Discontinuities and species aggregations for mammals in the Central Platte River Valley. The $\log_{10}$ body masses of all mammal species are represented by points (black) along the x-axis. Dark green points indicate the omnivorous mammal species selected for habitat network analysis. The points are jittered for illustrative purposes. The power statistic (~0.50, n = 49) is shown by the slashed horizontal line (black). All gaps between species are represented by triangles; light green triangles indicate discontinuities between species aggregations. Species aggregations (defined as groups of three or more species), representing scale domains, are shaded (gray) and numbered 1-8 at the upper left of each shaded area.

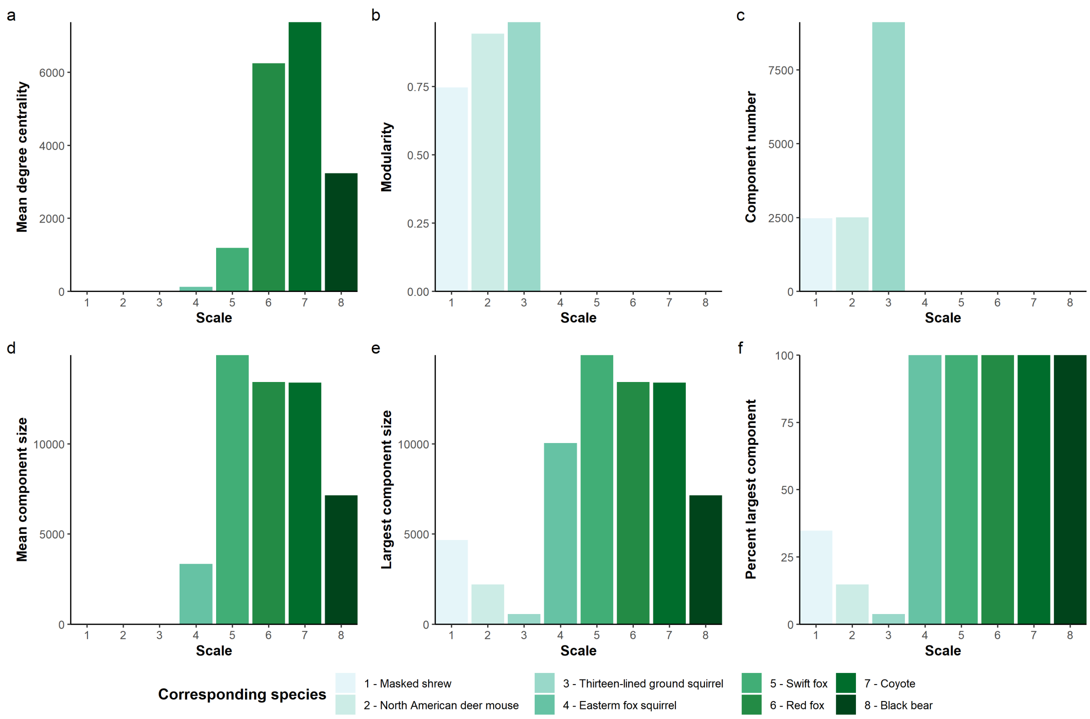

Figure 3.3. Connectivity metrics for eight mammal habitat networks in the Central Platte River Valley. (a) Bars represent mean degree centrality, or the mean number of edges adjoining each node in the network. (b) Bars represent modularity, indicating the degree of division of the species habitat network into highly connected subgroups of nodes with few connections between subgroups in the network. Modularity measures the extent to which there are highly connected subgroups of nodes with few connections between subgroups in the network (c) Bars represent the number of components in each species habitat network. (d) Bars represent the mean number of nodes in each component in each species habitat network. (e) Bars represent the number of nodes in the largest component in each species habitat network. (f) Bars represent the percent of total network nodes in largest component in each species habitat network.

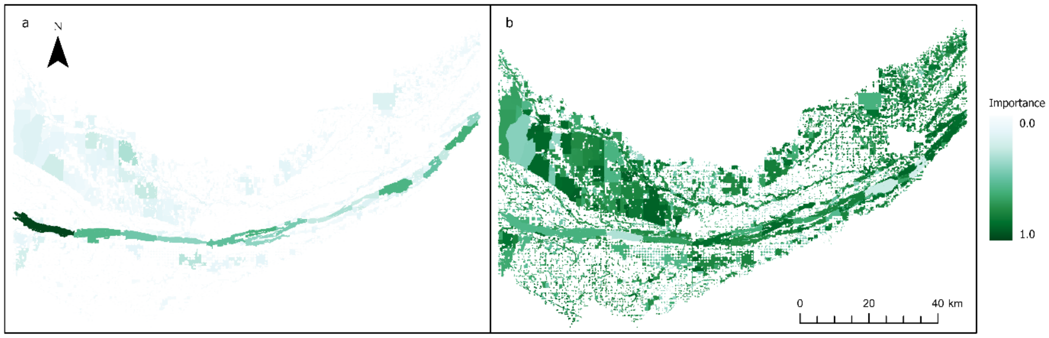

Figure 3.4. Normalized importance scores of habitat patches for (a) masked shrew and (b) red fox in the Central Platte River Valley. Importance scores were calculated by sequentially removing each node, recalculating mean degree centrality of for the network, and replacing the node before repeating the process for the next node. The importance scores were normalized to a range between 0 (lowest importance) and 1 (highest importance). Figure developed using spatial data from the Rainwater Basin Joint Venture Nebraska Land Cover Development (2016 Edition) (Bishop et al., 2020) dataset.

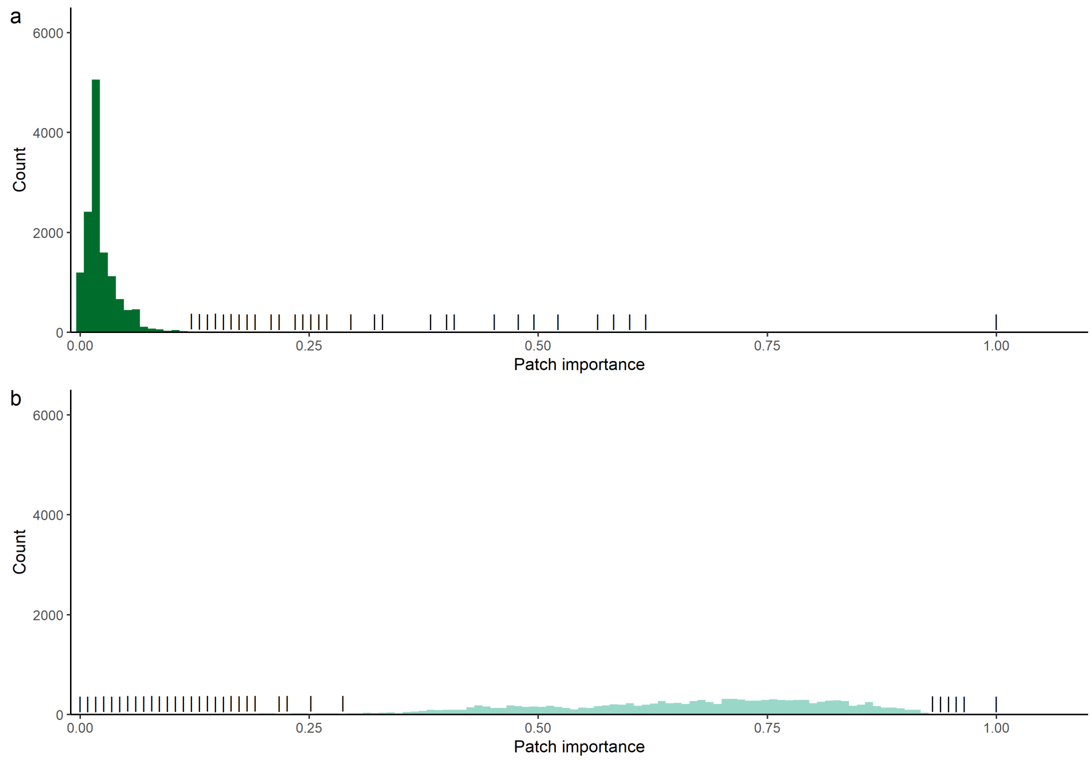

Figure 3.5. Histogram of normalized patch importance scores for (a) masked shrew and (b) red fox. The importance scores were normalized to a range between 0 (lowest importance) and 1 (highest importance). Black tick marks identify bins with low counts (20 ≥ count ≥ 0) for illustrative purposes.

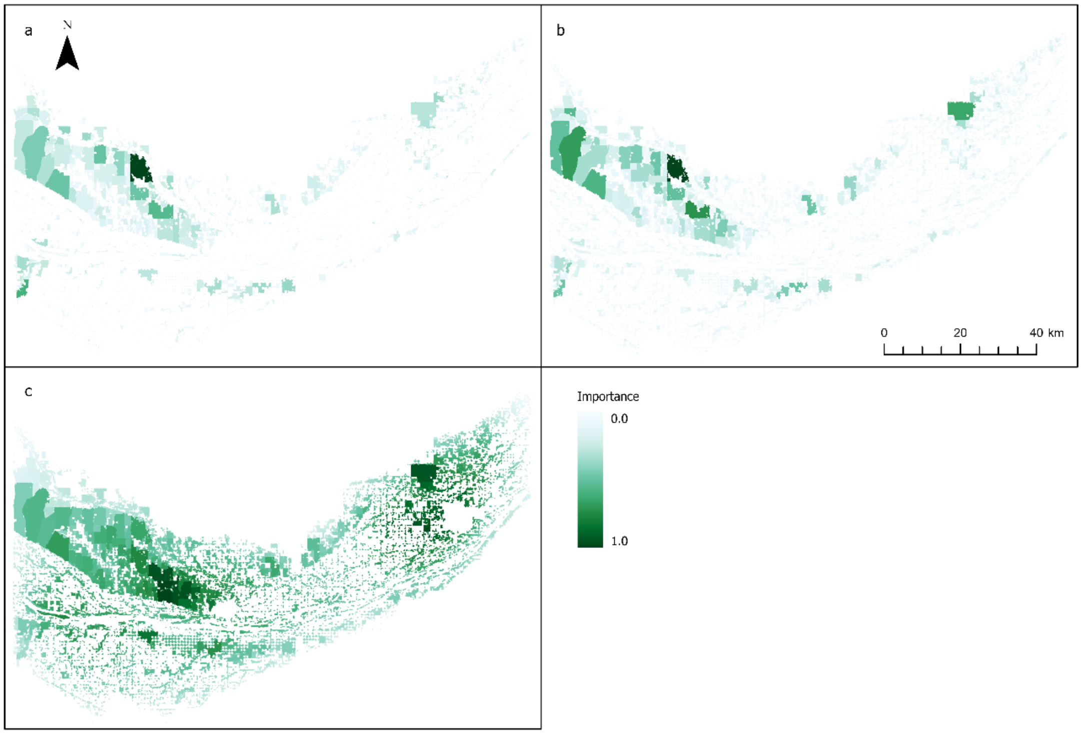

Figure 3.6. Normalized importance scores of habitat patches for (a) North American deer mouse, (b) thirteen-lined ground squirrel, and (c) swift fox in the Central Platte River Valley. Importance scores were calculated by sequentially removing each node, recalculating mean degree centrality of for the network, and replacing the node before repeating the process for the next node. The scores were normalized to a range between 0 (lowest importance) and 1 (highest importance). Figure developed using spatial data from the Rainwater Basin Joint Venture Nebraska Land Cover Development (2016 Edition) (Bishop et al., 2020) dataset.

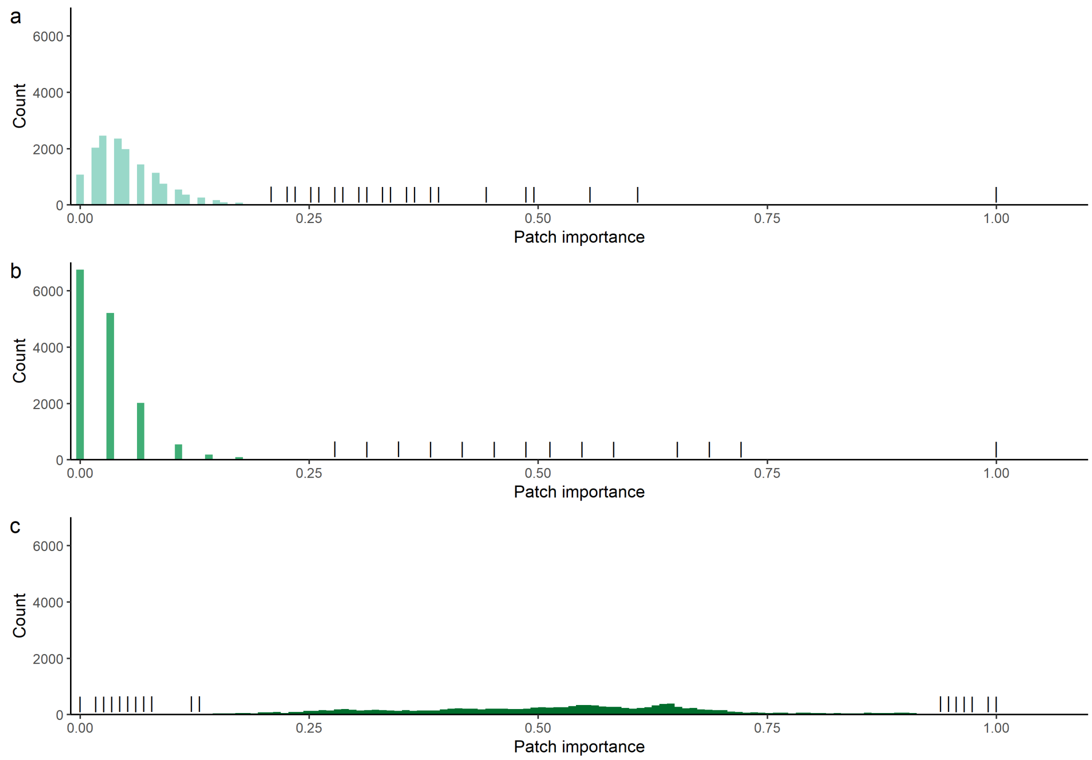

Figure 3.7. Histogram of normalized patch importance scores for (a) North American deer mouse, (b) thirteen-lined ground squirrel, and (c) red fox. The importance scores were normalized to a range between 0 (lowest importance) and 1 (highest importance). Black tick marks identify bins with low counts (20 ≥ count ≥ 0) for illustrative purposes.

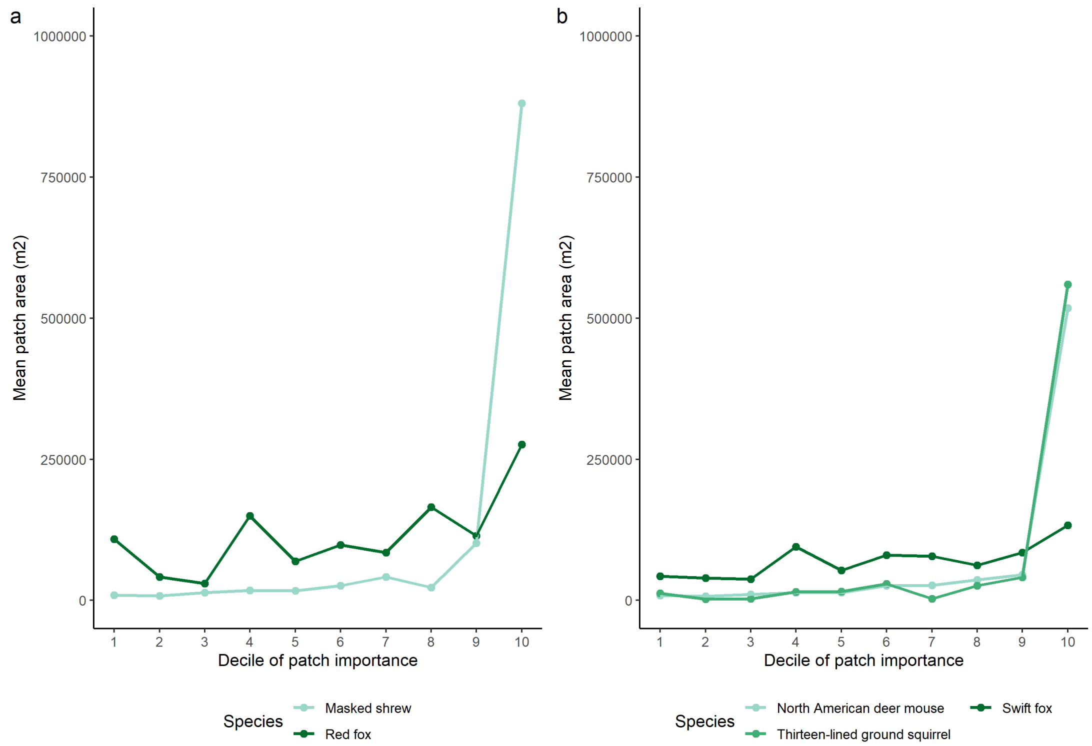

Figure 3.8. Patch importance and patch area for two sets of mammal species in the Central Platte River Valley. (a) Decile of patch importance and mean patch area for masked shrew and red fox. (b) Decile of patch importance for North American deer mouse, thirteen-lined ground squirrel, and swift fox. Range of deciles is from 1 (bottom 10% of importance) to 10 (top 10% of node importance).

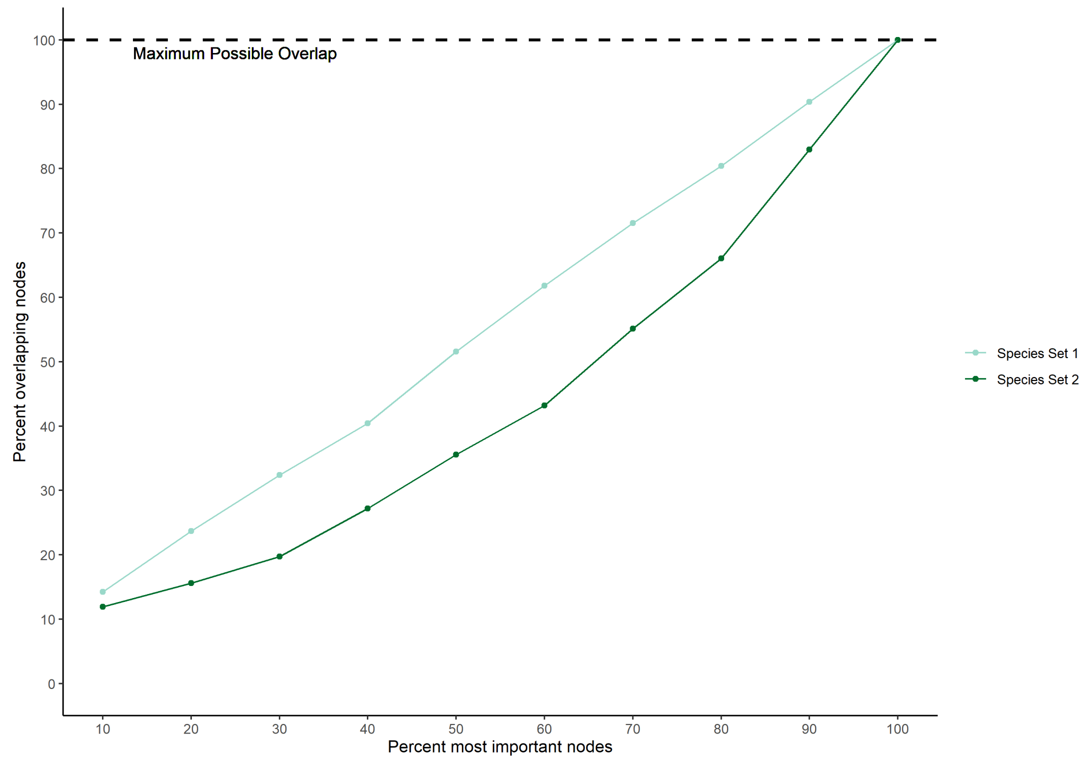

Figure 3.9. Percent overlap of most important nodes in the habitat networks for two sets of mammal species in the Central Platte River Valley. Species Set 1 includes masked shrew and red fox. Species Set 2 includes North American deer mouse, thirteen-lined ground squirrel, and swift fox. Dashed horizontal line shows the maximum possible percent overlap of nodes (100%) among the species within each set.

CHAPTER 4. LANDSCAPE CHANGE IN THE GREAT PLAINS: PERCEPTIONS OF RANCHERS IN NEBRASKA AND COLORADO

Abstract

Rapid socio-environmental change, ranging from woody encroachment to global warming, is reshaping grass-dominated Great Plains landscapes. However, little is understood about how ranchers, who are the primary managers of the region's rangelands, perceive and cope with these changes. Ranchers' perceptions of change in the landscape influence their responses to change, which makes understanding their perspectives useful for the development of coping strategies. I explored ranchers' perceptions of landscape change at multiple scales and their perspectives on potential coping strategies through interviews with 12 ranchers in the Great Plains states of Nebraska and Colorado. Ranchers identified a range of changes affecting the landscape including both large-scale changes, which they largely perceived as uncontrollable and negative, and ranch-scale changes associated with their own rangeland management practices, which they generally perceived as positive. Ranchers expressed an interest in learning and described how they had adopted new management practices in order to meet their management goals, specifically related to profitability and land stewardship. The management challenges and uncertainties presented by landscape change, in combination with the ranchers' willingness to adopt new practices, indicates a need and opportunity for research and management partnerships between governmental and nonprofit entities and the ranching community. Such partnerships have the potential to incorporate multiple sources of knowledge on rangeland management in order to enhance understanding of the

impacts of landscape change, develop effective coping strategies in response to change, and foster trust among these groups.

Introduction

The landscapes of the Great Plains region have undergone substantial change during the last two hundred years, largely driven by the conversion of native grassland including tallgrass, mixed-grass, and shortgrass prairie to cropland (Joern & Keeler, 1995; Vickery et al., 1999; Samson et al., 2004; Cunfer, 2005; Augustine et al., 2021). The historical loss and fragmentation of grassland in the region has caused a multitude of impacts such as the drastic decline of grassland-dependent bird populations (Vickery et al., 1999; Coppedge et al., 2001; Fuhlendorf et al., 2002; Correll et al., 2019). Although the rate of cropland conversion has slowed in recent decades (Waisanen & Bliss, 2002; Drummond et al., 2012), increasing commodity prices and demand for biofuel production have further driven the conversion of grassland to cropland in recent decades (Wright & Wimberley, 2013; Lark et al., 2015; Wright et al., 2017; Lark et al., 2020; Lark et al., 2022). These land conversions are currently occurring in tandem with other ongoing (e.g., woody encroachment; see Engle et al., 2008) and emerging (e.g., energy development; see Allred et al., 2015 and Yahdijan et al., 2015) sources of landscape change in the Great Plains, which are generating increasing uncertainty about the future of the region.

For example, the Great Plains is experiencing ongoing changes in climate. Decreased snowpack in the Rocky Mountains and warming temperatures are expected to decrease water availability and increase variability in the Northern Great Plains, while warming temperatures and increasing evapotranspiration are expected to cause drier summers in the Southern Great Plains (USGCRP, 2018). Throughout the Great Plains, the predicted increase in the frequency of extreme weather events such as heavy rainfall may cause flooding, erosion, and damage to agriculture and infrastructure (USGCRP, 2018). These changes in climate, coupled with altered grazing and fire regimes, biological invasions, and land use and landcover change, are causing substantial shifts in vegetation composition. For example, driven by intensive grazing and the absence of fire, native but formerly uncommon woody species including eastern red cedar (*Juniperus virginiana*) have greatly increased in abundance in the Great Plains (Van Auken, 2009). The expansion of woody species is associated with the loss of ecosystem services including carbon sequestration and biodiversity (Twidwell et al., 2013) and an increase in the risk of large wildfires (Donovan et al., 2020). Changes in climate and disturbance regimes have also led to an increase in the abundance of invasive C3 grasses such as smooth brome (*Bromus inermis*) and Kentucky bluegrass (*Poa pratensis*) in the grasslands of the Plains (Cully et al., 2003; DeKeyser et al., 2013; DeKeyser et al., 2017). Although some of these grasses were introduced forages and have value in livestock production (e.g., Phillips & Coleman, 1995), they are also able to outcompete other species and are linked to an overall decline in plant species diversity (Miles & Knops, 2009; Ellis-Felege et al., 2013). Notably, future climate change including increased CO_2 levels may further facilitate the expansion of these invasive C3 grasses (Morgan et al., 2008).

These ecological and climate changes in the Great Plains are occurring at the same time as demographic and socioeconomic changes. Although the area of cropland in the Great Plains has remained the same or increased in recent decades (Drummond et al., 2012; Wright & Wimberley, 2013; Lark et al., 2020), the number of agricultural producers has notably declined due to the mechanization and consolidation of agriculture (Brown et al., 2005). The rural population of the Great Plains is also aging (Parton et al., 2007) due to youth leaving rural areas for urban areas (Johnson & Rathge, 2006), and the average age of agricultural producers (57.5 years old) continues to increase nationally (NASS, 2017). Although limited information is available about land ownership trends in the Great Plains, studies in neighboring agricultural states such as Iowa also suggest an increase in the number of non-operating and absentee farmland owners (Duffy & Smith, 2008; Zhang et al., 2018), who may make different management decisions than owner-operators such as being less likely to engage in conservation practices (Nickerson et al., 2012).

The demand for energy production in the Great Plains has also increased (Ott et al., 2021), with 50,000 new oil wells drilled every year in central North America (Allred et al., 2015) and numerous wind energy facilities already scattered across the Great Plains (Diffendorfer et al., 2017). Recreation is also an increasingly common reason for purchasing land in the Great Plains, which may be a factor contributing to rising land prices in the region (Nickerson et al., 2012). In other words, who is managing the landscapes of the Great Plains and, in turn, how these landscapes are being managed is changing. Understanding the non-stationarity of Great Plains agroecosystems and the processes affecting these landscapes across time and space, in addition to human responses to the aforementioned changes, will be crucial in fostering the resilience of these agroecosystems going forward such that they continue to provide desirable ecosystem services (Walker et al., 2002; Craig, 2010).

Ranchers constitute a crucial group of land managers in the Great Plains. Nearly half of all land in the Great Plains remains as grassland or shrubland (Augustine et al., 2021), encompassing both private and public land used for grazing (Sayre et al., 2013; Congressional Research Service, 2019). More than three-quarters of the Northern Great Plains, for example, is privately owned, with less than two percent of the region in public protected areas (Freese et al., 2010). At the scale of their ranch, ranchers have the ability to generate landscape change through their management practices such as by implementing different grazing systems. However, as land managers, ranchers will also be required to respond to the multitude of aforementioned larger-scale changes affecting Great Plains landscapes in order to avoid the loss of ecosystem services ranging from biodiversity to livestock production (Fuhlendorf et al., 2012; Augustine et al., 2021). Multiple studies have examined Great Plains ranchers' perceptions of and response strategies to specific phenomena such as drought (e.g., Haigh & Knutson, 2013; Colston et al., 2019; Haigh et al., 2019) and woody encroachment (e.g., Symstad & Leis, 2017; Stroman et al., 2020). Other studies have examined these ranchers' perceptions of and willingness to implement conservation practices (e.g., Kennedy et al., 2016; Becerra et al., 2017; Sliwinski et al., 2018a; Sliwinski et al., 2018b). However, few studies have broadly explored how ranchers perceive and respond with management to the multitude of changes affecting rangelands in the Great Plains. Ranchers' perceptions of landscape change are an important factor determining if and how they respond to changes with management. Better understanding ranchers' perceptions of landscape change is therefore useful for identifying areas for further research and collaboration with the ranching community in the development of strategies for coping with global change. The aim of this study was to explore ranchers' perceptions of landscape change in the Great Plains and how this influences management and decision-making.

Methods

I used a qualitative approach involving in-depth, semi-structured interviews with ranchers in the Great Plains states of Nebraska and Colorado. Specifically, I implemented a phenomenological research approach, which is beneficial in situations when a phenomenon or subject needs to be explored and provides a deep, detailed understanding of the phenomenon to inform practices or policies (Creswell & Poth, 2018). This approach allowed me to capture the nuance and richness in ranchers' perceptions of landscape change, including the relationship between landscape change and management decision-making and uncertainty and ranchers' use of potential coping strategies.

Data collection

Ranchers involved in several rangeland management programs and organizations in Nebraska and Colorado (e.g., collaborative adaptive rangeland management programs) were contacted as potential participants. I also asked rangeland researchers to identify ranchers who might be willing to participate. Participants were initially recruited verbally at program or organization meetings and/or via email. Ranchers were offered $100 for interview participation. Interviews were scheduled with interested individuals depending on the participant's preference for time, method, and, if applicable, location for the interview. A total of 12 interviews were conducted with ranchers, including three in Colorado and nine in Nebraska, between December 2021 and March 2022. Interviews were conducted via Zoom web-conference (10), via phone (1), and in-person (1) and lasted between 35 minutes and one hour and 40 minutes, averaging one hour in duration.

I concluded interviewing when saturation was reached, which I defined as the point at which interviews revealed little or no novel information related to ranchers' experiences of the phenomenon of landscape change (Morse, 1995; Creswell & Creswell, 2018).

A semi-structured interview guide with open-ended questions was used to gather data. Interviews began with general questions regarding the participants' personal background, experience, and approach to ranching, e.g., "What are your primary goals in managing your ranch?" and "Are there any obstacles to or challenges in achieving those goals?". More specific questions were then asked regarding observed changes in the landscape at the scale of the participant's ranch, the region, and the Great Plains, including the anticipated rate of change in the future and the participants' perceived control over future change. Subsequent questions asked about uncertainties in rangeland management and the participants' rangeland management practices and decision-making, including questions related to collaboration, willingness to adopt new practices, and timeframe of management goals. Participants were also directly asked how landscape change affects their rangeland management. Follow-up, probing, and clarifying questions were asked in order to elicit additional information or examine topics that were not included in the interview guide but were raised by the participant. Interviews were audio-recorded and transcribed verbatim.

Data analysis

Interview transcripts were first read multiple times to become familiar with the data, and interesting or salient statements and commonalities among the transcripts were noted. With the aid of Taguette 1.2.0 (Rampin & Rampin, 2021), interview transcripts were then coded in order to identify the data relevant to understanding ranchers' perceptions and experience of landscape change and to organize and categorize the relevant data. The codes were then collapsed into themes which represented the commonalities and connections across the participants' experiences of landscape change in the Great Plains, although each theme also captures the multiple perspectives of the ranchers interviewed (Creswell & Creswell, 2018). I use direct quotes from the ranchers to provide rich, thick descriptions as evidence in support of the themes (Creswell & Poth, 2018). Members of the research team met regularly to discuss the process of thematic analysis. In order to further ensure the credibility of the study, an expert in qualitative research methodology reviewed the thematic analysis process and assessed the consistency of the interpretation of the data.

Results

Six themes, which are described in detail below, emerged through the thematic analysis of the data: (1) challenges of managing for the weather; (2) increasing impacts of invasive species; (3) outside influences on agriculture; (4) land ownership, land use, and population shifts; (5) high costs of doing business; and (6) stewardship is a priority.

Theme 1: Challenges of managing for the weather

In the scope of landscape change, many ranchers discussed how "weather is huge" and described how drought in particular poses a major challenge to rangeland management. Capturing the sentiment echoed by many participants, one rancher said, "Oh, the big obstacle's Mother Nature and not bringing us any rain when you need it." Several ranchers further described how recent conditions have exemplified this challenge: "I think the fact that it's been very dry for the last couple of years is a huge challenge…to being able to keep cattle moving on our pastures without hurting our pastures." The ranchers interviewed also emphasized the uncontrollability of the weather and how responding to the conditions can be challenging: “we all depend on Mother Nature…you just have to live with it, and so I don’t know what you can do to change anything other than possibly, like I said, change your grazing management.” Discussing extreme weather events, one rancher similarly said, “again, nothing you can do about it other than look at your production and see what can you do next with those types of situations.”

In the face of changing weather conditions, the ranchers regarded flexibility and adaptability as critical to good management: “it’s kind of one of those that you just gotta kind of get out and get a feel for it and be ready to change, I guess, is the biggest thing, ‘cause you can make a 10-year plan, but Mother Nature, she’s got her own plan.” Another rancher similarly stated, “you might have a plan, and that plan’s gotta change pretty quick if it doesn’t rain and gets hotter.” The ranchers interviewed detailed a variety of strategies to cope with drought including trading and purchasing land, adjusting how they utilize grasses in grazing, running more yearlings, and custom haying. Destocking was viewed as a last resort—“It’s pretty painful to have to decrease numbers.”—although another rancher emphasized that in times of drought, “You can’t be afraid to sell off cattle and do something else.”

All ranchers interviewed discussed long-term goals such as passing their ranch onto the next generation, and many described how weather conditions affect their ability to plan for the long term. One rancher said:

> Well, we are at the mercy of the weather conditions, so it affects management because we have to deal with things on a monthly basis or a weekly basis rather than saying, okay, five years from now, I’m going to do so and so…we’d like to

> be here for the next generation and the next generation, but that is controlled by a day-to-day or weekly management scheme due to the conditions that we have to put up with.

Another rancher observed, “But as far as multiple-year planning, gosh, if it doesn’t rain, we’re not going to have grass…you kind of just got to graze what grass you get to graze and that’s all.”

A number of ranchers specifically discussed long-term trends in climate in the Great Plains, in particular related to moisture. Several ranchers mentioned receiving less rainfall and snowfall than in the past, while others described an increase in extreme weather events such as heavy rainfall and high temperatures: “It just seems like the weather just keeps getting crazier every year. Not very often you just get an inch or inch and a half of rain. Seems like it comes in four or five a time.” Looking to the future, ranchers expressed uncertainty about how changes in climate would affect rangeland management:

> We don’t need a lot of rain but we need some to grow the grass…so if there is something to the global warming, and it continues to get hotter and drier…that seems like that would be the biggest cause to what could happen.

Another stated, “you never really know is this just a cycle that we’re going through or is this kind of an upward trend…all you can do is base your management decisions on what you do know which is in the past.” One rancher considered the time-delay of research focused on how climatic changes will affect rangeland management: “I don’t know as we’re going to know how this is going to affect any of that sort of thing until it’s 20 years down the road.”

Theme 2: Increasing impacts of invasive species

Invasive species were on the minds of many of the ranchers interviewed, with one Nebraska rancher stating in reference to the landscape of their ranch, "the biggest change, which is our biggest challenge, is the increase of invasive species." Many of the ranchers interviewed discussed changes in grass species composition related to invasive species, in particular the increase of cool-season grasses such as smooth brome and sericea lespedeza (*Lespedeza cuneata*). One rancher thought that the increase in cool-season grasses was due to changes in rainfall that favor these species over warm-season grasses, while another rancher speculated that some producers fail to properly utilize cool-season grasses, allowing them to get ahead of warm-season grasses in their pastures. Ranchers also described changes in grass species composition associated with increases in noxious weeds such as leafy spurge (*Euphorbia esula*), musk thistle (*Carduus nutans*), cutleaf teasel (*Dipsacus laciniatus*), and more recent invaders such as Caucasian bluestem (*Bothriochloa bladhii*).

For some ranchers, woody encroachment was a substantial change to the landscape and a significant challenge that requires large amounts of time and money to manage. These ranchers primarily discussed the increase of eastern redcedar, with one rancher reflecting, "some has been an ongoing problem, but some pastures are newer, just trees getting closer to them, and I don't know. Funny, I don't remember it being as much of a problem when I was younger." Another rancher said:

> It just changed everything…I've heard some people say cedar trees were a generation's folly, and meaning by that we brought them in for the right reasons,

> but we didn't exactly know what we were gonna end up with in the end and how prolific they would be.

One rancher described red cedar encroachment as an "upward spiral or a downward spiral" because of the enlarging seed source, while another connected the increase of woody species with the conversion of pastureland to other uses such as recreation and, in turn, recreational landowners who do not properly manage the invasive species on their properties.

Several of the ranchers interviewed also expressed concern and frustration about how other ranchers are managing red cedar encroachment. One rancher lamented the unwillingness of some ranchers to address red cedar, stating:

> [I]t's frustrating. I will say that because there's some of us that have invested a lot of money and time to really get this under control, and then there's a lot that aren't…it's just one of those things where everybody's priorities shake out a different way.

Another said, "some people are just not doing anything, and so the trees are taking over, but they're still running the same amount of cattle out there, so their grass resource is just—is nothing." One eastern Nebraska rancher shared a strong warning for those located farther west:

> [W]e're not realizing what's going on, and it's going faster and faster, and as I go out to central Nebraska and western Nebraska…we're seeing two- and three- and five-foot cedar trees, and they're scattered in their pasture. They don't realize what's coming because it comes gradual, and all of a sudden now we've got a problem.

Multiple ranchers mentioned prescribed burning as a practice they had recently implemented or were interested in implementing in order to control red cedar after earlier generations were hesitant to do so. For example, in light of a nearby wildfire fueled by cedar trees, one rancher in a "touchy area for burning" shared a mix of apprehension and interest in prescribed burning, emphasizing the importance of staying in control of a burn yet expressing a willingness to get involved with a prescribed burn association. Notably, several participants currently engaged in prescribed burning emphasized the benefits of collaborating with neighbors on burning such as being able to use roads as fire breaks and pooling resources.

Theme 3: Outside influences on agriculture

All of the ranchers interviewed discussed the influence of external entities such as the federal government and environmental groups on rangeland management, and the majority of ranchers expressed that government regulation would negatively impact ranching in the future. Several ranchers were concerned about the regulation of water, including the regulation of wet meadows and "[w]hat water we can use, can't use, [and] what we can do in and around water." One rancher believed that current regulations on animal husbandry were reasonable but "in the future, it might get out of line", and several others pointed to recently proposed legislation in Colorado related to artificial insemination, pregnancy checking, and slaughter age as a harbinger of deleterious regulations to come. Several ranchers who graze on federal lands also expressed uncertainty regarding the future of federal grazing permits and stocking rates and were concerned that "we're not that far away" from problematic restrictions due to pressure from environmental groups. Multiple ranchers suggested that government regulation could ultimately threaten the sustainability of family ranching. For example, one rancher speculated that future regulations will favor large ranches over small ranches in a process similar as to what has occurred in the meatpacking industry, while another stated, “the possibility for change is much greater now than it was 20 years ago…I don’t know what’s going to happen.”

For many ranchers interviewed, government regulation reflected a growing public misunderstanding of ranching linked to a decrease in agricultural producers, and public misconceptions about ranching and rangeland management were a source of frustration for several ranchers. One rancher lamented that the younger generation has an unrealistic picture of “nice, tall grass blowing in the wind” and does not understand the role of grazing in rangelands. Another was concerned about “people who would probably like to…return to the natural state where buffalo were roaming” and remarked, “that’s all fine and great, but at the same time, we still gotta feed the world.” Several ranchers directly connected the misunderstanding of agriculture to misplaced governmental regulation: “each generation you have people more and more removed from the land, and so some of the regulations and laws and different things you work under can be made by people who don’t understand the thing”, emphasizing that this disconnect can create hardship for ranchers. Another stated, “I’m quite certain not many people are willing to do what we’re doing, but a lot more of them are willing to decide how we should do it.” Regulations related to methane emissions were also of particular concern for several ranchers:

> [M]y fear is that because agriculture makes up such a small part of the population, it’s going to be blamed for a lot of what is happening even though scientifically

> that's not true. Cattle produce less than 3% of the greenhouse gases in the country, but everybody wants to have meatless Mondays.

Several ranchers specifically mentioned the need to better connect with both the public and politicians in order to address misconceptions about agriculture, including bringing people out to their ranches to show the practices that they are using and the positive impact they are having on the land.

Theme 4: Land ownership, land use, and population shifts

Changes in the structure of the ranching industry, including ranch ownership and ranch size, were also discussed by the ranchers interviewed. For example, one rancher described how ranchers are an aging population, noting that older producers may not be able to implement especially hands-on management practices such as rotating cattle frequently, which could ultimately affect the land itself. Several other ranchers discussed an increase of absentee-owner or corporate-owned ranches in Nebraska, with those interviewed expressing mixed perspectives on such ranches. One rancher discussed the "good managers" on many of these ranches right now yet expressed hesitation about "corporate ownership of our land." He stated, "I want to keep the individual ranches out there…I don't want to see us—our whole landscape go in that direction." Another rancher described concerns about the quality of management by "large companies buying ranches." He elaborated:

> They don't tend to give a damn…they'll be understaffed, and they'll have foremen strung around on these ranches, and the foremans don't have much control over things…I know some very poorly operated ranches because of the wealthy family that owns them.

The effects of ranch ownership change were not limited to the rangeland itself, with another rancher saying in reference to an observed increase in absentee-owner ranches, “I don’t think that is good for anybody…it’s really hard on the communities.”

The majority of ranchers interviewed also discussed the conversion of land in the region from ranching to other uses. One rancher speculated that the region is at “the tip of the iceberg” of land ownership transfer and that “if land comes up for sale ranchers are usually not the ones buying it”, resulting in less land being owned by families like theirs. Those changes in ownership bring uncertainty:

> There’s going to be different goals there…it worries me a little bit because I don’t know if those goals are going to be goals that line up with what’s best for the resources that are here and the species that are here.

Several ranchers specifically discussed the conversion of rangeland in the region to row crop agriculture, with one stating, “Grass being broke out into row crop, absolutely. It’s huge. Do I like it? No.” The ranchers generally attributed these conversions to economics: “doesn’t help when corn runs at $7.” Another rancher explained, “a lot of this has gotten row cropped because of the challenges of grass…‘cause we’re not [ranching] because it makes sense. We’re doing it because it’s what we love to do.” Ranchers also discussed the recent conversion of Conservation Reserve Program (CRP) land back into farmland, which one rancher described as a cycle driven by the price of corn. Another rancher called the conversions “a waste” yet also lamented that grassland in CRP is not available for grazing in a time when ranchers need access to more land. For ranchers, conversion of rangeland to row crop agriculture presented a variety of potential challenges. One rancher interviewed pondered how the conversions may affect cow herds, speculating that with a lack of land to graze, cattle may need to be dry-lotted. Another rancher observed that the increase in irrigation pivots has lowered the water table, forcing them to drill deeper to obtain water. The increase of cropland conversions can also affect the process ranch succession: “If I sell the ranch now, and I sell it to somebody, I gotta be careful who I might sell it to… the plow is going to, not necessarily a plow anymore, but it’s going to be broke up.”

The ranchers interviewed also commented on the conversion of rangeland from agriculture to other uses entirely. A couple of ranchers discussed the recent purchase of nearby land for recreational purposes, and one rancher expressed frustration describing how these landowners do not manage well, particularly related to the absence of grazing and the increase of woody species. One rancher recounted a conversation with a new neighbor: “the first thing he told me he says, ‘I never want a cow on my piece of ground’.” These ranchers described how recreational landowners were mistaken in managing for woody species on their property and that the resulting forest would be too dense to hunt in: “he will be wanting to come over on my land so that he can find deer.” The ranchers interviewed also expressed mixed sentiments about the use of rangelands for energy production. One described that ranchers in his area didn’t mind the construction of wind turbines because the government pays them well enough to put them in, but another opposed wind energy development due to the impact on migratory birds. The ranchers also described how the construction of oil and gas pipelines and associated infrastructure tears the ground up and requires several years for the grass to fully grow back or, in some cases, takes a small amount of land permanently out of production: “they pay you for it, but it’s not the same as not having a road.”

Multiple ranchers observed an increase in population in the Great Plains region associated with new housing development and increased property prices. One rancher said, “Well, the Front Range of Colorado…they’re building houses after house from—all the way from like Cheyenne to Pueblo.” Another observed new houses in remote areas “you never thought would have houses” and how the county must dig ill-equipped homeowners out from blizzards in the winter. One rancher described how people purchasing these acreages is driving up property values such that ranchers are unable to enlarge their operations to be sustainable for future generations. Several ranchers also observed that the increase in housing development was affecting groundwater levels and causing a drop in the water table, and one expressed concern about how development in Colorado could affect water availability for the broader region: “You can believe they’re all looking at the Ogallala Aquifer figuring out how they can get that water to go to Denver. And when that happens, if that happens, it’s going to be pretty tough on us.”

Despite the increase in population at the regional scale, many ranchers interviewed observed an ongoing depopulation of their communities primarily associated with the mechanization of ranching: “people are trying to cover a lot more acres with a lot fewer people, and it’s just—it’s very difficult.” One rancher described there being “hardly enough kids in the school to have a school anymore”, while several others described the difficulties of population loss such as keeping service providers like grocery stores and hospitals in the community. Depopulation was also associated with difficulties related to labor: “it’s really harder than it’s ever been to find people that want to work on a ranch and you can get to stay at the ranch.” Although, one rancher conveyed cautious optimism that technology such as video conferencing could allow the younger generation to “come back and live where they want to live, but still have a job to support the landscape where they live”, alluding to the possibility of remote employment.

Theme 5: High costs of doing business

Many of the ranchers interviewed identified profitability as a primary goal for their ranch operation, although one rancher clarified, “keep it somewhat profitable. I don’t guess you can say profitable ‘cause there’s never much of a profitability.” For the ranchers, maintaining profitability was critical in allowing them to continue to steward the land they ranch and maintain the ranch for future generations. Yet, all of the ranchers interviewed discussed how economic factors present a challenge to rangeland management. Many ranchers stressed the uncertainty and uncontrollability of cattle markets, which they described as influenced by factors ranging from the markets for other commodities such as corn to events like a meatpacking plant fire and international conflict. As such, one rancher described how ranching “takes a lot of free thought” and that a savvy rancher must closely watch the markets to know the cost of inputs such as hay and protein supplement and know when to sell and buy cattle. The costs of inputs themselves also presented a challenge for ranchers:

> [E]specially this year input prices are pretty scary. And I think our input prices will at least double, but I’m pretty sure the prices won’t double…that becomes a very interesting and difficult challenge is to how do you…keep your place productive and keep that balance between inputs and income.

Ranchers specifically mentioned increasing prices for fuel, vaccines for cattle, new machinery, and parts to maintain existing equipment such as tractors.

Several ranchers expressed an interest in or a need to expand the size of their ranching operation, but they identified multiple economic challenges in doing so including property taxes, the high price of land and cattle, and a lack of availability of land. One rancher summarized the challenge of expanding his operation as: “Grass is hard to get. It’s real expensive to buy. Hard to find a lease, and the leases are high if you do find it.” Regarding purchasing cattle, another rancher “wouldn’t call it a problem, but sometimes it can be very challenging” and emphasized the benefit of buying and trading cattle with neighbors. Regarding high property taxes, another rancher considered, “we’d love to expand. But there’s no possible way we can. It just doesn’t pencil out.” One rancher was interested in their daughter or granddaughter returning to the ranch but that they need “enough land to be able to support all these people.” Accordingly, they are looking to purchase land from neighbors nearing retirement: “we’re very careful with the way we operate. Right now, we don’t buy new tractors and lots of fancy equipment because we’re trying to conserve our funds in case we get a chance to purchase more land.”

Many ranchers emphasized the difficulty and narrow financial margins associated with making a living ranching. One rancher speculated that maybe others “can afford to make a mistake. I can’t…we have to make our checkbook work out every year…and the only income we get is from these calves.” Another observed an increasing challenge of profitability: “when Dad was my age, him and Grandpa lived off 200 cows, and now the bankers say it takes about 500 cows per family, I guess, if it’s just a straight cow-calf operation to make ends meet.” Another confirmed the need to increase the size of ranching operations: “It takes a lot of acres now to pencil out. Make it work. You’re just more economically feasible on scale for us to make a living doing it." One rancher concluded, "we like what we do so much that we're willing to go broke doing it. I don't know why. It's just what we do."

Several ranchers emphasized their willingness to adopt new management practices in order to ensure profitability and provided diverse examples of how they have done so. One rancher summarized, "hands down, I'm willing to change to stay in this business." The ranchers interviewed mentioned changes in the management of their cow herds including delaying calving dates, custom grazing, grazing only yearlings, and keeping more heifers to calve as strategies they have implemented to maintain profitability. More broadly, ranchers described other methods to support profitability such as stopping haying, raising other livestock such as sheep, trying different marketing approaches, and using government programs such as through the Natural Resources Conservation Service (NRCS) to develop fencing and water tanks.

Theme 6: Stewardship is a priority

All of the ranchers interviewed discussed the importance of taking care of the rangeland, and for many participants, stewardship was key to their rangeland management. For example, one rancher described his goal as to "not harm the grass…so the grass is productive year after year. Not overgraze it, manage it correctly." Another rancher emphasized that "God has given us this land to take care of and not abuse it but to make it better than when we received it" so that future generations will have the same quality of land. Many participants directly or indirectly connected caring for the land through management with their goals of maintaining the ranch for future generations and remaining profitable. Multiple ranchers stressed how "there's always a repercussion" to management decisions and for that reason one must examine how management today affects the land in the future. One rancher stated, “I do feel what we do today probably will have a pretty significant impact.” For several ranchers, caring for the rangeland and profitability were inherently connected:

> [W]hat’s good for long-term goals and long-term longevity and productivity of that land and of those grasses is important for profitability of the ranch, so it’s nice that all ties together. So you don’t have to do short-term things to make money.

Similarly, several participants described cattle and grazing as a crucial tool in achieving these goals:

> My mindset is that our ranching practices that we employ, mainly grazing, they’re a tool that we use, they’re an economic tool, obviously, but also they are an environmental tool, and so for me it’s how do I use that tool so that the land and all the species that are out here are supported.

In order to meet the aforementioned goal of stewardship, the ranchers interviewed expressed interest and willingness to “try and learn, but change, if it’s for the better.” Ranchers described a variety of methods they use to obtain information on management practices including attending events such as seminars and field days, engaging with university research and extension, and above all, learning from fellow ranchers. A number of participants were involved in formal and informal ranching organizations. For instance, one rancher described his participation in a local range management organization: “they took a look at what we did and could critique us, but we could take a look at what they did and critique, and we learned from each other. And that’s been extremely important." Another common response was regarding the importance of simply talking with other ranchers about ranching topics ranging from cattle health problems to pasture management, in particular during collaborative activities such as brandings or prescribed burns. One rancher said:

> We talk a lot. And talk is cheap, but if you got somebody on kind of the same wavelength as you, you can visit about things and see what they're doing and kind of put their ideas with yours or yours with theirs.

Similarly, another rancher emphasized the importance of teaching the next generation of ranchers how to manage and being willing to share what you've done wrong so that others can learn from your mistakes.

The ranchers interviewed generally expressed an interest in improving their management and a willingness to adopt new rangeland management practices to do so: "If I thought I could do something different, or better, I would do that." However, some of those interviewed also stressed the importance of incremental change and the need to see evidence of a positive effect before implementing a new practice: "I'll accept changes as long as—look at them carefully and make sure they're positive." One rancher expressed that "technology is not my answer", although he would be willing for his children to try out new technologies in the future. Another rancher similarly noted that there were limits in his willingness to adopt new practices: "I would like to think I'm openminded about things like that. I'm not gonna start running sheep, though."

The majority of participants discussed having implemented changes in their grazing system, in particular adopting rotational grazing or modifying their prior rotational grazing system. For these ranchers, using rotational grazing was associated with improved pasture health and a greater ability to utilize and manage their pastures under dry conditions. For example, one rancher observed that with rotational grazing "there's always something there to turn cattle out on." Those interviewed described additional benefits of rotational grazing including decreased erosion, increased grass cover and diversity, improved drought resilience, and greater productivity. In addition to rotational grazing, the ranchers also described changes in management such as returning to cow-calf from yearlings to mitigate the harsher impact of grazing yearlings on pastures in the Nebraska Sandhills and taking in herds for custom grazing, which allows for better management of the grassland. Another rancher more broadly described, "we shifted from being solely a cow-calf producer to being more of a land steward and realizing that the biggest asset we have is our land." For this producer, a change in mindset encouraged them to change their practices for the purpose of keeping the rangeland healthy and ensuring that future generations had the same opportunities and quality of life as they do.

Many of the ranchers interviewed cautioned against poor management, in particular overgrazing, and emphasized that it could take years for the ground to recover from this type of management. One rancher thought that some people in the Nebraska Sandhills were trying to "intensively graze some pretty sandy spots" and "might have been pushing it a little too hard on what they were trying to do", while three other ranchers lamented those people who, despite running larger cattle and experiencing drier conditions, "just do what they've done forever" with little understanding of the effect on the land. At the same time, another rancher believed that management in the region had generally, but not universally, improved:

> [T]he average land manager…is better than what they were when I was younger. They may not do things like I would, but they do it better than what they used to…I still see places where I kind of shake my head, but on average, the management's better.

Discussion

Through interviews with ranchers in two Great Plains states, Nebraska and Colorado, I examined ranchers' perceptions of landscape change and potential strategies to respond to landscape change in the Great Plains region. My interviews highlight the numerous large-scale landscape changes affecting ranchers in the region, including both ongoing processes such as the conversion of grassland to cropland and newer drivers of change such as energy development and climate change. The ranchers interviewed also described the substantial impact of rangeland management practices on the landscape at the ranch scale, including change induced by their own ranching practices. Generally, the ranchers I interviewed regarded changes associated with their own management as positive and certain, i.e., the impacts of their management practices on the landscape are known to them and relatively clear. For example, many participants discussed grazing as a crucial grassland management tool, and the majority of those interviewed specifically discussed positive changes to their land associated with adoption of practices such as rotational grazing including increased productivity and decreased erosion. In contrast, the ranchers perceived larger-scale, external changes such as those associated with climate and government regulation as uncontrollable and a challenge to rangeland management and the sustainability of ranching.

The landscape changes occurring at regional or larger scales that were identified by the ranchers in this study, as well as their perspectives on those changes, mirrored those identified in other regional studies. For example, the changes in precipitation patterns and increasing frequency of extreme weather events identified by several of the ranchers align with predicted climate changes in the region (USGCRP, 2018), and their concern regarding the future impacts of those changes on livestock production is echoed in recent studies of Great Plains agricultural producers (e.g., Kachergis et al., 2014; Grimberg et al., 2018; Campbell et al., 2019). Similarly, the ranchers' concerns surrounding woody encroachment are substantiated in both biophysical assessments (e.g., Engle et al., 2008; Hendrickson et al., 2019) and studies of landowners' perceptions of woody encroachment (e.g., Stroman et al., 2020).

Notably, the ranchers I interviewed identified socioeconomic and political factors as sources of landscape change of a similar or greater magnitude as the aforementioned biophysical drivers. In some cases, these factors were identified as causes of biophysical landscape change such as how recreational landowners, who are growing in number, implement management practices that favor woody species (Stroman et al., 2020) and facilitate woody encroachment. Many of the ranchers identified socioeconomic factors such as high land and lease prices, high property taxes, and a lack of available land as obstacles to their goals, including their ability to expand the size of their operations in order to remain sustainable into the future. Recent studies of Great Plains ranchers including Auger and Haggerty (2016) and Haggerty et al. (2018) similarly identify high land prices and lack of land, profitability, and family succession among the most pressing challenges facing livestock producers in the region. Another example of the socioeconomic changes identified by the ranchers is the increase in absentee or corporate land ownership in the region. Some ranchers associated this change with differing approaches to rangeland management, an observation consistent with existing research suggesting that absentee owners are less likely to collaborate with agencies (Petrzelka et al., 2013) and with neighbors (Yung & Belsky, 2007). Additionally, the ranchers felt strongly that future government regulation related to animal husbandry practices, water use, and methane emissions were likely and that these regulations could alter rangeland management practices and threaten the viability of family ranching in the region. Importantly, the predominance of rancher concerns regarding government regulation appears to be shared by the ranching community beyond the Great Plains (e.g., Roche et al., 2015) and indicates a potential challenge to partnership among government agencies and ranchers in developing strategies to ensure the resilience of Great Plains agroecosystems undergoing change.

As evidenced in my interviews and supported by other biophysical and social research, landscape change presents and will continue to present substantial management challenges for Great Plains ranchers and, in turn, necessitates the development and implementation of strategies to cope with these changes. The ranchers I interviewed generally expressed a willingness to change their management practices, and they provided examples of changes they had previously made to improve their management. As observed in previous studies of practice adoption and decision-making (e.g., Didier & Brunson, 2004; Kennedy & Brunson, 2007; Turner et al., 2014; Wilmer et al., 2018a), the willingness of the ranchers I interviewed to adopt new practices was generally linked to the interconnected long-term goals of profitability and land stewardship. Furthermore, my interviews revealed that, in some cases, ranchers were making changes to management practices specifically to address challenges related to the landscape changes they were experiencing, including change in climatic conditions such as drought. The ranchers described a variety of strategies to cope with drought, exemplifying the management flexibility described in other studies as critical in drought response (Kachergis et al., 2014). More broadly, risk perception has previously been linked to willingness to adapt to climate change amongst agricultural producers (Mase et al., 2017), which may explain the relatively strong interest of these ranchers in adopting new practices given the current challenges they identified associated with weather and climate. Interestingly, although the ranchers interviewed recognized the non-stationarity of Great Plains landscapes and indicated a willingness to change practices in response to landscape change, in the minds of these ranchers, rangeland management may be equated with a goal of increasing stationarity or, in other words, keeping the landscape the way it is. For example, many ranchers expressed a desire to maintain the rangeland in its current condition for future generations and expressed concern regarding many changes in these landscapes including woody encroachment, shifts in land use, and climate change.

The multiplicity of changes occurring in the landscape of the Great Plains, in addition to the willingness of the ranchers interviewed to adopt new practices, suggests the importance and value of engagement with the ranching community in research and management. Such engagement might identify knowledge gaps related to the impacts of landscape change on production, as well as the efficacy of coping strategies to respond to these changes. However, from the perspective of the ranchers I interviewed, present and future governmental regulation is largely an obstacle to ranching, with the exception of some NRCS conservation programs, which is a sentiment that has been shared in other studies of rancher decision-making (Roche et al., 2015), prescribed burning (Yoder et al., 2004), and adoption of innovations (Didier & Brunson, 2004). As such, research and management that involves ranchers as stakeholders and facilitates the co-production of knowledge may be especially beneficial as it provides an opportunity to incorporate multiple knowledge sources and perspectives on rangeland management and fosters trust among those involved (Briske, 2012; Roche et al., 2015; Wilmer et al., 2018b; Briske et al., 2021).

The existing uncertainty regarding the drivers and effects of landscape change in the region also points to the need for science-management partnerships that specifically focus on understanding landscape change in Great Plains agroecosystems and the efficacy of potential coping strategies to aid the livestock producers vulnerable to the aforementioned changes (Derner et al., 2018; Augustine et al., 2021). Importantly, given that landscape change is in some cases rapidly occurring, approaches to resource management such as collaborative adaptive management (CAM) that emphasize learning through management and the reduction of uncertainty may be especially well-suited for management in complex, interconnected systems undergoing change such as Great Plains landscapes (Scarlett, 2013; Wilmer et al., 2018b; Fernández-Giménez et al., 2019). As these landscapes continue to change, the rangeland management practices most effective in achieving both ecological and economic goals may similarly change, necessitating that research and management are connected so that producers can make informed management decisions in response to the changing landscape, which may in turn affect the productivity and structure of the landscape itself. In other words, by providing ranchers with information to support their rangeland management decisions, which are within their control, these individuals may be better able to respond to larger-scale, external landscape changes that are outside of their control. Furthermore, research and management should include the holistic evaluation of rangeland management practices by including productivity, economic, and ecological dimensions in order to provide information that aligns with producers' goals related to profitability and sustainability for future generations, as well as stewardship. These approaches to rangeland management in the region will likely be crucial to developing strategies to cope with change that ensure the future of livestock production and other ecosystem services in the Great Plains.

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CHAPTER 5: CONCLUSION

Great Plains landscapes currently support a wide variety of ecosystem services ranging from crop and livestock production to biodiversity and carbon storage (Sala et al., 2017). However, the landscapes of the Great Plains are non-stationary and have changed during the last several hundred years following European settlement of the region, as have the ecosystem services they provide, largely due to the extensive conversion of the region's grasslands into cropland (Samson et al., 2004; Augustine et al., 2021; Rollinson et al., 2021) and the alteration of the region's pre-European settlement disturbance regime (Briggs et al., 2002; Briggs et al., 2005; Engle et al., 2008; Twidwell et al., 2013). More recently, although the conversion of grassland to cropland slowed during the 20th century (Waisanen & Bliss, 2002; Drummond et al., 2012), national biofuel policy has reaccelerated conversion to cropland for corn production (Wright & Wimberley, 2013; Lark et al., 2015; Wright et al., 2017; Lark et al., 2020; Lark et al., 2022). In the present, other biophysical factors are also driving landscape change in the Great Plains include climatic changes, characterized by changes in precipitation patterns and water availability (USGCRP, 2018), and an increase in invasive plant species, including the encroachment of juniper (*Juniperus* spp.) across the region (Engle et al., 2008; Van Auken, 2009).

In tandem with these biophysical changes occurring in the Great Plains, the landscapes of the region are also being affected by demographic and socioeconomic changes which affect the use and management of Great Plains landscapes and, in turn, the land itself. For example, Great Plains landscapes are increasingly being used for energy production, including both oil and gas and renewable energy (Allred et al., 2015;

Diffendorfer et al., 2017; Ott et al., 2021), as well as for non-productive land uses such as recreation (Nickerson et al., 2012). Land ownership is also shifting, as research in neighboring agricultural regions suggests that the number of absentee landowners is increasing (Duffy & Smith, 2008; Zhang et al., 2018). More generally, fewer agricultural producers are owning more land in the region due to the consolidation of agricultural production in the Great Plains (Brown et al., 2005).

However, uncertainties remain regarding the impacts of many of the aforementioned changes on the landscapes of the Great Plains and their influence on the provisioning of ecosystem services (e.g., Morford et al., 2021), as well as the best management strategies to respond to these changes (e.g., Maestas et al., 2022). Great Plains landscapes are complex socioecological systems characterized by multiple sources of complexity ranging from non-linear processes to multiple scales and diverse stakeholder perspectives (Walker et al., 2002). Better understanding the impacts of landscape change in these complex systems is necessary in order to ensure that the resilience of these landscapes is not eroded to such a degree that these systems and the ecosystem services they provide become fundamentally different (Holling, 1973; Angeler & Allen, 2016). Investigating how humans are responding to the aforementioned changes and identifying effective strategies to cope with those changes is also critically important for maintaining the present desirable functions of the system (Walker et al., 2002; Angeler & Allen, 2016). As such, this Master of Science thesis sought to examine landscape change in the Great Plains, focusing on the role of scale and human response to change in the context of resource management in non-stationary landscapes.

To meet this objective, this thesis employed both quantitative and qualitative methods through three research projects centered on the topics of landscape change, scale, and human response to change in the Great Plains. In the second and third chapters, I combined discontinuity theory and graph theory to evaluate the connectivity of the Central Platte River Valley (CPRV) in Nebraska, USA, a highly fragmented agricultural landscape undergoing land use and landcover change, at multiple scales and for multiple mammal species. Broadly, I found that the landscape of the CPRV was highly connected for mammal species interacting with the landscape at larger scales and relatively unconnected for mammals at smaller scales. More specifically, I identified the presence of a connectivity threshold at which the landscape became highly connected between the 500 m and 6,500 m dispersal distances for mammal species. In addition to these differences in connectivity across scales in the landscape, I also illustrated how the patches of habitat most important for connectivity for mammal species interacting with the landscape at different scales differed. Using the results from these chapters, I suggest that ecosystem management in the CPRV should account for the following considerations in order to support diverse species communities in the changing landscape: (1) a multiscale approach to management will be most effective in ensuring landscape connectivity for a diverse suite of mammal species interacting with the landscape at different scales, and (2) the effects of management for connectivity are unlikely to flow up or down across scales, such that the utility of umbrella species management approaches for connectivity may be limited.

In the fourth chapter of the thesis, I used interviews with ranchers in the Great Plains states of Nebraska and Colorado to better understand Great Plains ranchers' perceptions of and responses to landscape change, given ranchers are important land managers in the Great Plains and will be affected by and required to respond to landscape change. The ranchers interviewed identified numerous biophysical, socioeconomic, and demographic changes affecting the landscape at the scale of their ranch, their region, and the broader Great Plains. The ranchers also conveyed an interest in learning about management, which was connected to their expressed desire to meet management goals such as stewardship and profitability. These ranchers' interest in improving management suggests an opportunity for collaboration with this group of land managers in developing approaches to rangeland management in response to landscape change. Notably, the ranchers largely viewed the government as an obstacle to management, suggesting that further collaboration in research and management among institutions such as universities and governmental agencies and the ranching community will also be important in building trust with ranchers in the Great Plains. These collaborations will ultimately be useful in supporting the highly valued ecosystem services ranging from livestock production that Great Plains landscapes currently provide.

Examining the results of these chapters cumulatively, several conclusions can be drawn relevant to landscape change in the Great Plains and the role of scale and human responses to change in this phenomenon. First, the non-stationarity of Great Plains landscapes may be viewed as both desirable and undesirable, illustrated in this thesis by (1) Nebraska and Colorado ranchers' generally negative view of the large-scale, external changes occurring in these landscapes and their desire to maintain the characteristics of the current landscape for future generations (Chapter 4); and (2) the relatively low level of landscape connectivity for mammal species interacting with the landscape at smaller scales in the highly altered and increasingly stationary CPRV (Chapters 2 and 3). Second, this thesis emphasizes the role of scale in the complex socioecological systems that are Great Plains landscapes. The pair of connectivity analyses (Chapters 2 and 3) demonstrate that connectivity in a fragmented agricultural landscape varies for mammal species interacting with the landscape at different scales, and the interviews with Great Plains ranchers identified landscape changes occurring at multiple scales (i.e., the ranch, the region, the Great Plains) and that the drivers and perceptions of these changes may vary (Chapter 4). For example, the fourth chapter revealed that the ranchers generally identified landscape changes on the scale of their ranch as positive, controllable, and driven by their own management, whereas they described the landscape changes occurring at larger scales as primarily uncontrollable, external, and as having a negative impact on the landscapes of the Great Plains. Third, these chapters highlight that the management of Great Plains landscapes must change in order to respond to the landscape changes currently occurring and projected to occur and to sustain the current provisioning of ecosystem services. For instance, the current management of the CPRV under the Platte River Recovery Implementation Program (PRRIP) focuses on a small subset of avian species with substantial dispersal capability without explicitly evaluating or addressing the needs of mammal species, including shorter-dispersing mammal species that may be vulnerable to habitat loss and reconfiguration and currently experience a relatively unconnected landscape. Additionally, in the rangelands of Nebraska and Colorado, ranchers recognize a variety of ways landscape change is directly or indirectly affecting their management and expressed substantial uncertainty regarding the future of ranching in the Great Plains, indicating the importance of better understanding the effects of landscape change on rangeland management and developing strategies for livestock producers to cope with those changes.

Ultimately, a lack of change in approaches to ecosystem management in the Great Plains region may result in the loss of ecosystem services ranging from livestock production to biodiversity which, in some cases, are already eroding (e.g., increase of invasive plant species has been associated with a decline in plant species diversity in Great Plains grasslands; see Miles & Knops, 2009; Ellis-Felege et al., 2013). Looking forward, as illustrated by these chapters, resource management in the Great Plains should approach the region's landscapes as complex socioecological systems and explicitly address sources of complexity – and change – including the presence of multiple scales and diverse stakeholder perspectives and responses to change. Tools such as discontinuity analysis and graph-theoretic network analysis that incorporate or address dimensions of complexity yet are relatively accessible to researchers and managers (e.g., limited data requirements, can be performed using open-source software; see Angeler et al. (2016) and R Core Team (2021)) will be vital in furthering our understanding of landscape change in the Great Plains. Furthermore, strategies such as actively collaborating with agricultural producers, including ranchers, in research and management in order to develop partnerships and, in turn, create novel solutions to challenges, will also be important to ensure that management meets both agricultural and ecological objectives in the region (Derner et al., 2018; Augustine et al., 2021).

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APPENDIX A. RANGE, DISPERSAL, AND BODY MASS DATA FOR MAMMAL SPECIES IN THE CENTRAL PLATTE RIVER VALLEY

Scientific name	Common name	Range source	Body mass (kg)	Body mass source	Dispersal distance (m)	Dispersal source
Cryptotis parva	North American least shrew	Genoways et al. (2008b)	0.0043	Silva & Downing (1995)		
Sorex cinereus	Masked shrew	Genoways et al. (2008b)	0.0049	Silva & Downing (1995)	260.5	Oleinichenko et al. (2020)
Reithrodontomys montanus	Plains harvest mouse	Genoways et al. (2008b)	0.00645	Geluso & Wright (2019)	67	Goertz (1963)
Perognathus flavescens	Plains pocket mouse	Genoways et al. (2008b)	0.009	Hazard (1982)	424.7[a]	French et al. (1968)
Reithrodontomys megalotis	Western harvest mouse	Genoways et al. (2008b)	0.011	Silva & Downing (1995)	67	Goertz (1963)
Peromyscus maniculatus	North American deer mouse	Genoways et al. (2008b)	0.0185	Silva & Downing (1995)	306.3	Rehmeier et al. (2004)
Zapus hudsonius	Meadow jumping mouse	Genoways et al. (2008b)	0.0232	Silva & Downing (1995)	362	Schorr (2003)
Blarina brevicauda	Northern short-tailed shrew	Jones & Findley (1954); Jones (1964); Genoways et al. (2008b)	0.02335	Silva & Downing (1995)	94.7	Faust et al. (1971)
Onychomys leucogaster	Northern grasshopper mouse	Genoways et al. (2008b)	0.024	Silva & Downing (1995)		
Peromyscus leucopus	White-footed deermouse	Genoways et al. (2008b)	0.0269	Silva & Downing (1995)	25	Jacquot & Vessey (1995)
Synaptomys cooperi	Southern bog lemming	Genoways et al. (2008b)	0.029	Silva & Downing (1995)		
Microtus ochrogaster	Prairie vole	Genoways et al. (2008b)	0.0339	Silva & Downing (1995)	28.7	McGuire et al. (1993)
Microtus pennsylvanicus	Meadow vole	Genoways et al. (2008b)	0.0356	Silva & Downing (1995)		
Chaetodipus hispidus	Hispid pocket mouse	Genoways et al. (2008b)	0.0427	Silva & Downing (1995)	424.7	French et al. (1968)
Mustela nivalis	Least weasel	Genoways et al. (2008b)	0.0535	Silva & Downing (1995)		
Dipodomys ordii	Ord's kangaroo rat	Genoways et al. (2008b)	0.059	Silva & Downing (1995)	100	Gummer (1997)

Scalopus aquaticus	Eastern mole	Genoways et al. (2008b)	0.12	Silva & Downing (1995)		
Ictidomys tridecemlineatus	Thirteen-lined ground squirrel	Genoways et al. (2008b)	0.1465	Silva & Downing (1995)	53.1	Rongstad (1965)
Mustela frenata	Long-tailed weasel	Genoways et al. (2008b)	0.147	Silva & Downing (1995)	1000	Erlinge (1977)
Geomys bursarius	Plains pocket gopher	Genoways et al. (2008a); Genoways et al. (2008b)	0.27975	Silva & Downing (1995)	378	Quinn et al. (2011)
Poliocitellus franklinii	Franklin's ground squirrel	Genoways et al. (2008b); Jones (1964)	0.363	Silva & Downing (1995)		
Spilogale putorius	Eastern spotted skunk	Genoways et al. (2008b)	0.624	Silva & Downing (1995)		
Mustela nigripes	Black-footed ferret	Jones (1964); Genoways et al. (2008b)	0.74	Silva & Downing (1995)		
Sciurus niger	Eastern fox squirrel	Genoways et al. (2008b)	0.748	Silva & Downing (1995)	3300	Wooding (1997)
Cynomys ludovicianus	Black-tailed prairie dog	Jones (1964); Genoways et al. (2008b)	0.776	Silva & Downing (1995)	2400	Garrett & Franklin (1988)
Neovison vison	American mink	Genoways et al. (2008b)	0.8355	Silva & Downing (1995)	26554.18	Mitchell (1961)
Ondatra zibethicus	Common muskrat	Genoways et al. (2008b)	1.175	Silva & Downing (1995)		
Sylvilagus floridanus	Eastern cottontail	Jones (1964); Genoways et al. (2008b)	1.185	Silva & Downing (1995)	41.06	Chapman & Trethewey (1972)
Mephitis mephitis	Striped skunk	Genoways et al. (2008b)	2	Silva & Downing (1995)	3000	Rosatte & Gunson (1984)
Lepus californicus	Black tailed jackrabbit	Genoways et al. (2008b)	2.3	Silva & Downing (1995)	11000	Smith et al. (2002)
Vulpes velox	Swift fox	Jones (1964); Genoways et al. (2008b)	2.4	Silva & Downing (1995)	13100	Nicholson et al. (2007)
Didelphis virginiana	Virginia opossum	Genoways et al. (2008b)	2.465	Silva & Downing (1995)	5700	Beasley & Rhodes (2012)
Vulpes vulpes	Red fox	Genoways et al. (2008b)	4.03	Silva & Downing (1995)	44800	Gosselink et al. (2010)
Marmota monax	Woodchuck	Genoways et al. (2008b); Forrester et al. (2019)	4.1	Silva & Downing (1995)	685	Swihart (1992)
Urocyon cinereoargenteus	Common gray fox	Jones (1964); Genoways et al. (2008b)	4.205	Silva & Downing (1995)		
Lontra canadensis	North American river otter	Jones (1964); Genoways et al. (2008b)	7.4	Silva & Downing (1995)	3950	Erickson & McCullough (1987)

Castor canadensis	American beaver	Genoways et al. (2008b)	9.07	Silva & Downing (1995)	10150	Sun et al. (2011)
Taxidea taxus	American badger	Genoways et al. (2008b)	9.81	Silva & Downing (1995)		
Lynx rufus	Bobcat	Genoways et al. (2008b)	10.5	Silva & Downing (1995)	57900	Hughes et al. (2019)
Canis latrans	Coyote	Genoways et al. (2008b)	11.8	Silva & Downing (1995)	53200	Hibler (1977)
Procyon lotor	Common raccoon	Genoways et al. (2008b)	12.3	Silva & Downing (1995)	9700	Gehrt & Fritzell (1998)
Canus lupus	Gray wolf	Jones (1964); Genoways et al. (2008b)	25.3	Silva & Downing (1995)	87700	Jimenez et al. (2017)
Antilocapra americana	Pronghorn	Jones (1964); Genoways et al. (2008b)	39.5	Silva & Downing (1995)	26300	Jacques & Jenks (2007)
Puma concolor	Mountain lion	Jones (1964); Genoways et al. (2008b)	60.9	Silva & Downing (1995)	67400	Newby et al. (2013)
Odocoileus hemionus	Mule deer	Genoways et al. (2008b)	65.133	Silva & Downing (1995)	22800	Skelton (2010)
Odcoileus virginianus	White-tailed deer	Genoways et al. (2008b)	68	Silva & Downing (1995)	41000	Nixon et al. (2007)
Ursus americanus	Black bear	Jones (1964); Pelton et al. (1999); Genoways et al. (2008b)	75.5	Silva & Downing (1995)	40000	Costello (2010)
Cervus canadensis	Elk	Jones (1964); Genoways et al. (2008b)	209.5	Silva & Downing (1995)	118000	Petersburg et al. (2000)
Bison bison	American bison	Jones (1964); Genoways et al. (2008b)	480	Silva & Downing (1995)	136850	Jung (2017)

[a]Dispersal distance is for the surrogate species long-tailed pocket mouse (*Chaetodipus formosus*).

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APPENDIX B. HABITAT DESCRIPTION AND ASSOCIATED LANDCOVER TYPES FOR SELECT MAMMAL SPECIES

Species	Habitat description	Associated landcover types
Masked shrew (*Sorex cinereus*)	Moist fields, marshes, bogs, deciduous and coniferous forests, and other riparian areas (Jones et al., 1983; Whitaker, 1997). Variety of habitats, ranging from arid grassland to moist areas, woodlands, and tundra (Whitaker, 2004). Not found in barren areas (Whitaker, 2004).	Farmed playa, grassland playa, RWB farmed, RWB early successional, RWB late successional, emergent marsh, riparian canopy, exotic riparian shrubland, native riparian shrubland, wet meadow, floodplain marsh, upland woodland, eastern red cedar, mixedgrass
North American deer mouse (*Peromyscus maniculatus*)	Wide variety of habitats, including grasslands, brushy country, badlands, cliffs, coniferous woodlands, hedgerows, and shelterbelts (Jones et al., 1983). Prairies and other grasslands (Whitaker, 1997). Not found in deep woods or marshy areas; found in drier upland and moist grassy areas of the Sandhills (Freeman, 1998). Found in prairie dog colonies (Agnew et al., 1986).	Badlands, prairie dog town, mixedgrass
Thirteen-lined ground squirrel (*Ictidomys tridecemlineatus*)	Areas of well-drained soil, including in roadsides and pastureland (Jones et al., 1983). Originally shortgrass prairie (Whitaker, 1997). Found in transitional zone between grassland and forest with low grass, weeds, or shrubby cover (Forsyth, 1999). Found in prairie dog colonies (Agnew, et al., 1986).	Badlands, prairie dog town, mixedgrass
Eastern fox squirrel (*Sciurus niger*)	Follows riparian forest and woodland, as well as shelterbelts and tree plantings in the Great Plains (Jones et al., 1983). Particularly oak-hickory woods (Whitaker, 1997). In riparian areas in western Nebraska and the Sandhills (Jones et al., 1983; Freeman, 1998). Restricted to deciduous forest and riparian and urban woodland (Jones, 1964; Jones et al., 1985).	Riparian canopy, upland woodland, eastern red cedar

Swift fox (*Vulpes velox*)	Primarily shortgrass prairie, desert, and other arid areas (Jones et al., 1983; Whitaker, 1997; Freeman, 1998). In sandy loam to loam soils (Jones et al., 1983). Mainly in short and mixed-grass prairie (Harrison & Whitaker-Hoagland, 2003). Found in areas of sparse vegetation, including prairie dog towns, and grasslands (Sasmal et al., 2011).	Badlands, prairie dog town, mixedgrass
Red fox (*Vulpes vulpes*)	Wide variety of habitats, ranging from deciduous and coniferous forest to riparian areas in semidesert regions (Jones et al., 1983). Never found far from water (Jones et al., 1983). Mixed cultivated and wooded areas, and brushlands (Whitaker, 1997). Common in, but not restricted to, wooded areas; common in riparian areas in the treeless Great Plains (Jones et al., 1985).	Farmed playa, grassland playa, RWB farmed, RWB early successional, RWB late successional, emergent marsh, riparian canopy, exotic riparian shrubland, native riparian shrubland, wet meadow, floodplain marsh, upland woodland, eastern red cedar, mixedgrass
Coyote (*Canis latrans*)	Widespread distribution in the Great Plains, including open grassland, brushy country, badlands, and woodlands (Jones et al., 1983). In western U.S., found in open plains (Whitaker, 1997).	Farmed playa, grassland playa, RWB farmed, RWB early successional, RWB late successional, emergent marsh, riparian canopy, exotic riparian shrubland, native riparian shrubland, wet meadow, floodplain, badlands, prairie dog town, marsh, upland woodland, eastern red cedar, mixedgrass
Black bear (*Ursus americanus*)	Restricted to wooded areas, mostly heavily forested areas (Jones et al., 1983). In western U.S., found in forests and wooded mountains (Whitaker, 1997). Riparian forests provide cover and are a dispersal corridor in Nebraska (Hoffman et al., 2009).	Riparian canopy

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