12-2018

Landscape Structure and Dynamics of Recreational Fisheries

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LANDSCAPE STRUCTURE AND DYNAMICS OF RECREATIONAL FISHERIES

by

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A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Natural Resource Sciences

Under the supervision of Professors Mark A. Kaemingk and Kevin L. Pope

Lincoln, Nebraska

December, 2018

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Angler populations and the waterbodies they use are patchily distributed, creating putatively complex user-resource dynamics on the landscape. Spatially and temporally dynamic relationships between anglers and waterbodies can be difficult to track, understand, and manage. We often focus our efforts on the angler (directly or indirectly) with far less attention devoted to understanding the spatial structure and dynamics of fisheries on the landscape. Waterbodies serve as dynamic attractors on the landscape, shaping landscape patterns in angler participation. We surmise that by understanding the spatial structure and dynamics of recreational fisheries we can gain tremendous insight to cross-scale patterns that shape angler behavior.

We constructed waterbody-specific “anglersheds” that reveal critical links between anglers (i.e., users) and waterbodies (i.e., resources) on the landscape. Anglersheds represent the area of influence or spatiotemporal draw of anglers to a waterbody. Anglersheds were constructed from frequencies of anglers’ zip codes that were collected during on-site interviews (April-October 2014-2017) at eight prominent Nebraska waterbodies. We used these anglersheds to visually depict the spatiotemporal structure and dynamics of these recreational fisheries at multiple spatial scales and temporal levels. We then quantified these spatiotemporal dynamics by extracting multiple anglershed metrics. Anglersheds were dynamic in both space and time; anglershed features such as anglershed area (i.e., size), the degree of fragmentation (i.e.,

number of patches), and compactness (i.e., angler density) also differed among waterbodies. We then selected 11 independent variables that encompassed variation in the spatial socioeconomic structure, on-site attributes, and angler heterogeneity to explain changes in anglershed area for seven prominent Nebraska waterbodies. Anglershed area exhibited a positive relationship with air temperature, wind speed, and population density, but was unrelated to angler effort, catch rate, fuel price, household income, party size, precipitation, trip days, and waterbody size.

Anglersheds have the potential to "unlock" a wealth of information concerning the underlying spatial structure and dynamics of recreational fisheries. This approach has the ability to expose and capture cross-scale interactions within coupled social-ecological systems.

DEDICATION

To my mother and father, Judy and Jerry—for being my never-ending support throughout this entire process. You will always be my favorite fishing buddies.

ACKNOWLEDGMENTS

Completion of my thesis would not have been possible if not for many individuals who provided constant support and insight, and I thank them all. I am incredibly lucky to have such a great support system, which has been a huge contributor to my success. To my advisors, Dr. Kevin Pope and Dr. Mark Kaemingk, thank you for your never-ending support and encouragement throughout the entire process. You continued to stick with me even through my "work better under pressure" philosophy. I have learned a great deal from both of you, both professionally and personally. To Kevin, thank you for always taking the time to answer questions, sharing your knowledge whenever it was asked of you, and for your continued positivity and cheerfulness, which was always needed and welcome. To Mark, thank you for always having an open door whenever I needed to chat, and for always encouraging me and providing advice when I needed it the most. It was an honor being your first graduate student here at the University of Nebraska-Lincoln. I know you both have been and will continue to be an integral part in my success as a fisheries scientist. To the members of my committee, Dr. Erica Stuber and Dr. Richard Holland, your contributions to the development and completion of this work were instrumental throughout the process and I thank you for the great insight and commitment to my work.

The Nebraska Cooperative Fish and Wildlife Research Unit provided an incredible environment to learn and grow as a scientist. To Wilma and Caryl, thank you for your never-ending support and for always being willing to take the time to answer questions whenever needed. To my fellow peers whom I had the pleasure of sharing room 13 with, thank you for inspiring me in my own work, for the much-needed breaks in the office, and your willingness to take the time to give crucial advice throughout the process.

To the members of the CARP lab, both past and present, thank you for your endless hours of support both in and out of lab meeting. Thank you for showing genuine interest in my work, encouraging me along the way, and also sharing experiences and advice that were crucial to my success as a graduate student. You were such an incredibly welcoming and helpful group when I started my journey, and I am proud to have been a part of it.

To the Nebraska Game and Parks Biologists, thank you for your interest and support throughout the completion of my thesis research. You always provided valuable insight and perspective throughout the process. A special thank you to Keith Hurley, who provided technical assistance and support from the very beginning.

To all the creel clerks who worked out in the field during the creel seasons 2014-2017 to collect all the data that were the foundation of my research. To the 19,993 anglers who graciously gave up their time during their fishing trips to answer questions that were asked of them. It means a lot that I was able to recreate the experiences of the anglers who were out using and enjoying the resources.

In particular, I would like to say a special thank you to two of my fellow peers, Vicki Simenson and Alisha Grams. You both immediately became important people in my life and my career from the beginning, and I am so happy we were here at the same time. Thank you for the lunch dates, the two-hour phone calls, the never-ending encouragement, and your incredible friendships that I am so incredibly thankful for.

And last but certainly never least, thank you to my family and friends. There are not words that can effectively show my appreciation for your love and support through these past two and a half years, as well as throughout my entire life. To my parents, Jerry and Judy Ruskamp, you are the reason I am the person I am today and I am incredibly blessed to call you my parents. Thank you for always answering my endless phone calls, welcoming me home with open arms, and supporting me no matter the circumstances. I cannot thank you enough. To my sister and brother-in-law, Laura and Grahm Butler, thank you for always having an open door whenever I needed an escape. You are both such a huge part of my success through your never-failing love and support, and always will be my best friends in life. And lastly, thank you to my partner in life, Mark Bender. Thank you for listening to me when I needed to talk, encouraging me and pushing me when I needed it the most, and always providing a laugh even on the rough days. I appreciate you more and more each day. Completing something as daunting as a Master's program is a true team effort. I am incredibly blessed to have people in my life who would stand beside me no matter what.

This project was funded by Federal Aid in Sport Fish Restoration, project F-182-R, administered by the Nebraska Game and Parks Commission. This research was conducted under IRB protocols 20160616191, 20160616095, and 20160816375.

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GLOSSARY

Resource –provides users with provisioning, supporting, regulating, and cultural services

User – entity, organism or being looking to utilize services provide by resources

Anglershed – area of influence of a resource; the spatiotemporal draw of anglers to a waterbody on the landscape

Anglershed Area – spatial draw or coverage of angler participation on the landscape, measured as hectares

Anglershed Patches – degree of fragmentation of angler participation on the landscape, measured as number of fragments

Anglershed Compactness – degree of angler density for the primary anglershed relative to the median and total anglersheds, measured as a ratio of primary to median and primary to total anglershed area, respectively

CHAPTER 1: INTRODUCTION

Recreational fisheries are important to society; recreation comprises the predominate use of most inland waterbodies around the world, generating substantial economic gain as well as promoting social well-being (Arlinghaus and Cooke 2009). The benefits of recreational fishing are enjoyed by 46 million Americans annually, generating a total economic impact of $115 billion per year for the United States of America (Southwick Associates 2017). In Nebraska, there are over 222,000 fishing license holders in a year (Southwick Associates 2015) who distribut fishing effort across 618 Nebraska lentic public waterbodies. Managing these fisheries is a difficult task but essential to continue to reap the social-ecological benefits these fisheries provide. The main management challenge resides with optimizing resource use. The available ecological resources are diverse, but the angler population is also very diverse, with a range of angler preferences, specializations and motivations (Carpenter and Brock 2004; Johnston et al. 2010; Hunt et al. 2011; Matsummura et al. 2017). These waterbody resources serve as dynamic attractors for anglers on the landscape. The spatial structure and dynamics of recreational fisheries is currently unknown. However, managers and policy makers must account for spatial and temporal heterogeneity among resources and user groups to sustain these recreational fisheries.

Though it is important to recognize and incorporate resource and angler heterogeneity into fisheries management, we have overlooked the role of landscape patterns in shaping resource use. For example, at a basic level (ignoring heterogeneity) we have an unequal distribution of waterbodies and potential anglers on the landscape. This unequal distribution has resulted in areas of high population densities nested within waterbody-rich landscapes and other areas of low population density nested within waterbody-poor landscapes (Figure 1-1). We know that distance is an important consideration for anglers when choosing to participate in recreational fishing (Hunt 2005). Therefore, the spatial arrangement of waterbodies and anglers on the landscape should affect angler behavior. We also recognize that some anglers are willing to travel further because of different preferences, specializations, and motivations (Beardmore et al. 2013). The spatial arrangement and social-ecological heterogeneity among waterbodies and anglers can lead to emergent properties (Kaemingk et al. 2018). We know very little about how these waterbodies or resources influence landscape patterns in angler participation. How far are anglers willing to travel to participate in recreational fishing? Is the acceptable travel distance equal among all waterbodies or are some waterbodies able to attract a more spatially widespread and diverse angler groups? Are these landscape patterns in participation a function of spatial context or waterbody-specific attributes? We have developed a concept and tool that will aid in addressing these questions and understanding the landscape perspective of angler behavior. We hope that this tool will equip managers and researchers alike to sustain recreational fisheries for future generations.

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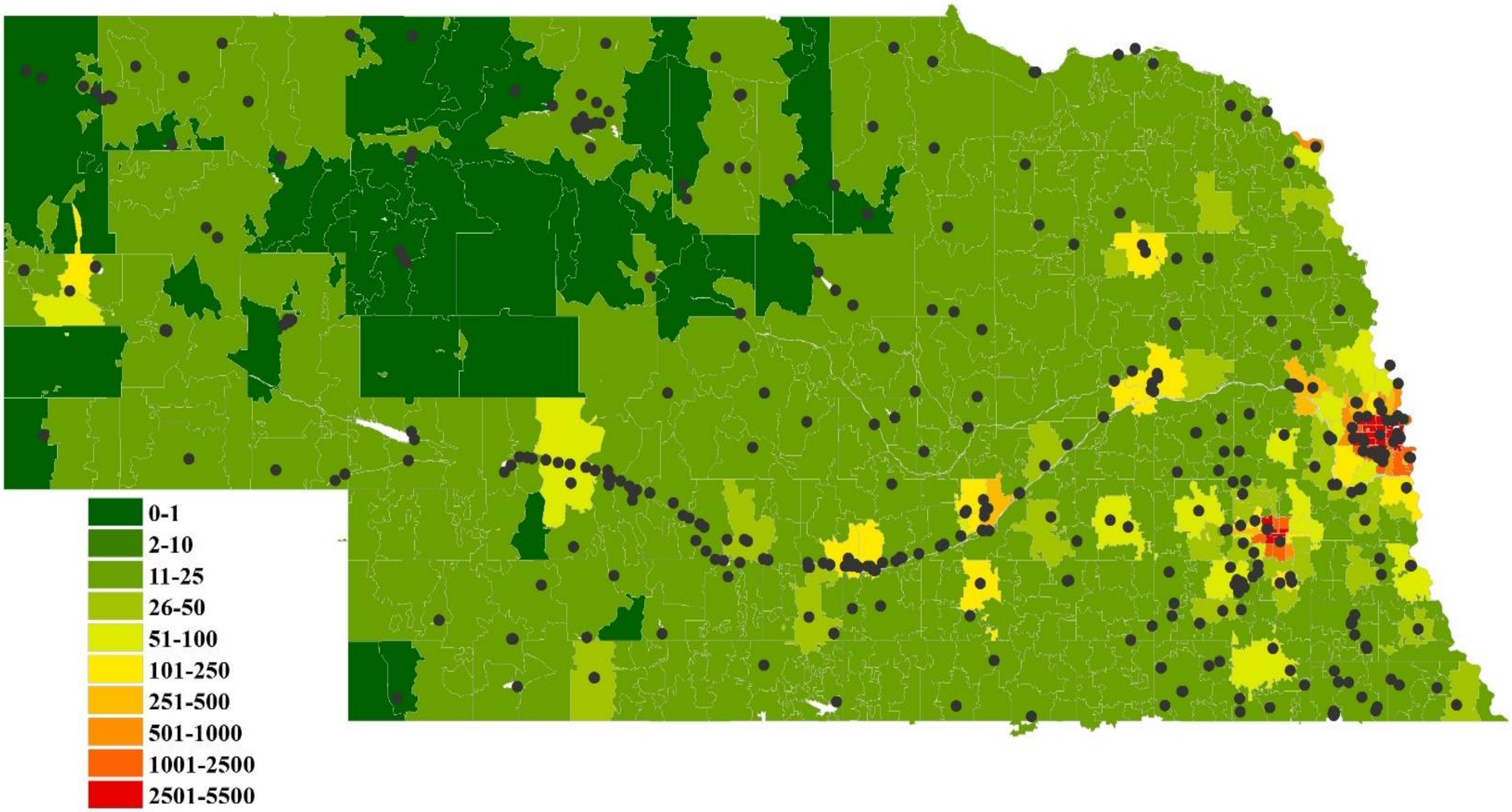

Figure 1-1. Population density (people/km^2) by zip code for Nebraska, USA, during 2018 and locations of lentic public waterbodies (black dots; N=618). Legend beneath map indicates population density with dark green indicating low population density, and dark red indicating high population density.

CHAPTER 2: VISUALIZING AND QUANTIFYING LANDSCAPE-SCALE ANGLER PARTICIPATION PATTERNS

INTRODUCTION

Anglers are highly mobile (Johnson and Carpenter 1994; Cox and Walters 2002; Cox et al. 2003; Post et al. 2008), but not all anglers are willing or able to travel large distances. The decision to travel may also vary through time for each angler (Hunt et al. 2007). Angler heterogeneity, such as the degree of specialization, or preferences (Fisher 1997; Oh and Ditton 2006) among anglers, can lead to different decisions about where and when to participate in fishing activities and resource selection in general (Bryan 1977). Anglers often consider many facets of the fishing experience during the site-selection process (Scrogin et al. 2004; Hunt 2005). For these reasons, angler heterogeneity combined with waterbody heterogeneity create unique patterns and dynamics of angler behavior that are difficult to understand, let alone track (Carpenter and Brock 2004; Johnston et al. 2010; Hunt et al. 2011; Matsummura et al. 2017). Angler behavior also differs across spatial and temporal scales, creating emergent properties in recreational fisheries that stem from local interactions to create large scale patterns in resource use (Kaemingk et al. 2018). Unfortunately, knowledge about how anglers interact with waterbodies across multiple spatiotemporal scales is lacking, especially at the landscape level. This information is required for effective cross-scale fisheries management.

To date, most human dimension fisheries research has focused on understanding the decision-making process of the angler to disentangle complex participation dynamics

(Johnson and Carpenter 1994; Arlinghaus et al. 2017). We often simplify this decision process and assume it is solely based on on-site perception of catch rates or an estimate of fish abundance at a waterbody (Johnson and Carpenter 1994; Beard et al. 2003; Cox et al. 2003). More recent research has recognized that this decision process is more complex than initially thought. Anglers decide to participate in fishing based on both social and ecological aspects of a recreational fishery that may include: available fish species, size of fish population, interference from other anglers, on-site amenities, regulations, and general waterbody aesthetics (Hunt 2005). Hunt et al. (2011) modelled angler behavior and expected that anglers should systematically fish waterbodies with the most productive stocks, ultimately attracting more overall fishing effort at these waterbodies, at least until stocks collapsed. This hypothesis was not supported because anglers sought to maximize overall angler utility, which includes more factors than just catch-related attributes (Hunt et al. 2011). Given this outcome, there is need to incorporate multi-utility attributes to successfully understand angler behavior (Johnston et al. 2010).

Indeed, angler heterogeneity is important but should we also consider waterbody heterogeneity as an integral part of angler behavior at the landscape level? Waterbodies are expected to attract different anglers based on inherent waterbody characteristics, such as amenities, fish-community composition, and aesthetics (Kaemingk et al. 2018). We rarely focus on how individual waterbodies may serve as dynamic attractors for anglers on the landscape. The spatiotemporal “draw” of anglers to a waterbody can be assessed to reveal how angler participation changes as a function of inherent waterbody features. Waterbody heterogeneity could support different subpopulations of anglers through time if anglers vary in their preferences and specializations (Hahn 1991; Fisher 1997;

Connelly et al. 2001). It is unclear how inherent waterbody characteristics could shape angler mobility and participation across spatial and temporal scales. Understanding patterns in angler behavior could reveal angler heterogeneity and waterbody heterogeneity on the landscape (Matsummura et al. 2017). Visualizing and quantifying where anglers reside (i.e., landscape-level spatial structure) could be tremendously valuable for local and regional fisheries management. The spatiotemporal draw of anglers to a particular waterbody may allow managers to better understand who is participating, when they are participating, and why they are participating – all very important fisheries management and conservation considerations.

The spatiotemporal draw of anglers to a waterbody may depend on the waterbody's spatial positioning or landscape context, in addition to inherent waterbody characteristics. Surrounding landscape features, such as human-population density and other competing recreational opportunities, may play a dominant role in a waterbody's ability to attract anglers. These landscape features, which may depend on where the waterbody is positioned relative to other landscape features, factor into angler-utility attributes, such as travel costs and avoidance of other anglers (Arlinghaus and Mehner 2004; Martin et al. 2015). Anglers may also choose to alter temporal patterns based on distance, leading to single-day and multi-day trips; anglers are more likely to take multi-day trips to waterbodies that are further from their residence (Hunt et al. 2011). Factors such as the urban (or rural) composition of the surrounding landscape and density of waterbodies (i.e., waterbody-rich or waterbody-poor landscapes) could affect spatiotemporal patterns of angler participation. For example, waterbodies situated in urban landscapes received greater fishing effort relative to lakes in rural landscapes

(Carpenter and Brock 2004; Post et al. 2008; Matsummura et al. 2017). Ultimately, surrounding landscape attributes should be considered when evaluating how angler behavior is shaped by a resource or waterbody.

The interaction of angler heterogeneity, inherent local or waterbody characteristics, and landscape context should be assessed to understand angler participation. Recreational fishing-effort models are often based on the assumption that participation rates are constant (Hunt et al. 2007). However, several studies highlight seasonal fluctuation in angler participation is related to catch rates and perceived catchability (Lux and Smith 1960). Furthermore, monthly fishing effort is highly variable (Johnson and Carpenter 1994) with anglers often preferring to fish on a particular day of the week (Hunt et al. 2007). Weather patterns can introduce variation in angler behavior across multiple temporal scales (Provencher et al. 2002; Barenklau and Provencher 2005). Temporal dynamics in angler participation can also vary across spatial scales. Local-level angler-participation patterns may form emergent properties at larger spatial scales. Large-scale synchrony in angler behavior emerged from local-level patterns that were associated with inherent waterbody characteristics (Kaemingk et al. 2018). Local-level processes likely shape decisions for less specialized anglers, whereas more specialized anglers shape their decisions at much broader spatial scales (Matsummura et al. 2017). It is evident that angler behavior is highly dynamic and depends on the scale of reference; this requires a more comprehensive evaluation of cross-scale angler behavior.

Our objective was to characterize and understand spatiotemporal structure and dynamics of angler behavior within inland, recreational fisheries. Specifically, we were interested in understanding landscape level angler participation. Resources, such as waterbodies, are predicted to shape landscape patterns in angler participation. It is unlikely that all resources or waterbodies function similarly on the landscape with respect to their ability to attract anglers, but it is unclear how waterbodies may differ. For example, do some waterbodies have the ability to attract anglers from distant locations, whilst other waterbodies can only attract local anglers? We expect that changes in the area of influence or spatiotemporal draw of a waterbody could reflect critical differences among landscape context, on-site attributes, and angler heterogeneity. We used angler ZIP codes collected from on-site interviews at eight Nebraska waterbodies to visualize and quantify the spatial structure and dynamics of recreational fisheries across multiple spatial levels and time scales. These "anglersheds" depicts the area of influence (Martin et al. 2015) or the spatiotemporal draw of anglers to a waterbody. We build on previous work by Martin et al. (2015) to include temporal dynamics, encompass a broader spatial context, and incorporate useful, derived anglershed metrics. This study provided greater insight on the spatial structure and dynamic nature of recreational fisheries across multiple spatial levels and temporal scales. Our results and techniques provide guidance for site-selection of public meetings to better target an intended audience, threat assessment of invasive species, and management actions intended to influence cross-scale angler participation.

METHODS

Study sites

We visualized and quantified anglersheds (i.e., spatial structure and dynamics) for eight Nebraska, USA, waterbodies that encompassed diverse locations, anglers, fishes, and amenities (Table 2-1). Waterbodies varied in distance from large urban centers (i.e., Lincoln and Omaha, Nebraska) and state borders, attracted different angler types (e.g., boat and bank) and species-targeting groups, and offered a range of on-site amenities (e.g., camping facilities, boat ramps) and fish species (Pope et al. 2017). Population densities of the counties in which waterbodies were located ranged from 1 (Calamus Reservoir and Merritt Reservoir) to 345 (Branched Oak Lake and Pawnee Lake) people per 100 ha. Annual angling pressure on these waterbodies during the 2017 open-water season ranged from 1,917 (Harlan County Reservoir) to 30,359 (Lake Wanahoo) bank-angling hours and from 5,178 (Pawnee Lake) to 240,919 (Lake McConaughy) boat-angling hours. Surface area of waterbodies ranged from 299 (Pawnee Lake) to 12,141 (Lake McConaughy) ha (Table 1-1).

Study design

In-person interviews of anglers were conducted at each waterbody during monthly periods of the open-water fishing seasons (April-October) during 2014-2017, though not all waterbodies were sampled every year (Table 2-1). Interview days were determined using a stratified multi-stage probability sampling regime (Malvestuto 1996). Days were stratified by type, with 10 week-days and six weekend-days sampled each month. An additional two interview days were included for “high use” or holiday periods during May (Memorial Day), July (Fourth of July), and September (Labor Day). Each interview day was further stratified into two periods, sunrise to 1330 and 1330 to sunset.

Clerks used automobiles to move (rove with the intent of gathering a representative sample of angler parties proportional to use) among parking areas around the waterbodies, and moved on foot along the shore and in parking lots to contact an angler party (i.e., group of individuals travelling together for the purpose of fishing); thus, data were collected on-site at the party level. Boat anglers were contacted at ramps (generally completed fishing for the day) and bank anglers were contacted at parking areas (generally completed fishing) or on the shoreline (active in fishing). A clerk interviewed one individual within a party who was designated the party-appointed spokesperson. The spokesperson was asked to provide the ZIP code of their home, which was used to estimate the anglers' residence or location from which they traveled.

Constructing anglersheds

An anglershed represents the spatiotemporal draw of anglers or landscape structure of a recreational fishery. We constructed anglersheds from ZIP codes of anglers' residences for each study waterbody. We filtered interviewed anglers to only include ZIP codes from Nebraska and bordering states (Colorado, Iowa, Kansas, Missouri, South Dakota, Wyoming) to avoid influence from extreme outliers and to facilitate logistics of computational limitations. Anglers residing outside of this region represented less than 1% of interviewed anglers for study waterbodies across study years (Table 2-2). Each ZIP code (or angler party) was randomly assigned, using a bootstrapping method, to a census block within the ZIP code to reduce spatial error and to better represent the regional distribution of anglers (Martin et al. 2015). Census blocks are determined by population size; number of census blocks within a ZIP code increases as population density increases. The centroid of a selected census block was used to represent the location of a respective angler's residence (Martin et al. 2015).

Kernel-density estimation (Worton 1989; Seaman and Powell 1996) was used to delineate anglersheds (Figure 1-1). Kernel-density estimation is a common wildlife-ecology technique for mapping spatial distributions, and was previously used to assess angler participation in an urban setting (Martin et al. 2015). Kernel-density estimation has also been broadly applied to determine placement sites for hospitals (Donthu and Rust 1989), quantify distribution of traffic accidents (Xie and Yan 2008) and crime hot-spots (Wang et al. 2013). Kernel-density estimation is the method of choice for modern studies of organism-space relationships (Marzluff et. al. 2004) because this method provides the ability to account for multiple centers of activity (Powell 2000; Kenward 2001; Kernohan et al. 2001) and is robust to changes in spatial resolution of data (Hansteen et al. 1997).

We used the kernelUD function (classic kernel method) in the adehabitatHR package in R (Calenge 2006) to characterize and quantify anglersheds. A bivariate normal kernel was used, which places a bivariate normal kernel over each observed point (angler residence) and uses a smoothing parameter, h, to control the width of the bivariate normal kernel (Martin et al. 2015). We calculated 10%, 50%, and 95% utilization distribution (UD) contours with h set using the ad hoc level, “href”. Utilization distribution contours are referenced henceforth as primary anglershed (10%), median anglershed (50%), and total anglershed (95%); these three utilization distribution contours represent different spatial levels of participation. The primary anglershed reflects the densest area of angler participation on the landscape. We expected the primary anglershed to include the area near the waterbody, or areas of high population density, as it represents the locations with minimal travel distance. Each anglershed (primary, median, total) captures different information about spatial arrangement and distributions of participating anglers on the landscape and temporal patterns of angler participation.

Anglershed metrics

We evaluated three anglershed metrics (across primary, median, and total anglersheds) to quantify spatial patterns of angler participation: area (ha), patches, and compactness (Table 2-2). Area represents the spatial draw or coverage of anglers on the landscape, and was estimated as the landmass encompassed by the utilization distribution contour(s). Patches represents the degree of fragmentation of angler participation on the landscape, and was estimated as the number of distinct and disconnected distribution contours. Compactness represents the degree of angler density for the primary anglershed relative to the median and total anglersheds, and was estimated as the proportion of area for an anglershed that was accounted by the primary anglershed (compactness of median anglershed = area of primary anglershed / area of median anglershed; compactness of total anglershed = area of primary anglershed / area of total anglershed). A large value for compactness is indicative of an increase in area of the primary anglershed and a small value is indicative of a decrease in area of the primary anglershed relative to the median and total anglersheds. There is little to no literature that applies landscape metrics, which are most commonly found in landscape ecology, to the spatial structure of angler participation. As a result, the process of deciding which metrics would be most informative was based on what we thought would provide unique information for visualizing and quantifying landscape-level angler participation. Area, patches, and compactness are well-studied landscape metrics, and thus also afforded the opportunity to quantify the spatial structure of angler participation. We expected these three anglershed metrics to vary among waterbodies, indicative of various social and ecological attributes.

Temporal Scale

We used three scales to evaluate the temporal dynamics of anglersheds: monthly, seasonal (Spring = April-May, Summer = June-August, Fall = September-October), and annual. Each of these scales provides differing levels of detail and variation because angler participation frequency and timing of angler participation differs spatially on the landscape (see Kaemingk et al. 2018). To further evaluate dynamics, we calculated the coefficient of variation (CV) for each time scale and spatial level (primary, median, total) for each waterbody, and compared variations across spatial levels and time scales. For example, a high CV in the monthly scale for the area of the total anglershed would indicate high variation in the spatial structure of a fishery.

RESULTS

A total of 21,026 angler-parties were interviewed across the 4 years at the 8 waterbodies sampled. In-state (i.e., Nebraska residence) anglers comprised 95% of all interviews (Table 2-3). Most out-of-state anglers traveled from Colorado (Table 2-3) and a majority of those anglers fished at Lake McConaughy. Interviewed anglers comprised 979 unique ZIP codes, 853 of which were contained within our study area (Nebraska and six adjacent states). In-state anglers resided in 526 (of 618 available) ZIP codes, representing 85% of the ZIP codes in Nebraska. Anglershed maps (Appendix 1, 2, 3) and metrics (Appendix 4, 5, 6, 7) illustrated dynamic landscape patterns in angler participation at multiple spatial levels (primary, median, and total) and temporal scales (monthly, seasonal, and annual). Anglersheds were most dynamic, as indicated visually and by the CV, at the monthly scale and least dynamic at the annual scale across all spatial levels for area (Figures 2-2, 2-3, 2-4), patches (Figures 2-5, 2-6, 2-7), and compactness (Figures 2-8, 2-9).

Monthly scale

The smallest and largest area of both primary and median anglersheds occurred during April and June, respectively (Table 2-4). However, the smallest and largest area of the total anglershed occurred during August and June, respectively. Branched Oak Lake and Lake McConaughy had the smallest and largest area of the primary, and total anglersheds at the monthly scale, respectively (Table 2-5). In contrast, Branched Oak Lake and Merritt Reservoir had the smallest and largest area of the median anglershed, respectively.

The fewest and greatest number of patches for the primary anglershed occurred during April and June, respectively. However, the fewest and greatest number of patches for the median anglershed occurred during June and August, respectively. The fewest and greatest number of patches for the total anglershed occurred during April and September, respectively. Branched Oak Lake, Harlan County Reservoir, Pawnee Lake, and Sherman Reservoir had the fewest number of patches and Calamus Reservoir had the greatest number of patches for the primary anglershed (Table 2-5). In contrast, Branched Oak Lake and Merritt Reservoir had the fewest and greatest number of patches for the median anglershed, respectively. Branched Oak Lake and Lake McConaughy had the fewest and greatest number of patches for the total anglershed at the monthly scale, respectively.

As expected (based on definition), compactness of the median anglershed was considerably higher than compactness of the total anglershed (Table 2-4). The lowest and highest compactness of the median anglershed occurred during May and June, respectively. However, the lowest and highest compactness of the total anglershed occurred during May and September, respectively. Branched Oak Lake and Lake McConaughy had the lowest and highest compactness, respectively, for both median and total anglersheds.

Seasonal Scale

The smallest and largest areas of the primary anglershed occurred during fall and spring, respectively (Table 2-4). However, the smallest and largest areas of the median anglershed occurred during summer and fall, respectively. In contrast, the smallest and largest area of the total anglershed occurred during spring and summer, respectively. Branched Oak Lake and Merritt Reservoir had the smallest and largest areas, respectively, of the primary, median, and total anglersheds at the seasonal scale (Table 2-5).

The fewest and greatest number of patches for the primary anglershed occurred during spring and fall, respectively (Table 2-4). However, the fewest number of patches for the median anglershed occurred during spring and summer and the greatest number of patches occurred during fall. The fewest and greatest number of patches for the total anglershed occurred during summer and fall, respectively. Branched Oak Lake, Harlan County Reservoir, Pawnee Lake, and Sherman Reservoir had the fewest number of patches for the primary anglershed and Merritt Reservoir had the greatest number of patches (Table 2-5). Branched Oak Lake, Harlan County Reservoir, Pawnee Lake and Sherman Reservoir had the fewest number of patches for the median anglershed and Merritt Reservoir had greatest number of patches. In contrast, Sherman Reservoir had the fewest number of patches for the total anglershed and Branched Oak Lake and Pawnee Lake had the greatest number of patches for the total anglershed at the seasonal scale.

The lowest compactness for the median anglershed occurred during spring and highest compactness occurred during summer and fall. However, the lowest and highest compactness for the total anglershed occurred during spring and fall, respectively. Sherman Reservoir and Pawnee Lake had the lowest and highest compactness for the median anglershed, respectively. In contrast, Merritt Reservoir and Branched Oak Lake had the highest and lowest compactness for the total anglershed, respectively.

Annual Scale

The smallest and largest areas of the primary and median anglersheds occurred during 2017 and 2015, respectively (Table 2-4). In contrast, the smallest and largest area of the total anglershed occurred during 2016 and 2014, respectively. Branched Oak Lake and Merritt Reservoir had the smallest and largest area of the primary, median, and total anglersheds at the annual scale, respectively (Table 2-5).

The fewest number of patches for the primary anglershed occurred during 2017 and the greatest number of patches occurred during 2014, 2015, and 2016 (Table 2-4). However, the fewest number of patches for the median anglershed occurred during 2014 and 2016 and the greatest number of patches occurred during 2015. The fewest number of patches for the total anglershed occurred during 2015 and 2017 and the greatest number of patches occurred during 2014 and 2016. Branched Oak Lake, Calamus Reservoir, Harlan County Reservoir, Pawnee Lake, and Sherman Reservoir had the fewest number of patches for the primary and median anglersheds and Merritt Reservoir had the greatest number of patches (Table 2-5). In contrast, Calamus Reservoir, Harlan

County Reservoir, Lake McConaughy, and Pawnee Lake had the fewest number of patches for the total anglershed at the annual scale and Branched Oak Lake had the greatest number of patches.

The lowest and highest compactness for the median anglershed occurred during 2017 and 2014, respectively. However, the lowest and highest compactness for the total anglershed occurred during 2017 and 2015, respectively. Sherman Reservoir had the lowest compactness for the median anglershed and Calamus Reservoir and Pawnee Lake had the highest compactness. In contrast, Merritt Reservoir and Branched Oak Lake had the highest and lowest compactness for the total anglershed, respectively.

Anglershed dynamics

Anglershed area generally increased from the primary-anglershed level to the total- anglershed level. However, anglershed area decreased from the monthly to the annual scale. The number of patches generally increased from the primary-anglershed level to the total- anglershed level, but the number of patches generally decreased from the monthly to the annual scale. Compactness was much larger in the median-anglershed level compared to the total-anglershed level, and decreased from the monthly to the annual scale.

There was no clear trend in CV for anglershed area across primary-, median-, and total-anglershed levels. However, the CV for anglershed area decreased from the monthly to annual scale (Figure 1-10). The CV in the monthly and seasonal scales were higher in the total-anglershed level and lower in the primary- and median-anglershed levels. However, there was not a clear pattern in CV at annual scale for the primary-, median-, and total-anglershed levels. The CV for number of patches showed a slight decrease from the monthly to the annual scale (Figure 2-11). The CV for anglershed compactness was generally higher in the total-anglershed level compared to the median-anglershed level. The CV for anglershed compactness decreased from the monthly to the annual scale (Figure 2-12).

DISCUSSION

Anglersheds provide insights of the dynamic interaction between anglers and waterbodies distributed across the landscape. Our ability to better understand resource–use, despite heterogeneity in both users and resources, was strengthened by the visualization and quantification of the spatiotemporal structure and dynamics of angler participation on a landscape. We characterized dynamics in angler participation by quantifying area, patches, and compactness of anglersheds across three spatial levels and three temporal scales for eight waterbodies. Our approach highlighted the dynamic behavior of angler participation; angler participation was dynamic in space and time across multiple scales. The visualization and quantification of anglersheds offer a novel way for disentangling complex spatiotemporal relationships between anglers and waterbodies at a landscape level. We believe this approach could be extended to other social-ecological systems that aim to understand landscape structure and dynamics in resource-use.

Kernel density estimation is an appropriate tool for constructing, visualizing, and quantifying anglersheds. Even so, caution is warranted especially toward the minimum sample size required to accurately depict a spatial distribution (Seaman and Powell 1996; Seaman et al.1999; Boyle et al. 2009). Anglersheds at the monthly scale were particularly vulnerable to sample size, especially at the beginning (i.e., April, May) and ending (i.e., September, October) of the fishing season when participation was low. For example, Seaman et al. (1999) recommends a minimum of 30 observations for calculating kernel densities and 4% (7 of 185 months) of our monthly samples fell below this benchmark. However, the recommended minimum sample size was easily met at both seasonal and annual scales. There was an obvious trend of decreasing anglershed area with increasing temporal scale; thus, the visual representation of the spatial draw of anglers to a waterbody appears to be related to the scale assessed, duration and intensity of angler interviews, and even the temperament of clerks, all of which affect sample size (i.e., number of parties interviewed). The monthly scale often had the largest anglershed size and the most variation compared to the other two time scales evaluated; these outcomes are likely related to a combination of spatiotemporal differences in participation rates and sample size. This is most likely a result of the fact that an increase in sample size at larger scales puts more points (i.e., angler locations) in the core area of the anglershed, which decreases the influence of outside points on the perimeter of the anglershed as seen during the monthly scale. However, we did not have a way of directly quantifying this relationship.

Examining anglersheds across three time scales (monthly, seasonal, annual) provided different insight to landscape patterns in angler participation. In the same way, three different spatial levels (primary, median, and total) afforded a unique understanding of anglershed dynamics. Applications of our findings should consider the appropriate temporal and spatial scale before making recommendations. For example, the monthly scale will provide greater insight if we are interested in participation dynamics at a waterbody during a year due to processes occurring at faster scales, such as fish catchability, air temperature, or boat-ramp congestion. Alternatively, the annual scale will provide greater insight if we are interested in participation dynamics at a waterbody across years due to processes occurring at slower scales, such as license sales, a strong year-class of fish, or inflation. The same approach applies to selecting the appropriate spatial level; more frequent participation should be assessed at the primary-anglershed level and less frequent participation at the total-anglershed level. Ultimately, based on our results, it is important to be mindful that it is not appropriate to generalize, for example, monthly anglershed patterns from annual-scale data or infer primary-anglershed patterns from total-anglershed data.

Our three anglershed metrics proved useful for further characterizing angler participation across space and time. Anglershed area ultimately provides a landscape view of the spatial draw or structure of a fishery, reflecting angler residences and their spatial positioning relative to the waterbody. Anglershed area allowed us to characterize individual waterbodies and their ability to attract anglers from a distance. There appears to be a positive relationship between anglers' willingness to travel and waterbody surface area (Hunt et al. 2007). However, this relationship should be empirically tested (see Chapter 2).

Lake McConaughy (largest study waterbody) and Merritt Reservoir have similar landscape contexts as they are both situated in rural settings, but it appears that the social-ecological attributes of these two waterbodies differ, uniquely affecting the spatial draw of anglers. We suspect that Merritt Reservoir had a larger than expected anglershed area because it is surrounded by a multitude of complementary outdoor recreational opportunities (e.g., Niobrara River [designated by U.S. Congress as a National Scenic River], Sandhills of Nebraska [largest tract of stabilized sand dunes in the Western Hemisphere], Snake River Falls, Valentine National Wildlife Refuge, and The Prairie Club [top ranked golf course]). We predicted that inherent waterbody characteristics could interact with the landscape context to create unique anglersheds. Smaller spatial draws of anglers to these waterbodies near urban centers (e.g., Pawnee Lake and Branched Oak Lake) could be a function of their landscape context and inherent waterbody characteristics. Somewhat surprisingly, Pawnee Lake consistently had a larger anglershed area than Branched Oak Lake even though Pawnee Lake is one-third the size (Table 2-1) of and has half as many anglers as Branched Oak Lake (Pope et al. 2017). Branched Oak Lake is attractive to recreational boaters during summer, and a negative relationship could exist between anglers' willingness to travel and perceived congestion at a waterbody (Hunt et al. 2007). Therefore, anglershed size was a meaningful metric that provided insight to social-ecological relationships and dynamics across different landscape settings.

The number of anglershed patches reflected the amount of fragmentation of angler participation on the landscape. In other words, less fragmentation (number of patches) indicates a more cohesive distribution of anglers on the landscape within an anglershed. Whilst more fragmentation demonstrates an unequal and less cohesive distribution of anglers on the landscape within an anglershed. Anglershed fragmentation could expose urban areas or dense population centers on the landscape from which a waterbody can draw anglers from. However, the relationship between urban centers and greater fragmentation assumes that angler participation is proportional to population size.

Angler heterogeneity would predict that participation patterns are unequal, especially between urban and rural areas despite population size (Arlinghaus and Mehner 2004). We found greater anglershed fragmentation at Branched Oak Lake and Pawnee Lake at the total level, whereas greater anglershed fragmentation occurred at Lake McConaughy and Merritt Reservoir at the median and primary spatial levels. We interpret these results to suggest that anglershed fragmentation could be a function of complex interactions among the surrounding landscape (i.e., population density), angler heterogeneity, and inherent local waterbody characteristics. Branched Oak Lake and Pawnee Lake are both situated near Lincoln and Omaha, NE, the two largest urban centers in Nebraska. Both of these lakes have smaller anglersheds that are likely sensitive to changes in angler participation. For example, sometimes the Branched Oak Lake and Pawnee Lake anglershed at the total level encompass both Lincoln and Omaha metropolitan areas (i.e., two separate regions). On the other hand, Lake McConaughy is situated in a rural setting and has a large anglershed that is likely less sensitive to changes in angler participation at the total level. The total anglershed was less fragmented for Lake McConaughy, but the primary- and median-anglersheds were often more fragmented and situated at an area near Lake McConaughy and one centered on or near Denver, CO. Dynamic participation patterns are most evident in the primary and median-anglersheds, which suggests that in this case, population supply (i.e., Denver) and high participation frequency (i.e., near Lake McConaughy) may explain why fragmentation occurred at these two smaller spatial levels. We believe that the extent of anglershed fragmentation is a meaningful way to evaluate the evenness and cohesiveness of angler participation on the landscape that can expose landscape aspects of population density, angler heterogeneity, participation rates, and inherent waterbody characteristics.

Compactness highlights the relative proportion of high participation areas (i.e., primary and median levels) to that of the entire range of participation (i.e., total level) on the landscape. In other words, compactness focuses on intra-anglershed patterns that depict changes in high participation areas relative to low participation areas within the anglershed. A change in anglershed compactness could result from a distance-based phenomenon that modifies the area (increase or decrease) of angler participation in the primary and median levels or the high participation areas of the anglershed. A "hot" white bass bite could trigger an immediate change in the high participation areas through 'word-of-mouth', spreading locally from the waterbody but not immediately modifying the less frequent or outlying participation areas. We did not see a distinct pattern in compactness among the waterbodies sampled for either the median or total compactness, but compactness increased from the monthly to annual scale. This may be a due to the increase of sample size, particularly in the primary anglershed, with a larger temporal scale as we are potentially adding more points nearby the waterbody, and decreasing the influence of outer points at the perimeter. If sufficient sample size is reached, compactness could also be evaluated at shorter temporal scales to detect subtle and quick changes within the anglershed. Anglershed compactness provides a unique view of angler participation that is not captured by anglershed area or patches.

Each anglershed metric highlights a specific facet of spatial participation on the landscape, but are not necessarily meant to be evaluated separately. Alternatively, they can work together to further characterize waterbodies to highlight spatial patterns that can be related to the spatial socioeconomic structure, inherent on-site waterbody attributes, or angler heterogeneity. For example, waterbody size could be used to explain landscape patterns in anglershed dynamics (Figure 2-13). This is only one example of the various relationships that could exist among waterbodies and anglershed metrics. Visualizing and quantifying anglersheds, or spatial structure and dynamics of recreational fisheries promotes the idea that the angler population is certainly not static but highly dynamic. Anglersheds also provide a tool for direct management applications. Anglersheds allow for targeted spatial approaches, revealing areas with and without active anglers. This information could bring about strategic placement of public meetings or marketing materials for current and future anglers.

There still remains a need to further evaluate anglersheds, particularly their dynamic nature not only in the area or patches, but also their spatial location on the landscape. We may not see changes in the area of the anglershed, but the spatial location of the anglershed may have shifted drastically. This is a clear "next step" in the continuation of our investigation of understanding the spatial structure and dynamics of recreational fisheries. Despite identifying pronounced spatiotemporal variation in anglershed dynamics, it is unclear what is responsible for these changes in landscape participation. This level of understanding is required for proper cross-scale management that will sustain and optimize these complex social-ecological relationships on the landscape.

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Table 2-1. Size in surface area (ha) and location of Nebraska waterbodies, and years anglers were interviewed.

Waterbody	Surface Area (ha)	Latitude (N)	Longitude (W)	Years Sampled
Branched Oak Lake	730	40.908741°	-96.865573°	2014, 2015, 2016
Calamus Reservoir	2,104	41.847825°	-99.220833°	2014, 2015, 2016, 2017
Harlan County Reservoir	5,463	40.057313°	-99.272493°	2014, 2015, 2016, 2017
Lake McConaughy	12,141	41.248224°	-101.683402°	2014, 2015, 2016, 2017
Lake Wanahoo	379	41.234510°	-96.614971°	2017
Merritt Reservoir	1,173	42.627675°	-100.871769°	2014, 2015, 2016
Pawnee Lake	299	40.838889°	-96.865556°	2014, 2015, 2016, 2017
Sherman Reservoir	1,151	41.302863°	-98.885985°	2014, 2015, 2016, 2017

Table 2-2. Summary of anglershed metrics used to quantify dynamics in angler participation.

Metric	Description	Meaning
Area	spatial area of primary (10%), median (50%), and total (95%) utilization distribution (UD) that comprise an anglershed	represents the spatial distribution of angler parties who were drawn in to participate at a waterbody; larger area values indicate greater spatial representation on the landscape
Patches	number of patches that make up the primary, median, and total UD that comprise an anglershed	indicates amount of fragmentation of spatial draw of the angler population participating at a waterbody; larger values indicate a more fragmented angler population and smaller values indicate less fragmented participation on the landscape (i.e., more cohesive)
Compactness	calculated as the proportion of the primary area within the median area (10% UD/50% UD) and the proportion of the primary area within the total area of an anglershed (50% UD/95% UD)	indicates intra-anglershed patterns of the relative proportion of high participation areas to that of the entire range of participation

Table 2-3. Number of in-state (Nebraska) and out-of-state (Colorado, Iowa, Kansas, Missouri, South Dakota, Wyoming) angler-parties interviewed across eight Nebraska Waterbodies during 2014-2017.

Location	Number of Parties	Percentage
In-State	19,949	94.88%
Out-of-State	1,077	5.12%
Colorado	778	3.70%
Iowa	89	0.42%
Kansas	97	0.46%
Missouri	9	0.04%
South Dakota	56	0.27%
Wyoming	48	0.23%
Total	21,026	

Table 2-4**.** Mean values of anglershed metrics (P = primary, M = median, T = total) across eight Nebraska waterbodies (see Table 2-1) by time scales (month, season, year).

	Area			Patches			Compactness	
Period	P	M	T	P	M	T	M	T
Month								
Apr	625,062	3,937,026	21,154,703	1.00	1.13	2.08	16.30	2.69
May	762,982	4,610,081	23,056,308	1.04	1.15	1.73	16.22	2.59
Jun	966,168	5,410,960	25,194,990	1.23	1.08	1.85	16.85	2.91
Jul	820,554	4,749,963	22,135,997	1.03	1.15	1.77	16.46	2.85
Aug	660,262	4,046,456	19,075,046	1.12	1.31	1.62	16.24	2.86
Sep	917,774	5,233,795	23,254,505	1.04	1.16	1.56	16.56	3.06
Oct	833,117	4,721,269	22,186,512	1.08	1.16	1.68	16.60	2.98
Season								
Spring	522,942	4,085,540	21,201,850	1.04	1.23	1.62	12.99	2.02
Summer	533,730	4,027,257	19,525,472	1.08	1.23	1.58	13.20	2.14
Fall	593,839	4,491,411	20,831,825	1.12	1.28	1.64	13.20	2.28
Year								
2014	461,645	3,690,584	19,154,763	1.14	1.29	1.29	12.67	1.85
2015	466,569	3,755,528	19,002,039	1.14	1.43	1.00	12.64	1.96
2016	406,551	3,394,518	16,332,414	1.14	1.29	1.29	12.46	1.92
2017	360,120	3,001,104	16,629,110	1.00	1.40	1.00	12.13	1.81

Table 2-5. Mean values of anglershed metrics (P = primary, M = median, T = total) across eight Nebraska waterbodies by time scales (month, seasonal, annual) (BO = Branched Oak, CA = Calamus, HC = Harlan County, MC = McConaughy, WA = Wanahoo, ME = Merritt, PA = Pawnee, SH = Sherman). Wanahoo does not have a mean value for year as it was only sampled one year.

	Area			Patches			Compactness	
Waterbody	P	M	T	P	M	T	M	T
Month								
BO	29,045	219,752	2,043,073	1.00	1.00	2.67	13.18	1.37
CA	581,068	4,284,619	19,698,722	1.16	1.36	1.48	13.56	3.01
HC	352,746	1,997,020	11,755,202	1.00	1.07	1.85	16.85	1.61
MC	2,700,208	12,810,805	58,307,705	1.11	1.33	1.15	20.97	4.54
WA	60,463	447,965	2,486,764	1.14	1.86	3.00	13.22	2.43
ME	1,775,408	12,901,703	58,129,367	1.12	1.31	1.62	16.24	2.86
PA	62,348	282,281	2,162,289	1.00	1.00	2.57	16.56	3.06
SH	188,731	1,431,177	9,274,754	1.00	1.04	1.46	16.60	2.98
Season								
BO	21,657	167,040	1,903,893	1.00	1.00	2.33	12.93	1.13
CA	515,177	3,970.309	18,398,896	1.36	1.55	1.58	12.96	2.81
HC	240,487	1,811,987	11,414,582	1.00	1.00	1.67	13.28	2.11
MC	1,553,042	11,734,645	54,549,298	1.67	1.50	1.08	13.17	2.81
WA	49,441	393,951	2,379,223					
ME	1,584,847	12,206,777	54,923,586	1.11	1.78	1.56	12.97	2.94
PA	29,691	210,816	1,975,559	1.00	1.00	2.33	13.96	1.42
SH	151,462	1,209,438	8,531,087	1.00	1.00	1.00	12.53	1.78

Table 2-5. Continued.

Waterbody	Area			Patches			Compactness	
	P	M	T	P	M	T	M	T
Year								
BO	15,341	122,211	1,783,222	1.00	1.00	1.67	12.54	0.87
CA	428,603	3,468,886	16,690,069	1.00	1.00	1.00	13.84	1.17
HC	201,333	1,569,346	10,575,500	1.00	1.00	1.00	12.82	1.90
MC	1,045,979	8,244,953	41,555,156	1.25	2.00	1.00	12.59	2.51
ME	1,275,814	10,865005	48,228,098	1.33	1.67	1.33	11.72	2.65
PA	22,756	161,180	1,925,614	1.00	1.00	1.00	13.84	1.17
SH	118,953	1,034,706	7,887,687	1.00	1.00	1.25	11.46	1.51

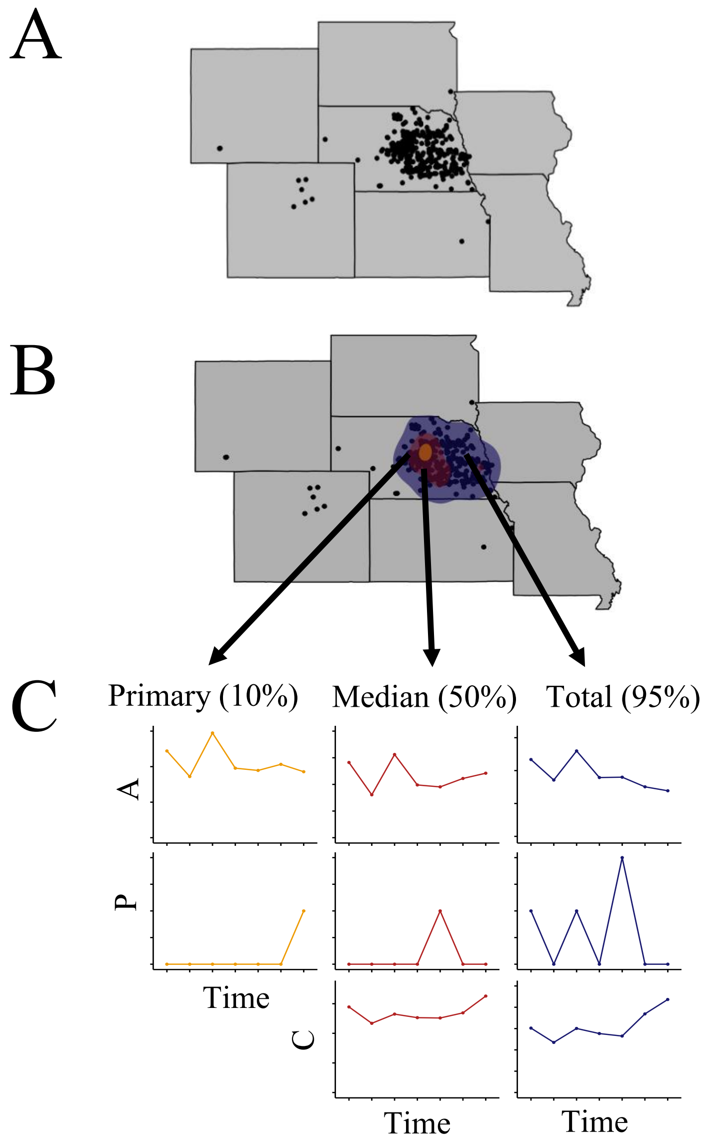

Figure 2-1. Methods diagram illustrating characterization and quantification of anglersheds. (A) shows all anglers who were interviewed at a waterbody within our study area (Nebraska, South Dakota, Wyoming, Colorado, Missouri, Iowa). (B) illustrates the results of the kernel density estimator showing the primary (10%), median (50%), and total (95%) anglershed. (C) illustrates the use of landscape metrics such as area (A), number of patches (P), and compactness (C) to quantify anglersheds through time.

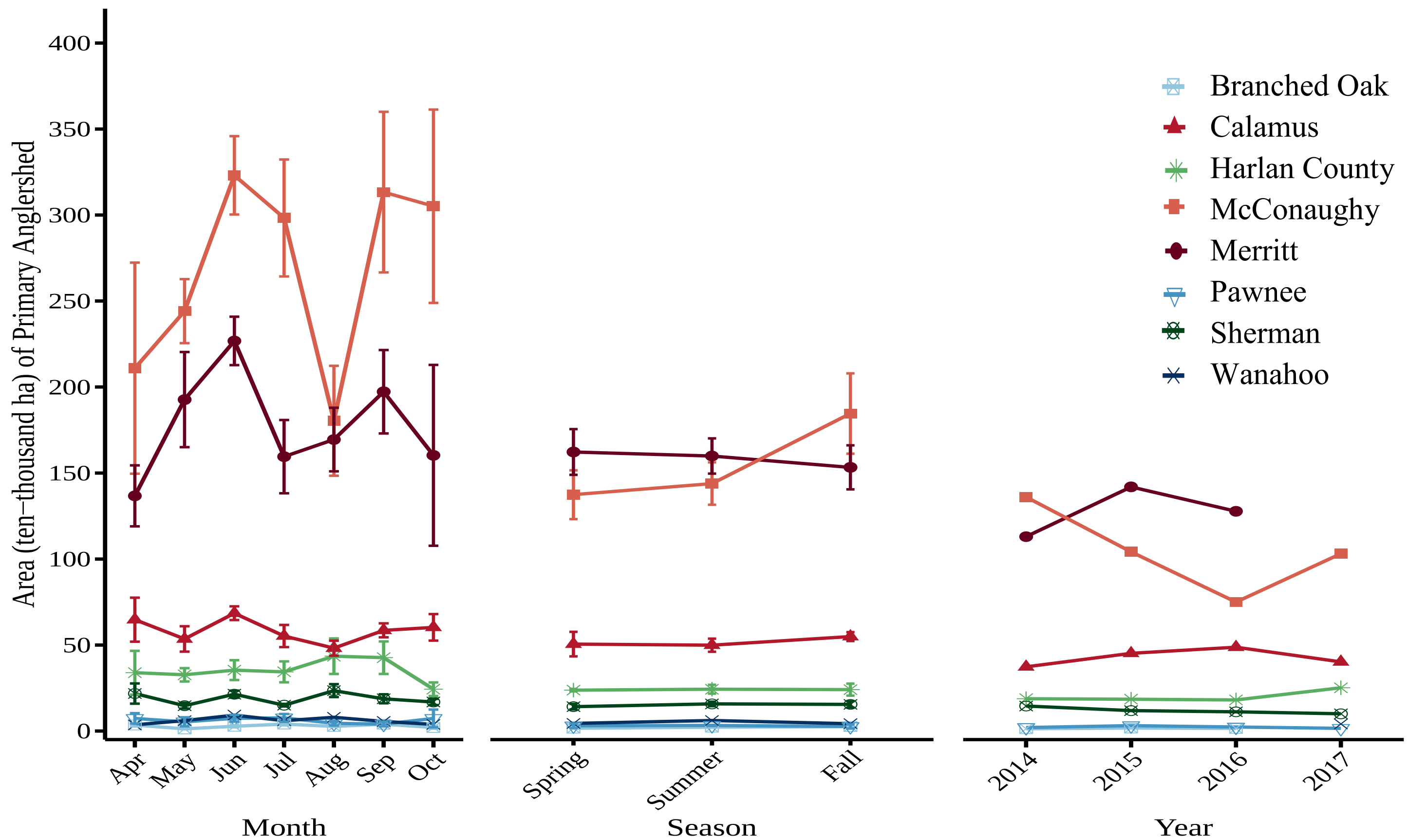

Figure 2-2. Area (mean ± SE) of the primary anglershed (10% UD) for eight Nebraska waterbodies at three temporal scales: monthly, seasonal (spring = April-May, summer = June-August, and fall = September-October), and annual. Standard error is not reported for the annual temporal scale (i.e., single observations) and Lake Wanahoo (i.e., sampled one year).

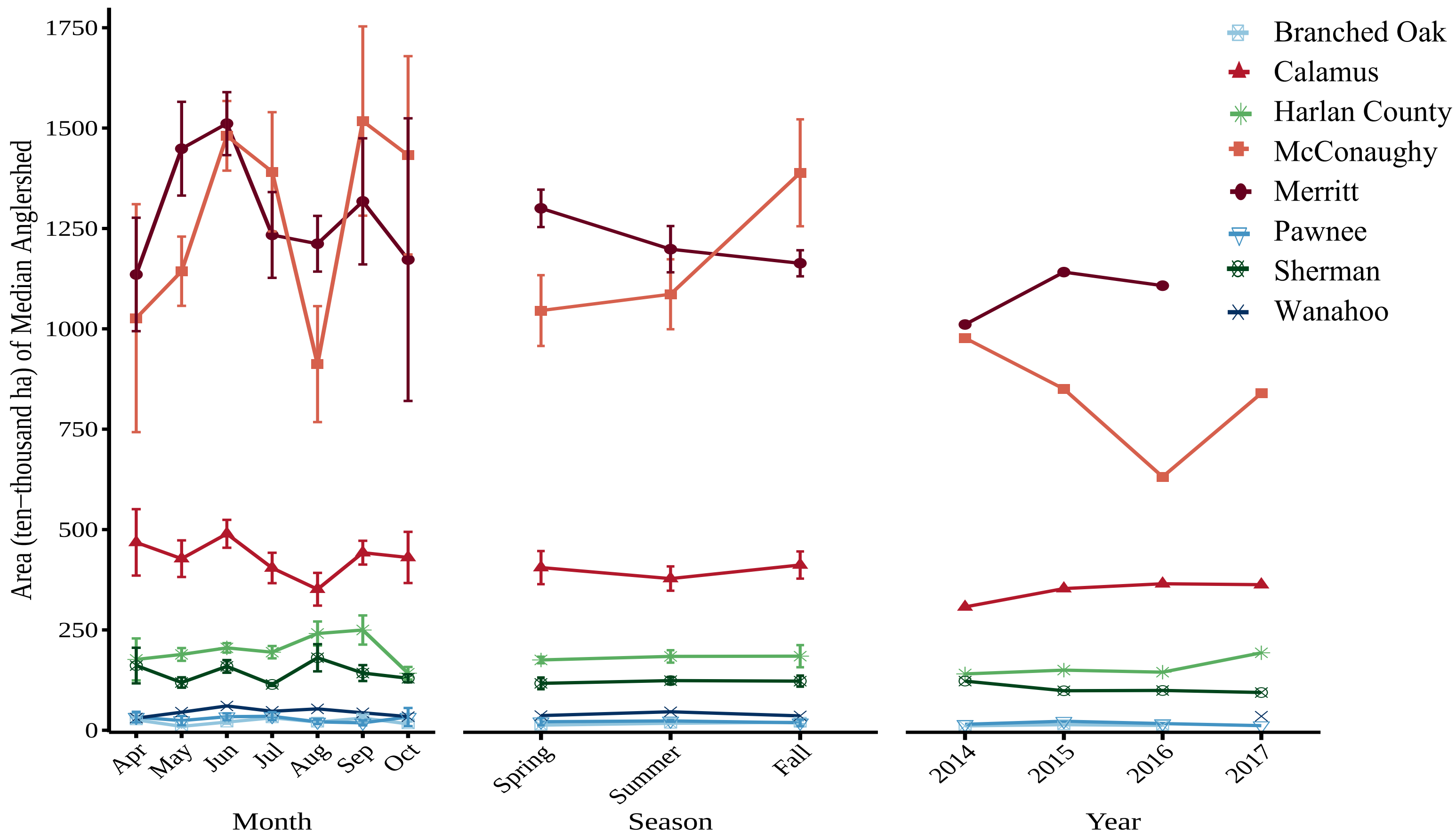

Figure 2-3. Area (mean ± SE) of the median anglershed (50% UD) for eight Nebraska waterbodies at three temporal scales: monthly, seasonal (spring = April-May, summer = June-August, and fall = September-October), and annual. Standard error is not reported for the annual temporal scale (i.e., single observations) and Lake Wanahoo (i.e., sampled one year).

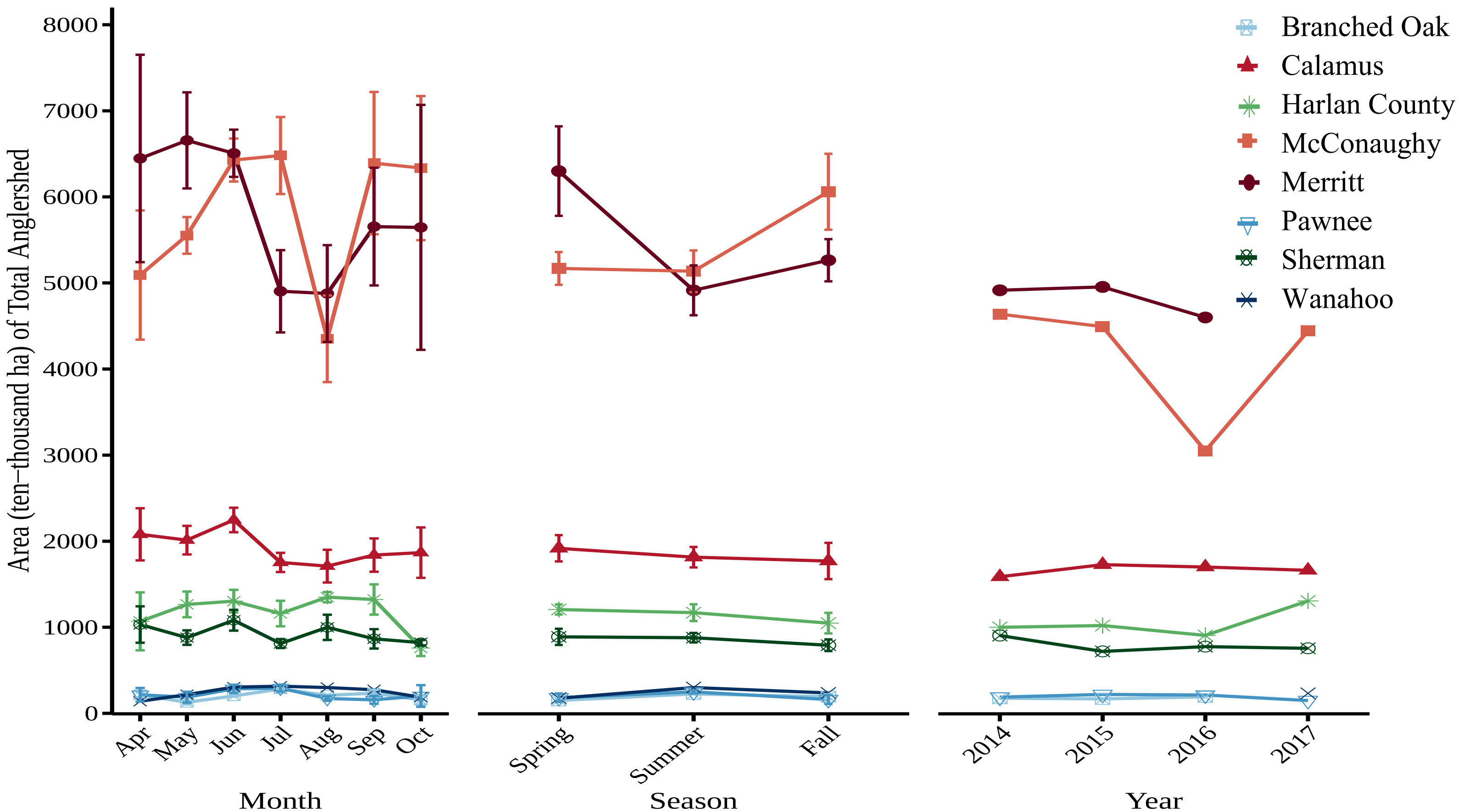

Figure 2-4. Area (mean ± SE) of the total anglershed (95% UD) for eight Nebraska waterbodies at three temporal scales: monthly, seasonal (spring = April-May, summer = June-August, and fall = September-October), and annual. Standard error is not reported for the annual temporal scale (i.e., single observations) and Lake Wanahoo (i.e., sampled one year).

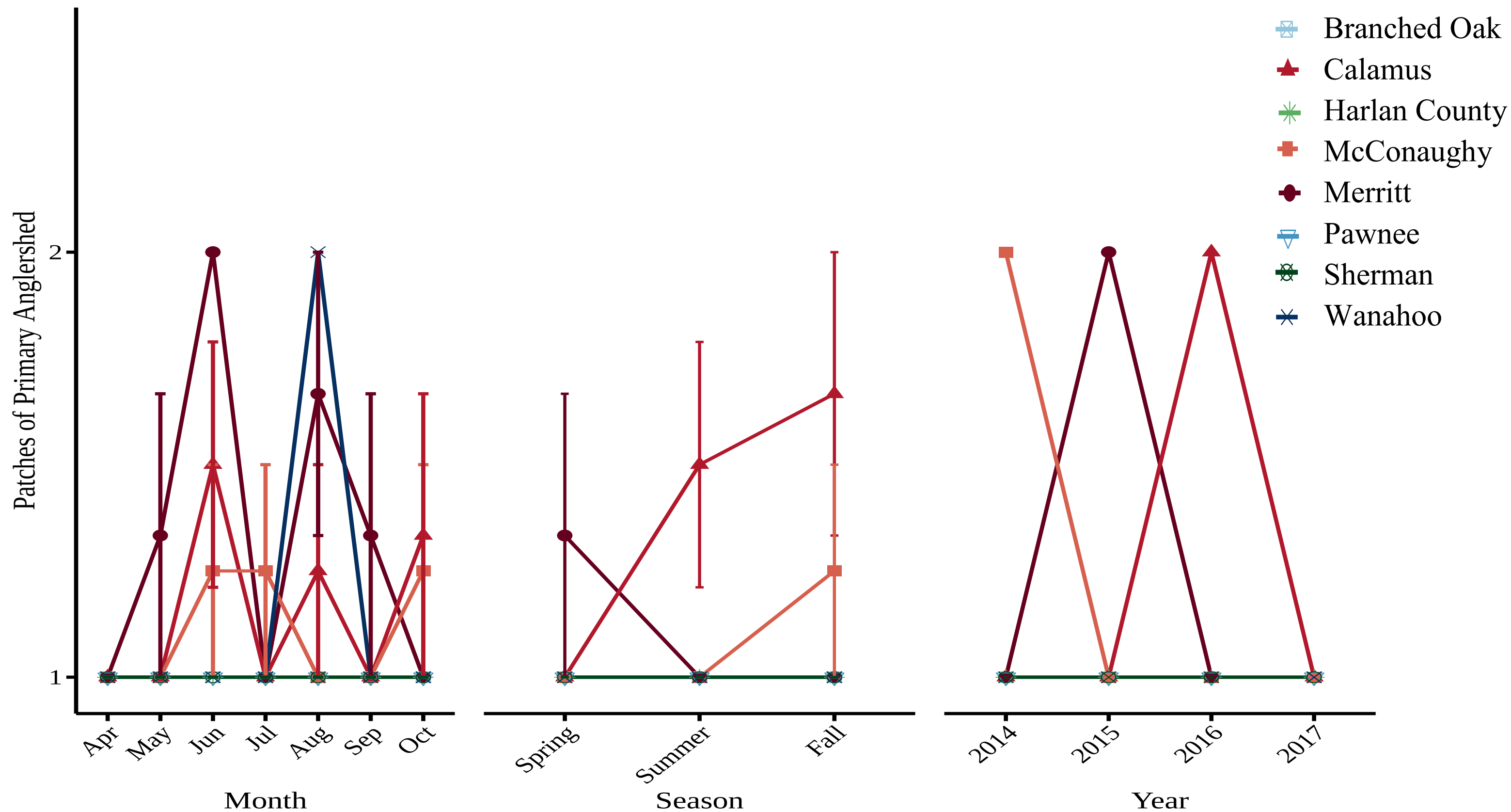

Figure 2-5. Patches (mean ± SE) of the primary anglershed (10% UD) for eight Nebraska waterbodies at three temporal scales: monthly, seasonal (Spring = April-May, Summer = June-August, and Fall = September-October), and annual. Standard error is not reported for the annual temporal scale (i.e., single observations) and Lake Wanahoo (i.e., sampled one year).

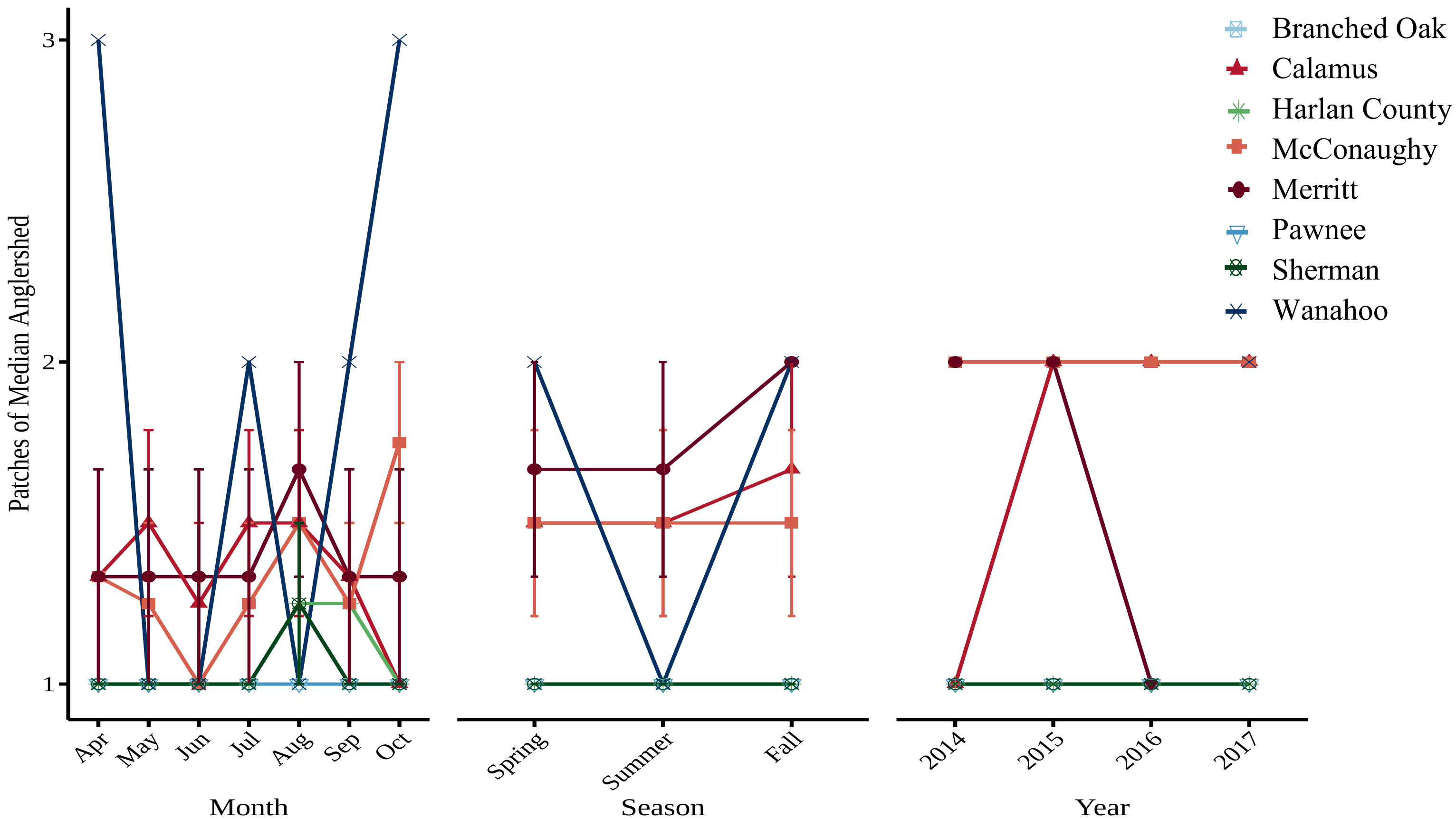

Figure 2-6. Patches (mean ± SE) of the median anglershed (50% UD) for eight Nebraska waterbodies at three temporal scales: monthly, seasonal (Spring = April-May, Summer = June-August, and Fall = September-October), and annual. Standard error is not reported for the annual temporal scale (i.e., single observations) and Lake Wanahoo (i.e., sampled one year).

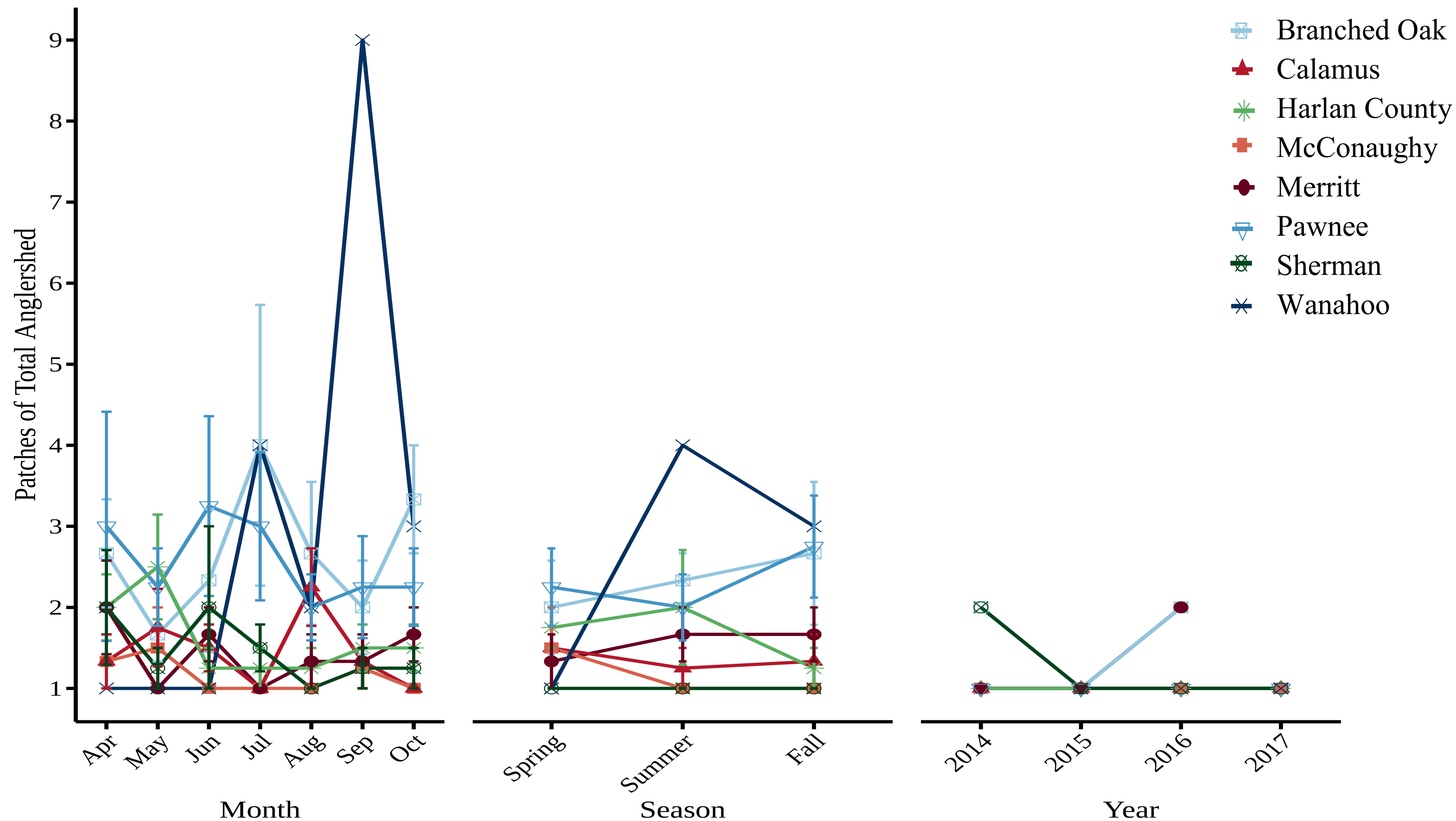

Figure 2-7. Patches (mean ± SE) of the total anglershed (95% UD) for eight Nebraska waterbodies at three temporal scales: monthly, seasonal (Spring = April-May, Summer = June-August, and Fall = September-October), and annual. Standard error is not reported for the annual temporal scale (i.e., single observations) and Lake Wanahoo (i.e., sampled one year).

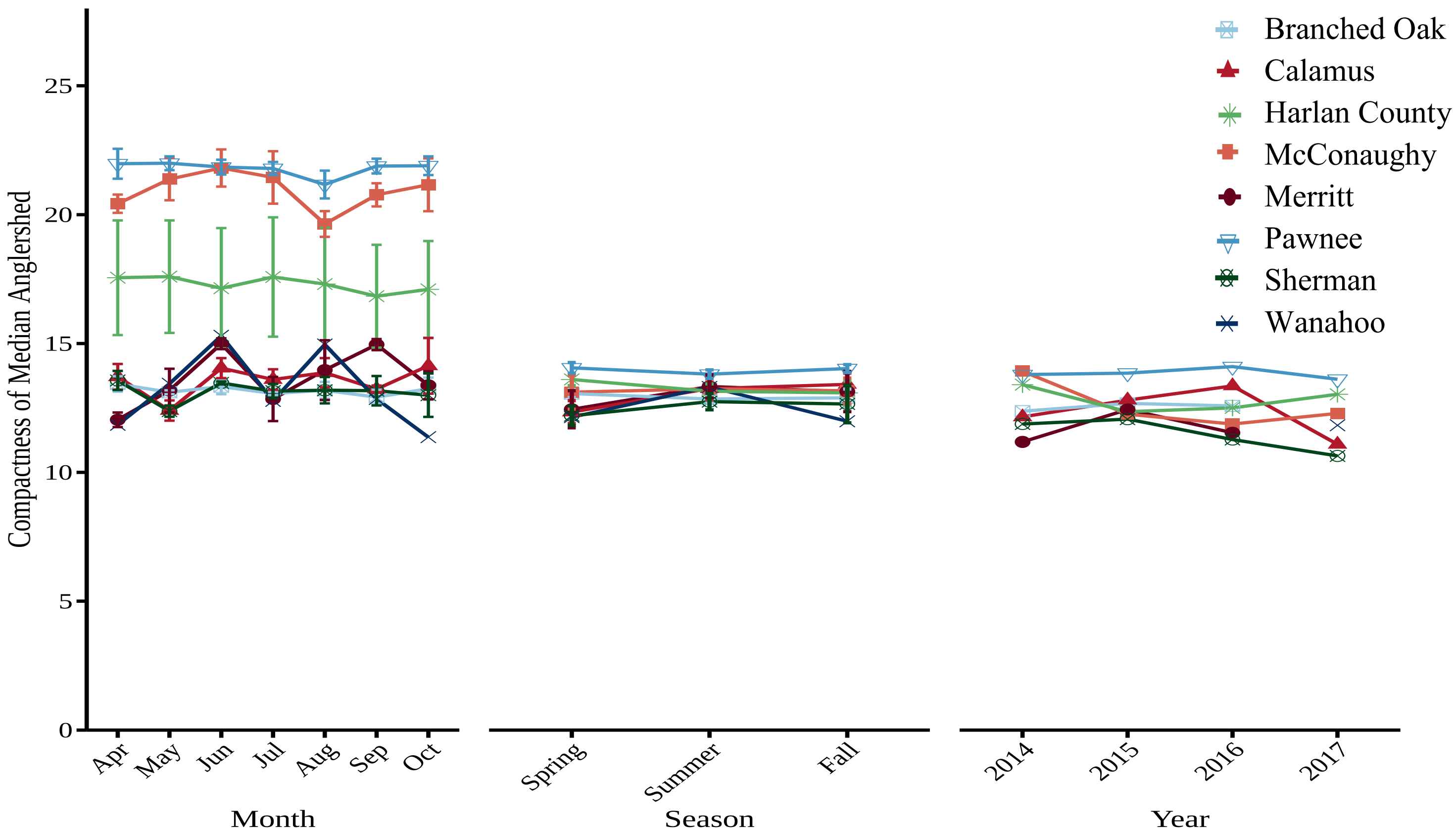

Figure 2-8. Compactness (mean ± SE) of the median (50% UD) for eight Nebraska waterbodies at three temporal scales: monthly, seasonal (spring = April-May, summer = June-August, and fall = September-October), and annual. Standard error is not reported for the annual temporal scale (i.e., single observations) and Lake Wanahoo (i.e., sampled one year).

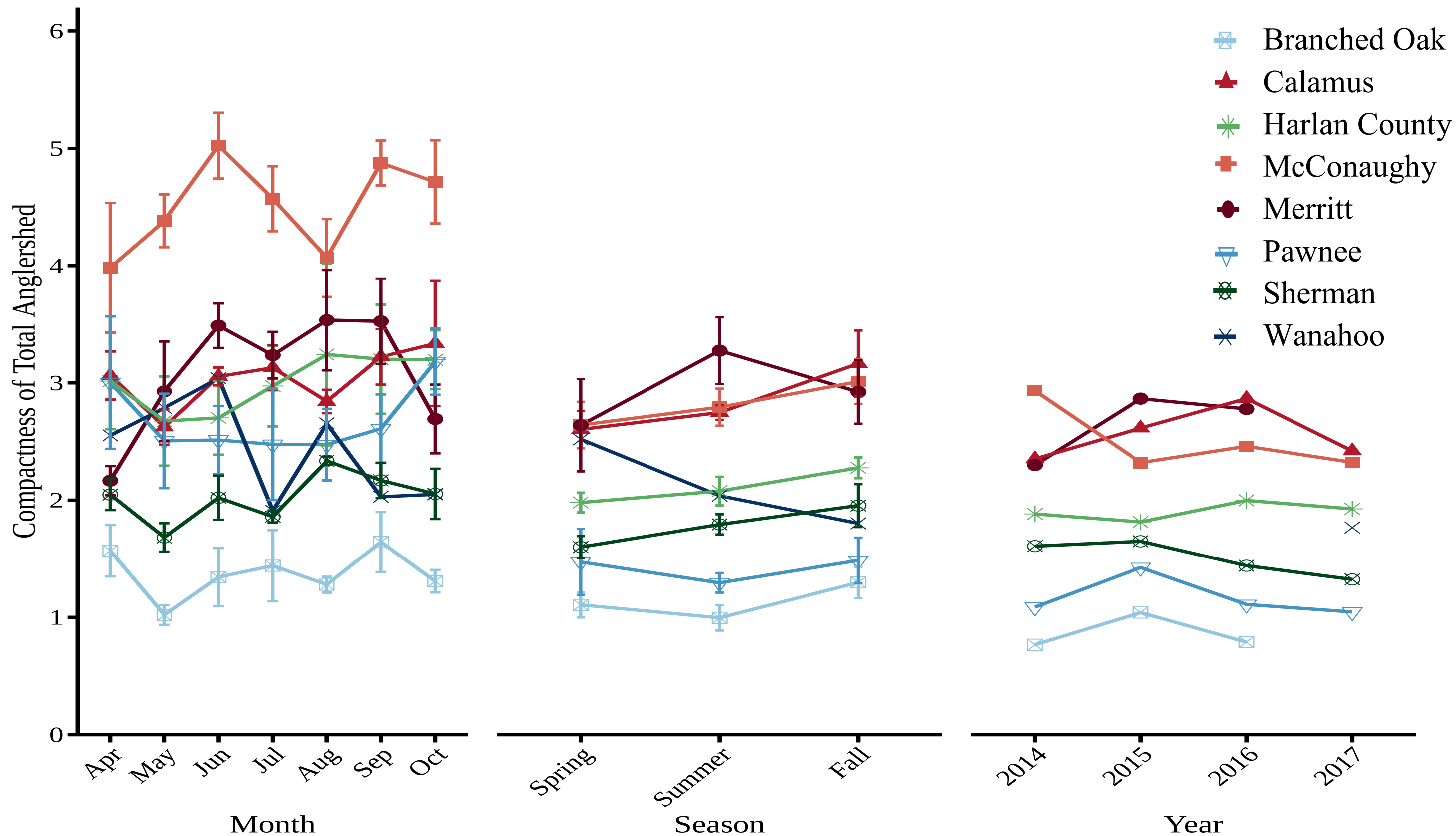

Figure 2-9. Compactness (mean ± SE) of the total (95% UD) for eight Nebraska waterbodies at three temporal scales: monthly, seasonal (spring = April-May, summer = June-August, and fall = September-October), and annual. Standard error is not reported for the annual temporal scale (i.e., single observations) and Lake Wanahoo (i.e., sampled one year).

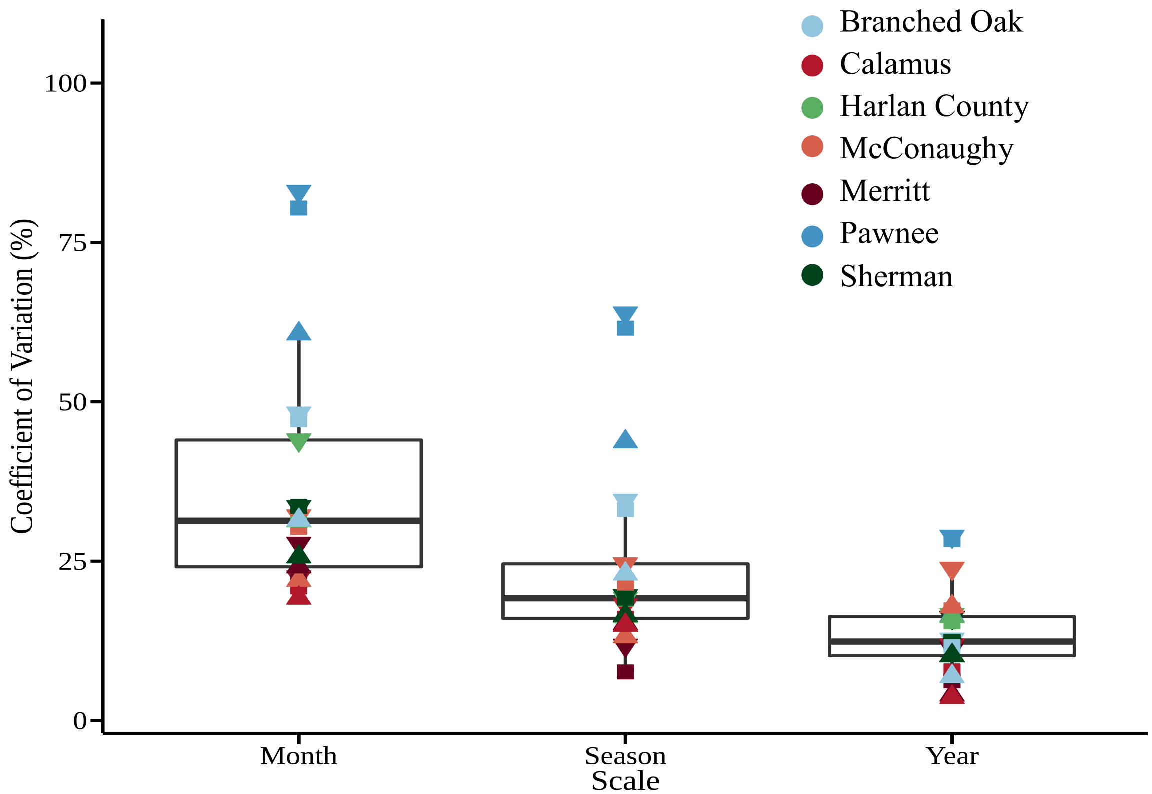

Figure 2-10. Box plot of coefficient of variation for area of primary (10% UD) = ▼, median (50% UD) = ■, and total anglershed (95% UD) = ▲ for seven Nebraska waterbodies at three temporal scales: monthly, seasonal (spring = April-May, summer = June-August, fall = September-October) and annual. Horizontal black lines represent the median, boxes represent the range from the 25th to 75th percentile, and whiskers extend from the box to the highest or lowest value within 1.5 times the interquartile range.

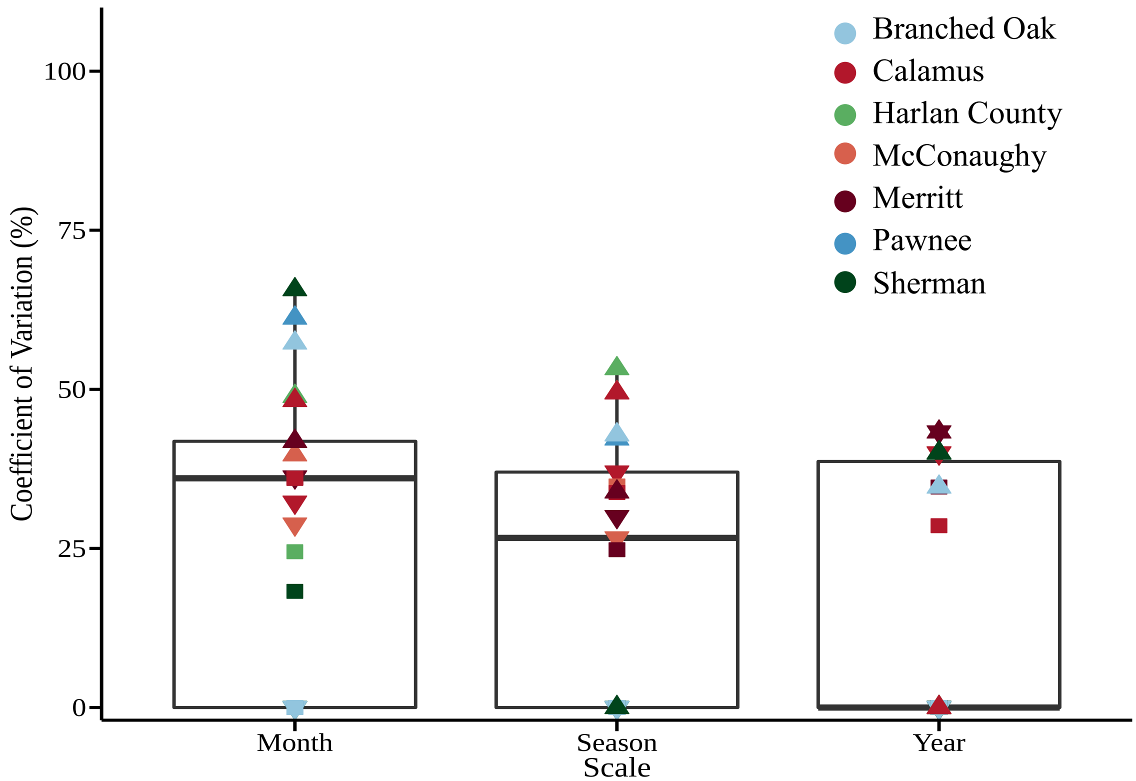

Figure 2-11. Box plot of coefficient of variation for patches primary (10% UD) = ▼, median (50% UD) = ■, and total anglershed (95% UD) = ▲ for seven Nebraska waterbodies at three temporal scales: monthly, seasonal (spring = April-May, summer = June-August, fall = September-October) and annual. Horizontal black lines represent the median, boxes represent the range from the 25th to 75th percentile, and whiskers extend from the box to the highest or lowest value within 1.5 times the interquartile range.

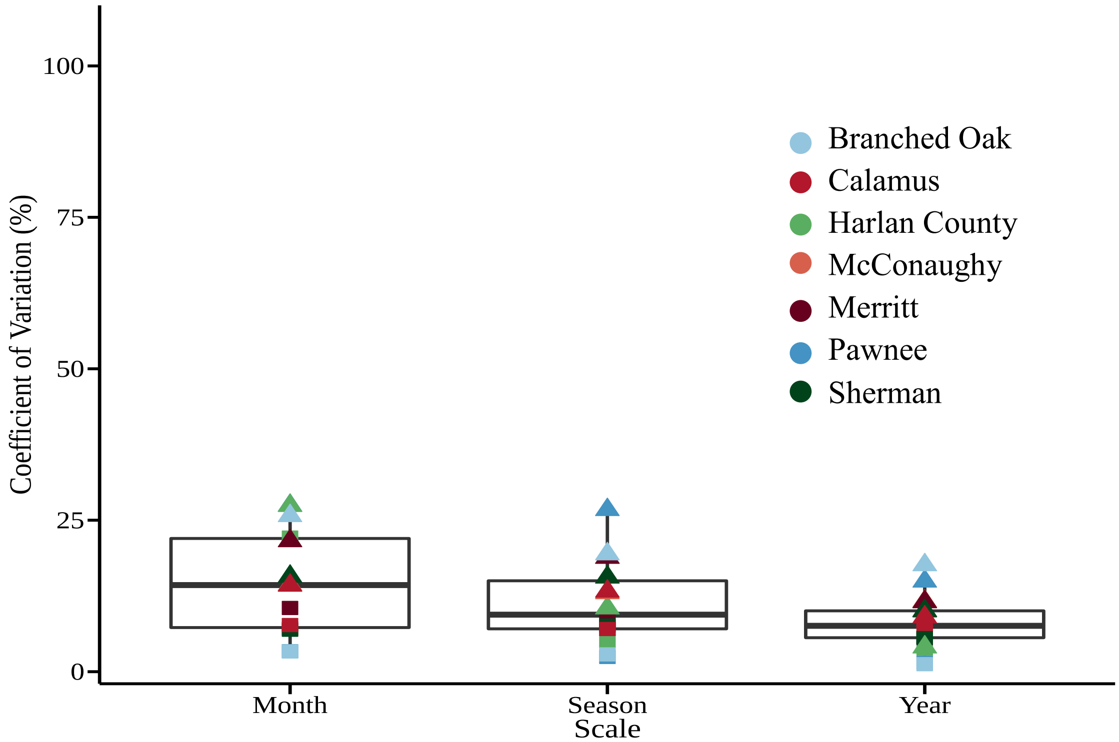

Figure 2-12. Box plot of coefficient of variation for compactness of the median (10% UD/50% UD) = ■ ,and the total anglershed (10% UD/95% UD) = ▲ for seven Nebraska waterbodies at three temporal scales: monthly, seasonal (spring = April-May, summer = June-August, fall = September-October) and annual. Horizontal black lines represent the median, boxes represent the range from the 25th to 75th percentile, and whiskers extend from the box to the highest or lowest value within 1.5 times the interquartile range.

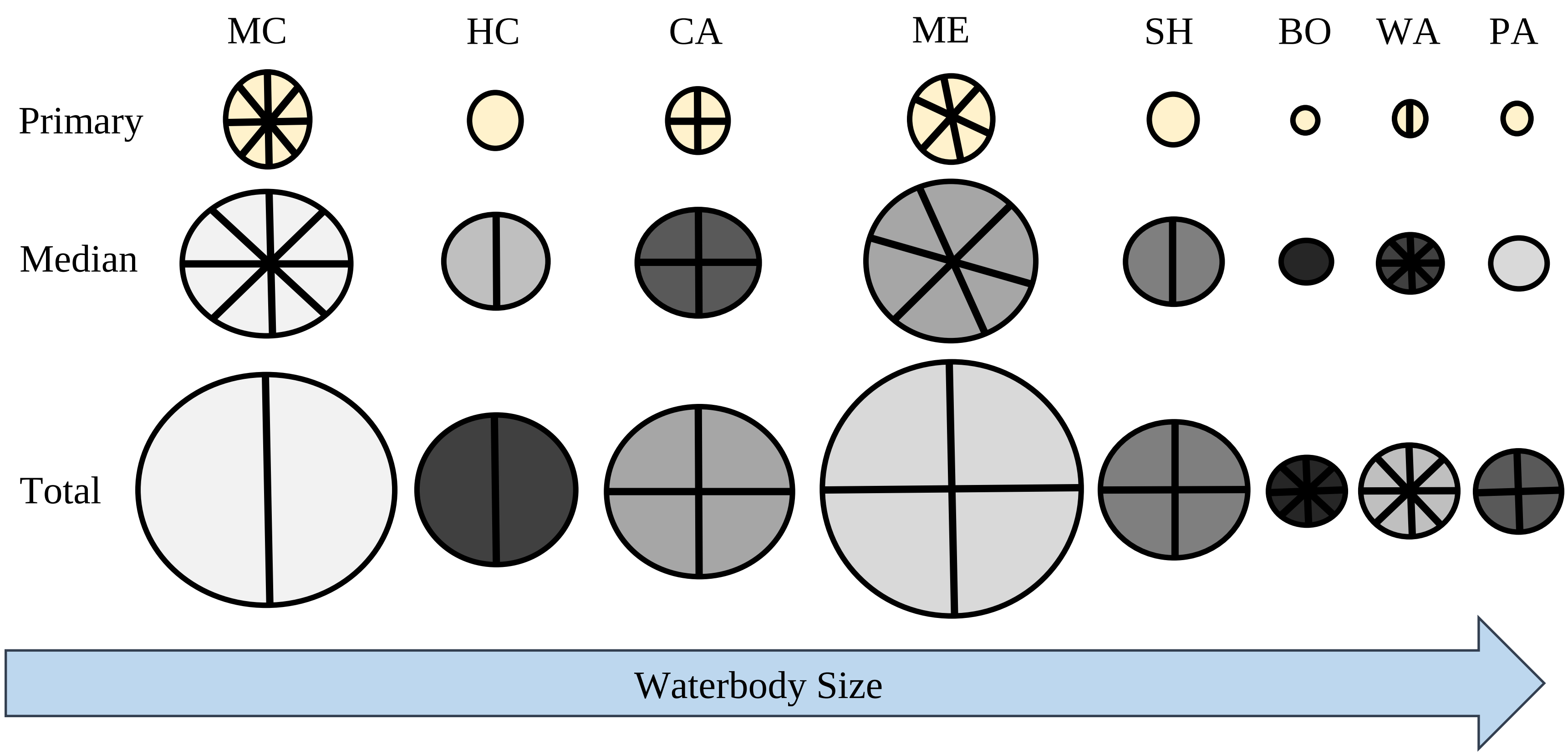

Figure 2-13. Conceptual figure illustrating the patterns exhibited by three anglershed metrics (i.e., area, patches, compactness) in relation to waterbody size. The size of the circle illustrates anglershed area, the shades of grey from dark to light indicate decreasing compactness, and the number of black lines indicate the number of patches or degree of fragmentation. The primary spatial level was not evaluated for compactness.

CHAPTER 3: EXPLAINING LANDSCAPE PATTERNS IN ANGLER PARTICIPATION

INTRODUCTION

Fisheries managers face challenges on how best to manage social-ecological resources that operate at multiple scales (Sainsbury et al. 2000; Carpenter and Brock 2004; Post and Parkinson 2012). Ultimately, policies or strategies that work at one scale, may not work at other scales (e.g., local vs. regional; Post and Parkinson 2012), leading to shortcomings in management strategies that disregard the scale of management (Lester et al. 2003). Improved fisheries management strategies require incorporation of appropriate spatial and temporal scales that recognize both angler mobility and unequal distribution of angler effort on the landscape (Lester et al. 2003). In fact, management strategies that have focused solely on the resource (e.g., fish population) alone have been blamed for creating "invisible" collapses across a landscape (Post et al. 2002). So then, what is the most efficient strategy for managing and maintaining a recreational fishery for long-term use (Post et al. 2008; Lester et al. 2003)? What is the appropriate management scale? In other words, can on-site or waterbody-specific changes influence resource use and participation? Likewise, will changes in landscape properties or attributes influence resource use and participation? To address these challenges we need to move towards a more proactive and sustainable management strategy that views angler behavior and resources as heterogeneous and dynamic properties on the landscape, operating at multiple spatial and temporal scales (Arlinghaus et al. 2017; Cox et al. 2003; Lester et al. 2003; Sullivan 2003).

Resources, such as waterbodies, serve as dynamic attracters for anglers on the landscape. The spatial arrangement and proximity between anglers and waterbodies should lead to spatial and temporal interactions given they are not homogenously distributed across the landscape, and both waterbody conditions and angler motivations change through time. Therefore waterbodies may vary in their ability to attract anglers to participate, but what factors cause disparities in resource selection and use among waterbodies? Previous work suggests that anglers should aim to optimize utility (Hunt 2005, Post and Parkinson 2012; Matsummura et al. 2017). Anglers likely consider the following social-ecological factors in the resource-selection process: (1) costs, (2) fishing quality, (3) environmental quality, (4) facility development, (5) social aspects, and (6) regulations (Hunt 2005). These factors broadly encompass the spatial socioeconomic structure, on-site attributes, and angler heterogeneity of a fishery.

The spatial socioeconomic structure of a fishery is often overlooked among managers and researchers, in particular the spatial distribution of where the human population lives in relation to the available resource or waterbody (Matsummura et al. 2017). The spatial socioeconomic structure ultimately affects travel costs for an angler, which is a primary factor for determining angler utility, and ultimately affects site choice (Hunt 2005; Post et al. 2008; Matsummura et al. 2017). Post et al. (2008) indicated an exponential decline in angling effort at waterbodies further from population centers. Despite this claim, because of angler heterogeneity, it is difficult to determine how anglers perceive travel costs when making site-choice decisions (Arlinghaus 2006; Post et al. 2008; Ward et al. 2016; Valdez et al. 2018). Various socioeconomic attributes may play a role in predicting angler participation. Therefore, an inventory of the socioeconomic attributes of populations surrounding a waterbody may provide invaluable information for managers. For example, previous work has suggested that participation frequency was higher for males (Greene et al. 1997; Montgomery & Needleman 1997; Morey et al. 2002), those who are older (Morey et al. 1993; Lin et. al 1996; Montgomery and Needleman 1997; Shaw and Ozog 1999; Morey et al. 2002), live in rural areas (Jakus et al. 1997), are unemployed (Hausman et al. 1995; Montgomery and Needleman 1997), have children (Montgomery and Needleman 1997; Shaw and Ozog 1999), and own a boat (Lin et al. 1996; Greene et al. 1997). Linking socioeconomic information to on-site participation could provide managers and researchers the ability to predict angler behavior across multiple spatial and temporal scales.

On-site conditions and attributes represent important considerations for anglers in the resource-selection process as well (Hunt 2005; Hunt et al. 2007). Resource quality can relate to the overall environmental conditions or more specifically, the water quality at a waterbody (Hunt 2005). Measures of water quality may include assessments of dissolved oxygen, phosphorus (Montgomery and Needleman 1997; Phaneuf et al. 1998), and secchi depth (Feather et al. 1995; Lupi and Feather 1998). Resource quality is often related to the size of the waterbody (i.e., surface area). Larger waterbodies are typically more diverse and have the potential to support more fish species, grow larger fish, and often offer more diverse fishing and recreational opportunities (Hunt 2005). Many studies that have incorporated waterbody size found that anglers tend to prefer to fish at larger waterbodies(e.g., Train 1998; MacNair and Cox 1999; Hauber and Parsons 2000). Weather conditions at a waterbody can also alter angler behavior. Berman and Kim (1999) studied anglers in Alaska, which indicated positive relationships between angler participation and temperature, and negative relationships between angler participation and wind speed. On-site attributes (e.g. catch rates, fish size) at a particular fishing site may be of more importance in the resource selection process and ultimately provide an angler with the maximum utility (Hunt 2005).

Accounting for angler heterogeneity is also crucial for understanding angler oriented behavior through space and time (Hahn 1991; Arlinghaus et al. 2008). Catch-related motivations are arguably the most important features in the resource selection process for anglers (Chen and Cosslett 1998; Jones and Lupi 1999; McConnell and Tseng 1999). Anglers seek a diverse range of experiences as some anglers are more harvest-oriented (Arlinghaus and Mehner 2004; Anderson et al. 2007; Beardmore 2014). Similarly, anglers also exhibit differing skill levels that are strongly correlated with catch rates (Bannerot and Austin 1983; Fisher 1997). Non-catch related motives may not be directly related to the process of catching a fish, but have also been recognized as important factors for anglers (Fisher 1997; Beardmore et al. 2011). For instance, anglers may actually be more interested in the social aspects of a fishing experience such as multi-day camping trips or fishing with of family and friends (MacNair and Cox 1999; Morey et al. 2002). Non-catch related motivations may also include an anglers desire to experience solitude or relaxation (Matinson and Shelby 1992; Banzhaf et al. 2001; Hunt 2005). Angler heterogeneity, reflected in both catch and non-catch oriented motives, is an important component in the resource selection process.

It is evident that angler behavior is highly dynamic and depends on the scale of reference; this requires a more comprehensive evaluation of cross-scale angler behavior. Herein, we use anglersheds (see Chapter 2) as an index to describe landscape dynamics in angler participation and how this relates to resource use. Anglersheds depict the area of influence of a waterbody (Martin et al. 2015) or the spatial structure of a fishery. Our objective was to explain variation in anglershed area for multiple waterbodies or resources. We explore how the spatial socioeconomic structure, on-site attributes, and angler heterogeneity shape the resource selection process for anglers. Knowledge gained from this study has broad implications for effective cross-scale resource management; in particular, this study provides guidance for selecting the appropriate management scale and potential consequences of actions taken at different scales. We can use this information to optimize the use of heterogeneous resources, such as the mosaic of waterbodies on the landscape available to anglers.

METHODS

Study design

We surveyed anglers at seven Nebraska, USA, waterbodies that encompassed diverse locations, anglers, fish communities, and amenities (Table 2-1). Lake Wanahoo is not included in this analysis due to limited temporal data (i.e., one year). Waterbodies varied in distance from large urban centers (i.e., Lincoln and Omaha, Nebraska) and state borders, attracted different angler types (e.g., boat and bank) and species-targeting groups, and offered a range of on-site amenities (e.g., camping facilities, boat ramps) and fish species (Pope et al. 2017). Average total anglershed areas were quantified in Chapter 2 and ranged from ~2,000,000 ha (Branched Oak) to ~58,000,000 ha (Lake McConaughy). Anglers were interviewed at each waterbody during seven months (April-October) during four years (2014-2017), though not all waterbodies were sampled every year (Table 2-1). Interview days were determined using a stratified multi-stage probability sampling regime (Malvestuto 1996). Days were stratified by type, with 10 week-days and six weekend-days sampled each month. An additional two interview days were included for “high use” or holiday periods during May (Memorial Day), July (Fourth of July), and September (Labor Day). Each interview day was further stratified into two periods, sunrise to 1330 and 1330 to sunset.

Angler interviews were conducted at the party level, which represented a group of individuals traveling together for the purpose of fishing. Clerks roved, with the intent of gathering a representative sample proportional to use, among parking areas and moved on foot along the shore and in parking lots to contact angler parties. Clerks interviewed one individual (i.e., representative of the party) to provide the ZIP code of their home residence (putative location from which they traveled). Additional information was collected from angler parties including party size, length of fishing trip (i.e., days), duration of that day’s fishing effort (i.e., hours), and catch and harvest numbers by species caught. We also documented angler effort by counting the number of bank and boat anglers for monthly estimates of fishing pressure at each waterbody (Malvestuto et al. 1996; Kaemingk et al. 2018).

Constructing anglersheds

We constructed anglersheds for each waterbody using ZIP codes of anglers’ residences (Martin et al. 2015); these anglersheds represent the spatiotemporal draw of anglers to a waterbody. We excluded anglers outside of a seven-state region (represented less than 1% of all interviews) to only include ZIP codes from Nebraska and bordering states (i.e., Colorado, Iowa, Kansas, Missouri, South Dakota, Wyoming) to avoid influence from extreme outliers and to facilitate logistics of computational limitations. Each retained ZIP code was randomly assigned, using a bootstrapping method, to a census block (i.e., finer spatial scale) within the ZIP code. The centroid of a selected census block was used to represent the location of a respective angler's residence (sensu Martin et al. 2015). This approach was used to reduce spatial error and to better represent the spatial distribution of anglers on the landscape (Martin et al. 2015).

Kernel-density estimation (Worton 1989; Seaman and Powell 1996) was used to delineate anglersheds based on the distribution (i.e., density and proximity to each other) of angler residences on the landscape (Figure 2-1). Kernel-density estimation is a common wildlife-ecology technique for mapping spatial distributions, and was previously used to assess angler participation (Martin et al. 2015). Kernel-density estimation has also been broadly applied to determine placement sites for hospitals (Donthu and Rust 1989), quantify distribution of traffic accidents (Xie and Yan 2008), and identify crime hot-spots (Wang et al. 2013). We used the kernelUD function (or classic kernel method) in the adehabitatHR package in R (Calenge 2006) to delineate and quantify the area of each anglershed. A bivariate normal kernel was used, which places a bivariate normal kernel over each observed point (i.e., angler residence) and uses a smoothing parameter, *h*, to control the width of the bivariate normal kernel (Martin et al. 2015). We calculated anglershed area by using the 95% utilization distribution (UD) contour with *h* set at the ad hoc level, "href". Anglershed area was evaluated at the monthly scale because of the high amount of variation compared to the annual and seasonal scale (see Chapter 2). Thus, we aimed to explain this high amount of monthly variation in anglershed area among the seven waterbodies.

Variables of interest

We initially selected 40 independent variables that were predicted to capture variation in monthly anglershed area (Table 3-1). Variables chosen were intended to encompass aspects of the spatial socioeconomic structure, on-site attributes, and angler heterogeneity that were previously identified in past studies as being important in the resource-selection process (Hunt 2005; Ward et al. 2013; Matsummura et al. 2017). Variables were calculated or estimated at the monthly level using means, sums, and proportions (to predict monthly anglershed area).

Data Analysis

We explored multicollinearity among our 40 independent variables prior to examining the relationship with anglershed area (Table 3-1). We expected high collinearity among our variables of interest given their importance in exploring fishery dynamics. Variables were removed based on strong correlation ($r > 0.6$), incomplete data sets, practicality for applied management, and knowledge of particular variables' relationship with angler participation as outlined by previous studies. For example, average temperature exhibited a strong correlation coefficient with water quality variables such as water temperature and oxygen. We chose to keep average air temperature as one of our predictor variables because water quality variables are often not collected for all waterbodies, or on a consistent basis. We reduced the initial set of 40 variables to 11 independent variables (Table 3-2).

We fit a linear mixed effects model using the 11 retained independent variables to predict monthly anglershed area (Table 3-2) for all seven waterbodies. Seven of the 11 variables were transformed using log and square root transformation to achieve normality. We evaluated model fit using the "lmer" function in the lme4 package (Bates et al. 2015) in R. We chose an alpha value of ≥ 0.10 to avoid committing a Type II error, since this assessment was largely exploratory. Total anglershed area served as the response variable along with 11 predictor variables in our mixed effects model. Waterbody code and month were explanatory variables and represented fixed effects and waterbody served as a random effect to account for variation among the seven waterbodies. Predictor variables were also scaled using the "scale" function in R.

RESULTS

Three of the eleven independent variables revealed significant relationships with monthly anglershed area across the seven waterbodies. Anglershed area was positively related to air temperature ($\beta = 0.15$, $p < 0.01$; Figure 3-1), wind speed ($\beta = 0.11$, $p = 0.03$; Figure 3-2), and population density ($\beta = 0.14$, $p = 0.05$; Figure 3-3). Variables that did not exhibit a relationship with anglershed area included: angler effort, catch rate, fuel price, household income, party size, precipitation, trip days, and waterbody size.

DISCUSSION

Our study highlights the utility of constructing anglersheds to explain changes in angler participation on the landscape, ultimately informing management objectives for a particular resource. Angler behavior is ultimately driven by perceived utility which manifested at multiple scales (Hunt 2005). For example, anglers are often viewed as optimizing on-site utility, but we should also consider the landscape structure and angler heterogeneity (Lester et al. 2003; Arlinghaus et al. 2017). Based on our findings, both on-site attributes and the socioeconomic structure were helpful for explaining changes in anglershed area across the seven waterbodies we examined. Anglershed area increased as a function of changes in air temperature, wind speed, and population density.

Anglershed area was positively related to air temperature across our seven Nebraska waterbodies. Thus, as temperature increased we observed more widespread angler participation on the landscape. Environmental or on-site conditions are an important consideration for anglers when selecting a fishing site (Smith et al. 2000, Isermann et al. 2005). For example, Hunt et al. (2007) determined that anglers were negatively affected by temperature and preferred cooler temperatures. Hunt et al. (2007) indicated that anglers may prefer a certain temperature range and once a threshold is met it may discourage participation (i.e., too hot). Kuehn et al. (2013) noted "poor weather" as an important constraint to participating, which not only encompasses temperature, but other weather conditions. The positive relationship exhibited with air temperature may represent multiple factors that are important for anglers in the resource selection process, as indicated by multicollinearity among air temperature and other variables. In particular, air temperature was correlated to water quality variables, such as, water temperature and dissolved oxygen. Water temperature appears to be the most commonly reported abiotic factor affecting overall catch rates (Stoner 2004; Stoner et al. 2006; Damalas et al. 2007; Ortega-Garcia et al. 2008), due to its notable influence on movement activity, metabolism, and foraging activity for fishes (Brown et al. 2004). Similar to water temperature, dissolved oxygen can also affect angler catch rates (Englin et al. 1997).

Anglershed area also exhibited a positive relationship with wind speed, indicating that as wind speed increased we saw an increase in the spatial draw of anglers to our waterbodies. Kuparinen et al. (2010) found that anglers caught more fish at higher wind speeds, specifically when it came to catch rates of Northern Pike (*Esox Lucius*). Wind speeds could affect the vulnerability of pike because of more turbid foraging conditions (Stoner 2004; Nilsson et al. 2009). However, most studies have identified a negative relationship between angler participation and wind speeds (Berman and Kim 1999; Provencher et al. 2002; Provencher and Bishop 2004; Barenklau and Provencher 2005). Anglers appear to be more influenced by daily fishing conditions rather than past trip experiences at a waterbody (Barenklau and Provencher 2005). Wind speed was correlated with the proportion of bank anglers participating at a particular reservoir. Lloret et al. (2008) expressed wind speeds as a limiting factor for the number of boats participating in recreational angling. Thus, wind conditions may cause a shift in angler participation at both local and landscape levels.

Air temperature and wind speed both represent seasonal conditions that can affect both angler and fish behavior. We observed the greatest changes in anglershed area during June and August (see Chapter 2). In Nebraska, the month of June is generally much cooler, therefore more comfortable, with generally high winds as well. the month of August is characterized by extreme hot temperatures that make outdoor activities uncomfortable, along with generally high winds. Not only are anglers influenced by weather conditions, but fish are also influenced by seasonal weather patterns and fluctuations. Van Poorten and Post (2005) indicated a significant decrease in angler catch per unit of effort beginning in the summer months and continuing until September. Variation in catchability is often caused by patterns of habitat use, which typically deviates due to reproductive behavior or prey distribution (Cox and Walters 2002). Based on our results, it is clear there may be a seasonal influence in anglershed dynamics that is correlated with air temperature and wind speed. While managers cannot control weather conditions such as temperature and wind, the ability to predict landscape patterns in angler participation using environmental conditions remains valuable.

Few studies have considered how the spatial socioeconomics structure contributes to shaping angler behavior (but see Matsummura et al. 2017). Our results indicated a positive relationship between anglershed area and population density indicating that we saw in increase in the spatial draw of anglers with an increase in population density. Matsummura et al. (2017) suggested that angler effort is strongly driven by the residential pattern or underlying population density on the landscape (e.g., rural vs. urban) relative to that of the resource particularly seen between rural and urban landscapes. For example, waterbodies residing in rural landscapes, such as Lake McConaughy, had anglershed areas that encompassed urban areas, such as the Denver metropolitan region. We could also expect behavioral differences, reflected in socioeconomic variables, between anglers residing in metropolitan areas compared to rural areas (Arlinghaus et al. 2008). Population density was correlated with many of our socioeconomic variables that were included in our initial dataset including: median age, household size, home value, and education level. Many studies highlight these factors as important features to explain angler behavior. For example, studies show that participation is higher among individuals who are older (Moyer et al. 1993; Lin et al. 1996; Montgomery and Needleman 1997; Morey 2002) and have more children (Montgomery and Needleman 1997; Shaw and Ozog 1999). Undoubtedly, features which reflect the socioeconomic structure surrounding a reservoir can impact angler behavior, but recognizing the relative role of these features in the decision process is more difficult.

All of the variables we included in our model to explain anglershed area have been previously noted as being important factors for angler participation, but most of these variables were unable to explain changes in the spatial structure of these fisheries. Variables that offered little explanatory power included: angler effort, catch rate, party size, trip days, fuel price, household income, precipitation, and waterbody size. As an outcome of chapter 2, we hypothesized that waterbody size could explain anglershed dynamics. However, waterbody size does not appear to significantly influence anglershed area despite its ability to predict other cross-scale social-ecological dynamics in recreational fisheries (Hauber and Parsons 2000). Similarly, we did not see an expected relationship between anglershed area and angler effort. Therefore, an increase in angling effort may not result in a concomitant increase in anglershed area.

There was a great deal of variation in anglershed area among and within our study waterbodies that may not have been accounted for in our assessment. Angler behavior and the associated mechanisms involved in the decision process may differ between anglers residing locally and distantly from a waterbody. Our approach was unable to detect changes in angler participation that could be related to geographic location and distance. For example, does an increase in the area of an anglershed represent the addition of anglers on the perimeter (i.e., adding to the total anglershed but not affecting the primary anglershed) or fewer anglers participating in the core area (i.e., reducing the primary anglershed but spreading out the total anglershed)? Therefore, we were able to assess changes in the size of the anglershed but this does not account for a potential shift in the spatial distribution of anglers on the landscape. Detecting a shift in the distribution of anglers at multiple scales is a necessary future step to better understand these complex social-ecological systems. Our study presents the need to visualize, quantify, and more importantly understand the landscape structure and dynamics of anglers participating in recreational fishing.

Our study provides more evidence for treating recreational fisheries as complex social-ecological systems that are best managed using a cross-scale approach (Post et al. 2008; Lester et al. 2013). Managing recreational fisheries at a single scale (i.e., waterbody-level or landscape-level) is not recommended. Specifically, our analysis revealed that on-site and spatial socioeconomic factors are important for predicting landscape patterns in angler behavior. We propose that management strategies should take into account cross-scale attributes of a fishery. The consideration and inclusion of multiple spatial and temporal scales of a fishery should ensure long-term sustainability of these valuable resources.

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Table 3-1. Variables included in the initial dataset were chosen to encompass aspects of the spatial socioeconomic structure, on-site attributes, and angler heterogeneity. The initial dataset was evaluated for multicollinearity in order to remove variables.

Variable	Description	Source
Alpha generation	Proportion of alpha generation in total population of zip codes in anglershed	ESRI Live Atlas
Air temperature	Average monthly air temperature; degrees Celsius	Nearest weather station
Angler effort	Month effort of all anglers interviewed at a waterbody; hours	Angler survey
Baby boomers	Proportion of baby boomers in total population of zip codes in anglershed	ESRI Live Atlas
Bachelor's degree	Proportion of population with bachelor's degree of zip codes in anglershed	ESRI Live Atlas
Boat anglers	Monthly proportion of boat anglers among all anglers interviewed at a waterbody	Angler survey
Catch rate	Average monthly catch rate of both harvested and released fish by anglers during a fishing trip; fish/hour	Angler survey
Chlorophyll a	Chlorophyll measured monthly; µg/l	Nebraska Department of Environmental Quality (NDEQ)
Dissolved oxygen	Dissolved oxygen measured monthly; mg/l	NDEQ
Fish harvested	Average number of fish harvested by anglers during a fishing trip	Angler survey
Fuel price	Average monthly fuel prices for the state of Nebraska; U.S. dollars	Nebraska Energy Office (NEO)

Table 3-1. Continued.

Variable	Description	Source
Graduate degree	Proportion of population with graduate degree of zip codes in anglershed	ESRI Live Atlas
Growing degree days	Total number of growing degree days	Nearest weather station
High school diploma	Proportion of population with high school degree of zip codes in anglershed	ESRI Live Atlas
Home value	Average home value of zip codes in anglershed; U.S. dollars	ESRI Live Atlas
Household income	Average household income of zip codes in anglershed; U.S. dollars	ESRI Live Atlas
Household size	Average household size of zip codes in anglershed; number of people	ESRI Live Atlas
Less than high school	Proportion of population with less than high school degree of zip codes in anglershed	ESRI Live Atlas
Maximum air temperature	Average minimum air temperature; degrees Celsius	Nearest weather station
Median age	Average median age of zip codes in anglershed	ESRI Live Atlas
Millennials	Proportion of millennials in total population of zip codes in anglershed	ESRI Live Atlas
Minimum air temperature	Average minimum air temperature; degrees Celsius	Nearest weather station
Older generations	Proportion of older generations of zip codes of anglershed	ESRI Live Atlas
Out of state anglers	Monthly proportion of out of state anglers among all anglers interviewed at a waterbody	Angler survey

Table 3-1. Continued.

Variable	Description	Source
Party size	Average monthly party size of anglers at a waterbody; measured in the number of people in an angler party	Angler survey
Population density	Average population density of zip codes in anglershed; people/sq. km.	ESRI Live Atlas
Precipitation	Total monthly precipitation; centimeters	Nearest weather station
Relative humidity	Average monthly relative humidity; measured as a percentage of moisture in the air	Nearest weather station
Secchi disk	Secchi (water transparency) measured monthly; centimeters	NDEQ
Some college	Proportion of population with some college of zip codes in anglershed	ESRI Live Atlas
Species richness	Average number of total species both harvested and released by anglers during a fishing trip; number of species	Angler survey
Total phosphorus	Total phosphorus measured monthly; phosphate-phosphorus; mg/l	NDEQ
Total nitrogen	Total nitrogen measured monthly; ammonia-nitrogen; mg/l	NDEQ
Trip length	Average monthly trip length of anglers at a waterbody; measured in number of days visiting the waterbody	Angler survey
Unemployed	Proportion of unemployed in total population (16+) of zip codes of anglershed	ESRI Live Atlas
Visible light time	Average monthly time of visible; time between the civil sunset and sunrise; total hours	Nearest weather station
Waterbody Size	Surface area of water; hectares	Nebraska Game and Parks

Table 3-1. Continued.

Variable	Description	Source
Water temperature	Water temperature measured monthly; degrees Celsius	NDEQ
Wind gust	Average monthly wind gust speed; kilometers/hour	Nearest weather station
Wind speed	Average monthly wind speed; kilometers/hour	Nearest weather station

Table 3-2. Variables included in final dataset and were evaluated for their influence on total anglershed area using a linear mixed effects model.

Variable	Description	Source
Air temperature	Average monthly air temperature; degrees Celsius	Weather station
Angler effort	Average monthly angler effort; hours	Angler survey
Catch rate	Average monthly catch rate of both harvested and released fish by anglers during a fishing trip; fish/hour	Angler survey
Fuel price	Average monthly fuel prices for the state of Nebraska; U.S. dollars	Nebraska Energy Office (NEO)
Household income	Average household income of zip codes in angler anglershed; U.S. dollars	ESRI Live Atlas
Party size	Average monthly party size of anglers at a waterbody; measured in the number of people in an angler party	Angler survey
Population density	Average population density of zip codes in angler anglershed; people/sq. mi.	ESRI Live Atlas
Precipitation	Total monthly precipitation; inches	Weather station
Trip length	Average monthly trip length of anglers at a waterbody; measured in number of days visiting the waterbody	Angler survey
Waterbody Size	Surface area of water; hectares	Nebraska Game and Parks
Wind speed	Average monthly wind speed; miles/hour	Weather station

Table 3-3. Results of the linear mixed effects model to predict anglershed area for seven Nebraska waterbodies. Significant variables are indicated by an asterisk.

Fixed effects	Estimate	Standard error	df	T value	Pr (>|t|)
Air temperature	0.147	0.047	161	3.145	0.002*
Angler effort	0.021	0.044	161	0.484	0.629
Catch rate	0.010	0.043	162	0.242	0.809
Fuel price	-0.031	0.030	161	-1.026	0.307
Household income	-0.020	0.036	161	-0.557	0.578
Party size	-0.018	0.044	162	-0.413	0.680
Population density	0.140	0.071	165	1.965	0.051*
Precipitation	0.002	0.032	161	0.066	0.947
Trip days	-0.032	0.052	163	-0.620	0.536
Waterbody size	0.855	0.566	5	1.510	0.193
Wind speed	0.108	0.049	161	2.212	0.028*

CHAPTER 4: ANGLERSHEDS AS A TOOL AND TECHNIQUE FOR FISHERY MANAGEMENT AND FUTURE RESEARCH NEEDS

ANGLERSHEDS AND FISHERY MANAGEMENT

The visualization and quantification of anglersheds provides insights to spatiotemporal dynamics of anglers on the landscape. In particular, anglersheds reveal a critical link and relationship between users (i.e., anglers) and the resources (i.e., waterbodies) on the landscape. We have demonstrated that anglersheds are dynamic through space and time and that not all resources are viewed and used equally among anglers (see Chapter 2). Rather, some resources are locally used whilst others are regionally used and this also varies across temporal scales. This variation in use was explained by variation in population density, air temperature, and wind speed (see Chapter 3). Below, we highlight the utility of anglersheds as a tool and technique to address three specific scenarios for fishery management and conservation:

Scenario A – Quantifying and categorizing landscape resource use:

Resources or waterbodies are unequally distributed across the landscape, providing a "buffet" of opportunities for a diverse and unequally distributed angler population (Post and Parkinson 2012; Matsummura et al. 2017; Carruthers et al. 2018). This unequal distribution and diversity among resources and anglers on the landscape should lead to complex patterns and dynamics in resource use (Post et al. 2008; Post and Parkinson 2012; Matsummura et al. 2017). Anglersheds provide insight to this complex relationship, potentially revealing the spatial and temporal structure of a fishery. For example, we can quantify the anglershed for a particular resource to describe its area of influence or spatial draw. We can use these anglersheds to categorize waterbodies as "local" or "regional" fisheries and create an inventory of waterbodies or resources that are available to anglers on the landscape. We assert that both local and regional fisheries are important and likely attract different anglers. Thus, understanding whether a waterbody attracts local vs. regional anglers is important and allows insight to potential differences in angler behavior (e.g., local – day trips; regional – multi-day trips). We use Merritt Reservoir and Pawnee Lake to illustrate our ability to quantify and categorize resource use on the landscape (Figure 4-1). Merritt Reservoir could be considered a regional fishery, its anglershed is widespread spatially, whereas Pawnee Lake is a local fishery, with an anglershed restricted in size and localized to surrounding communities. Distant anglers travelling to Merritt may not consider local environmental conditions (until arrival) as much as local anglers travelling to Pawnee Lake. Thus, we should anticipate that management actions applied equally at both reservoirs could create an unequal response in landscape-level angler participation.

Scenario B – Viewing and managing anglersheds as a network of fisheries on the landscape: A waterbody should be viewed as a single resource that is nested and connected to a mosaic of other waterbodies (Shuter et al. 1998). As such, multiple waterbodies on the landscape represents a network of fisheries whereby mobile anglers select waterbodies to participate in fishing (Martin et al. 2017). A scenario could exist where two waterbodies exist in close proximity to each other, but attract unique anglers from different geographic locations. In contrast, these two waterbodies may attract anglers from similar geographic locations. These resources may be complimentary or competing for anglers on the landscape. Recognizing the role of resources among a network of resources is an important consideration for management and conservation. For example, Calamus Reservoir and Sherman Reservoir are separated by less than 90 km, but do they attract anglers from similar geographic locations? Are they dependent of each other, as anglers may consider them to be a joint fishing opportunity? While we did not directly quantify the degree of overlap, visually we can see that anglersheds for Calamus and Sherman Reservoirs overlap. However, the degree of overlap changes through time with the highest level of overlap occurring in July and October and the lowest level of overlap in June and August (Figure 4-2). Periods of overlap and non-overlap may represent different anglers using these resources, or may be the same anglers using the resource at different times. Management strategies may be aimed to optimize competing or complementary resources within a network of resources instead of focusing on a single waterbody. Anglersheds provide a simple yet powerful way to visualize and quantify how management efforts on one resource may impact other resources on the landscape.

Scenario C – Assessing potential invasion risk on the landscape: There is a constant threat of the invasion and spread of invasive species that could compromise our use of ecological resources. Anglers are often viewed as vectors that transport invasive species from one waterbody to another (Minchin et al. 2002; Wacker and Elert 2003). Anglersheds could expose which waterbodies are at high risk to invasion to assist with prevention efforts. Waterbodies may range from low to high risk of invasion, furthering our ability to prioritize prevention efforts. The ability to capture monthly- or seasonal- variation in anglersheds also allows for more targeted control efforts. We use the anglershed for Lake McConaughy to assess the risk of zebra mussel (*Dreissena polymorpha*) invasion from a known infested waterbody (i.e., Lewis and Clark Reservoir). We can visually see that the anglershed for Lake McConaughy overlaps with Lewis and Clark Reservoir during May, September, and October (Figure 4-3). However, the risk of zebra mussel invasion is highest beginning in the spring to early fall (e.g., May-September; Wacker and Elert 2003) when water temperature is able to stay above 12 degrees Celsius (Borcherding 1991). This time frame highlights when reproduction begins and larvae or veligers are produced. Anglersheds afford the ability to assess the level of invasion risk through space and time. Detecting changes in anglersheds based on attributes such as the landscape structure, on-site attributes, and angler heterogeneity can further aid in predicting and planning for potential invasion threats.

FUTURE RESEARCH NEEDS

We believe that anglersheds can greatly aid in the management of complex social-ecological systems. This tool and technique offers yet another way for managers to effectively optimize important resources and make informed decisions about their spatial and temporal use within a landscape context. Anglersheds have the potential to "unlock" a wealth of spatiotemporal information concerning the relationship between resources and its users on the landscape. Our work represents a fraction of that potential and thus we envision widespread use of this tool and technique to address challenges and questions in other social-ecological systems. That being said, we propose several potential questions for future fisheries research:

1) Does anglershed heterogeneity (in terms of angler behavior) change across primary, median, and total spatial levels?
2) What other variables could be used to generate hypotheses regarding spatial and temporal dynamics of angler behavior at the landscape level?
3) Will our results apply to anglersheds in urban environments?
4) What could we learn about angler behavior by visualizing and quantifying anglersheds based on angler-types (e.g., boat vs. bank, species targeting) or other social-ecological attributes (e.g., catch rates, party size)?

5) Are there feedbacks or reinforcing mechanisms among anglersheds and social-ecological variables?
6) How resilient are anglersheds to social-ecological changes?
7) Are small or large anglersheds are more sensitive to changes in management, such as modifying stocking efforts or harvest regulation changes?
8) How does the spatial location of the anglershed change through time?

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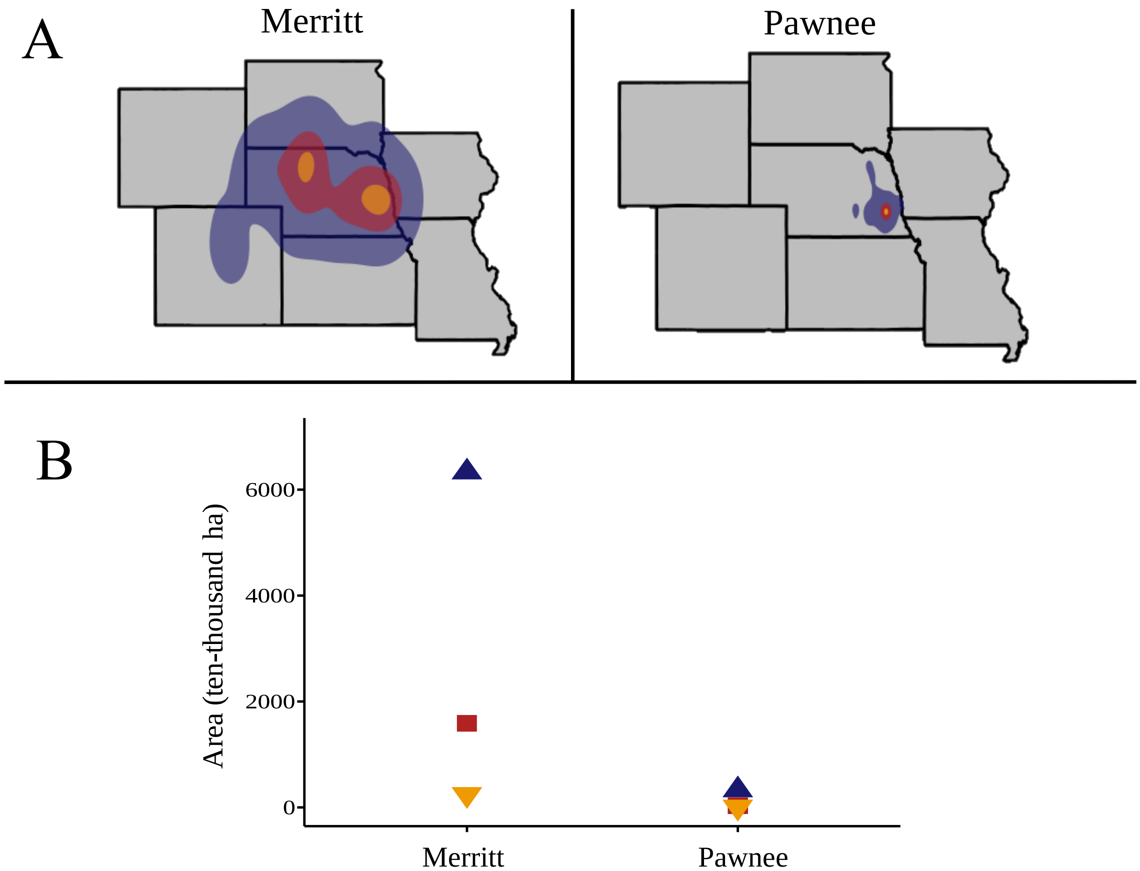


Figure 4-1. Anglersheds provide opportunity to visualize and quantify diversity of resources across the landscape. (A) illustrates a monthly primary (10%), median (50%), and total (95%) anglershed for Merritt Reservoir and Pawnee Lake. (B) illustrates the quantification of the area for the primary = ▼, median = ■, and total = ▲ anglershed revealing the drastic separation in area of influence by these two resources.

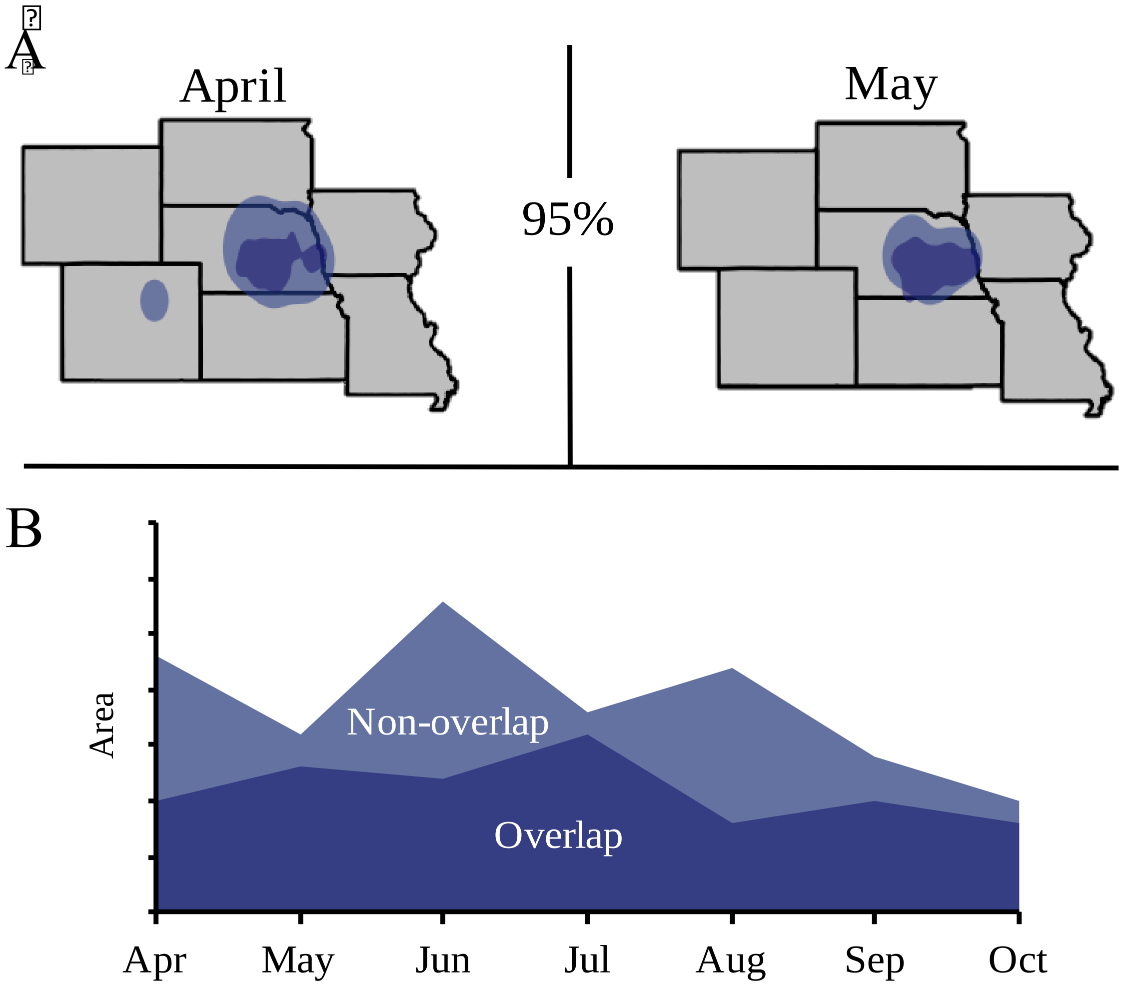


Figure 4-2. Anglersheds highlight the interaction between two nearby resources as they draw in anglers to participate. (A) illustrates the overlap in area that occurs between two Nebraska reservoirs, Sherman and Calamus Reservoirs. (B) illustrates the overlap in area that occurs through time, which may indicate potential competition for anglers between these two reservoirs, but also the potential to complement each other.

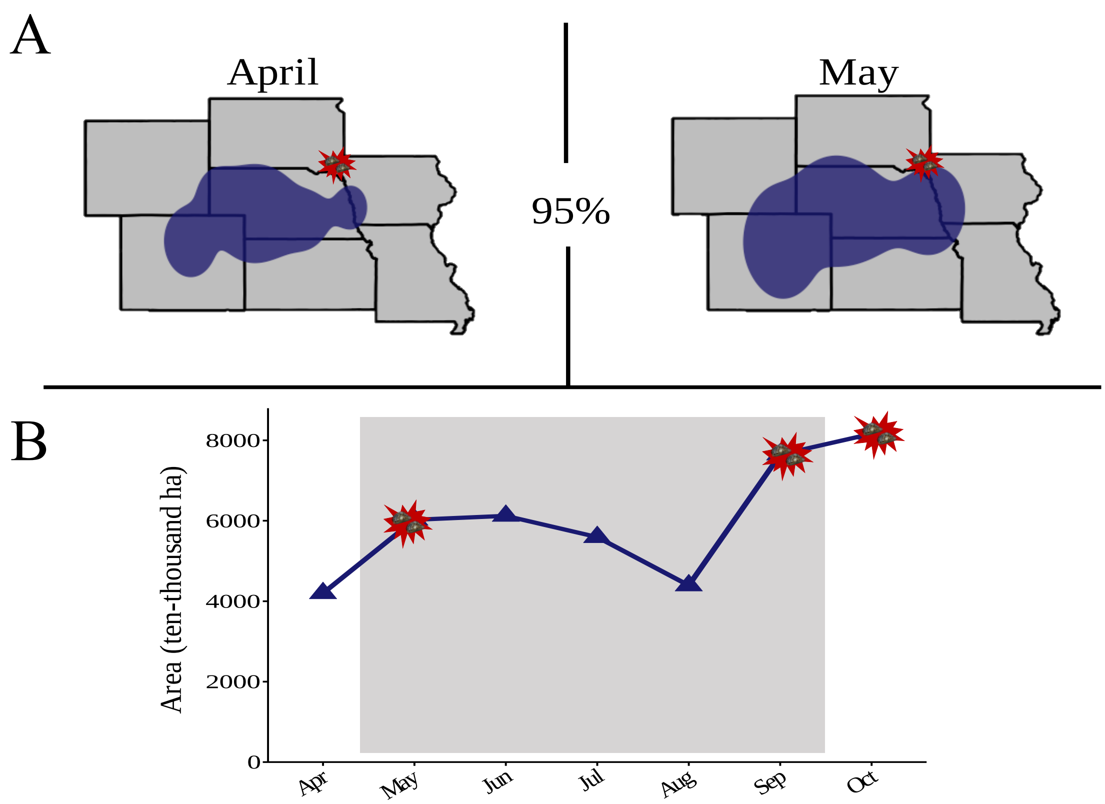
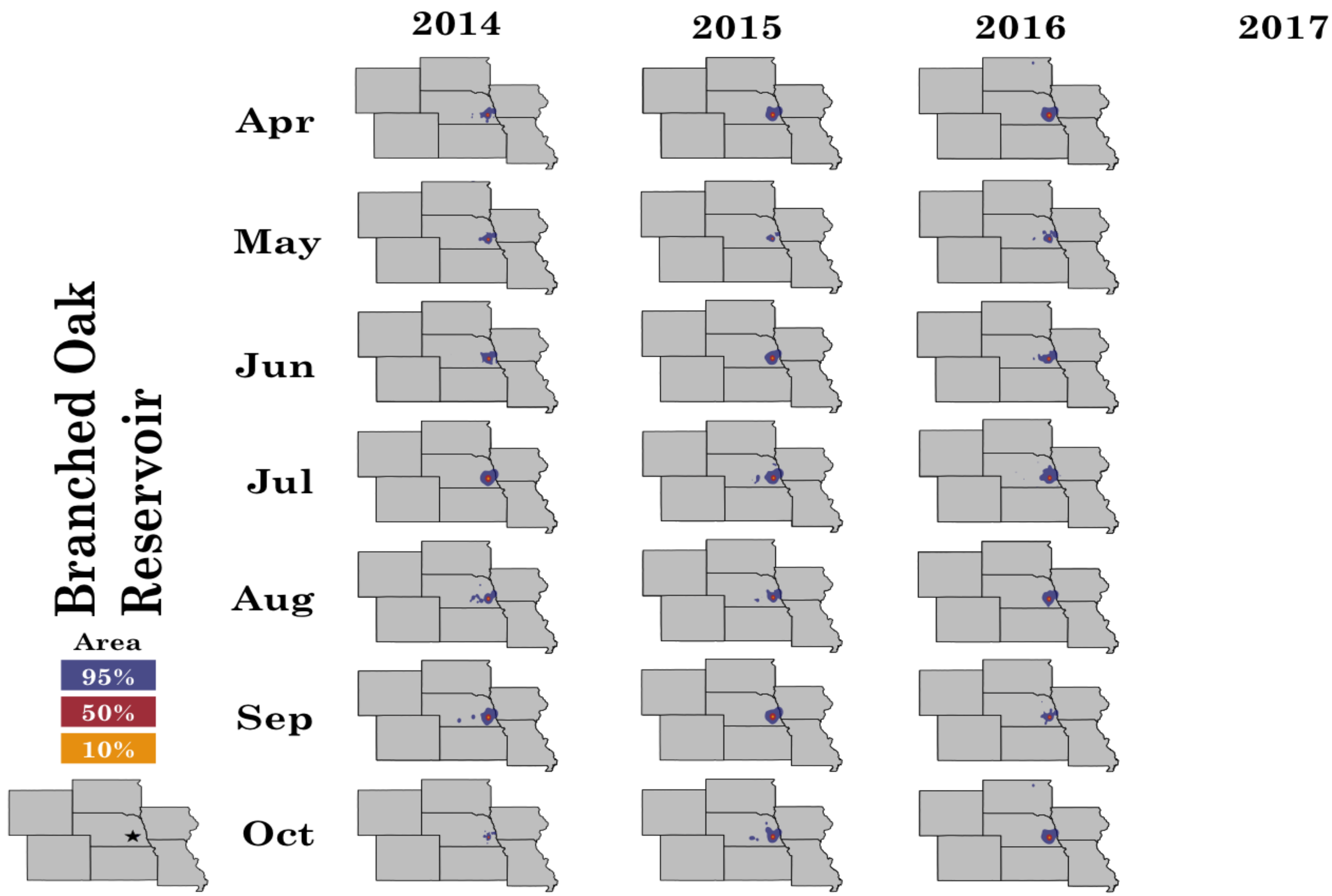
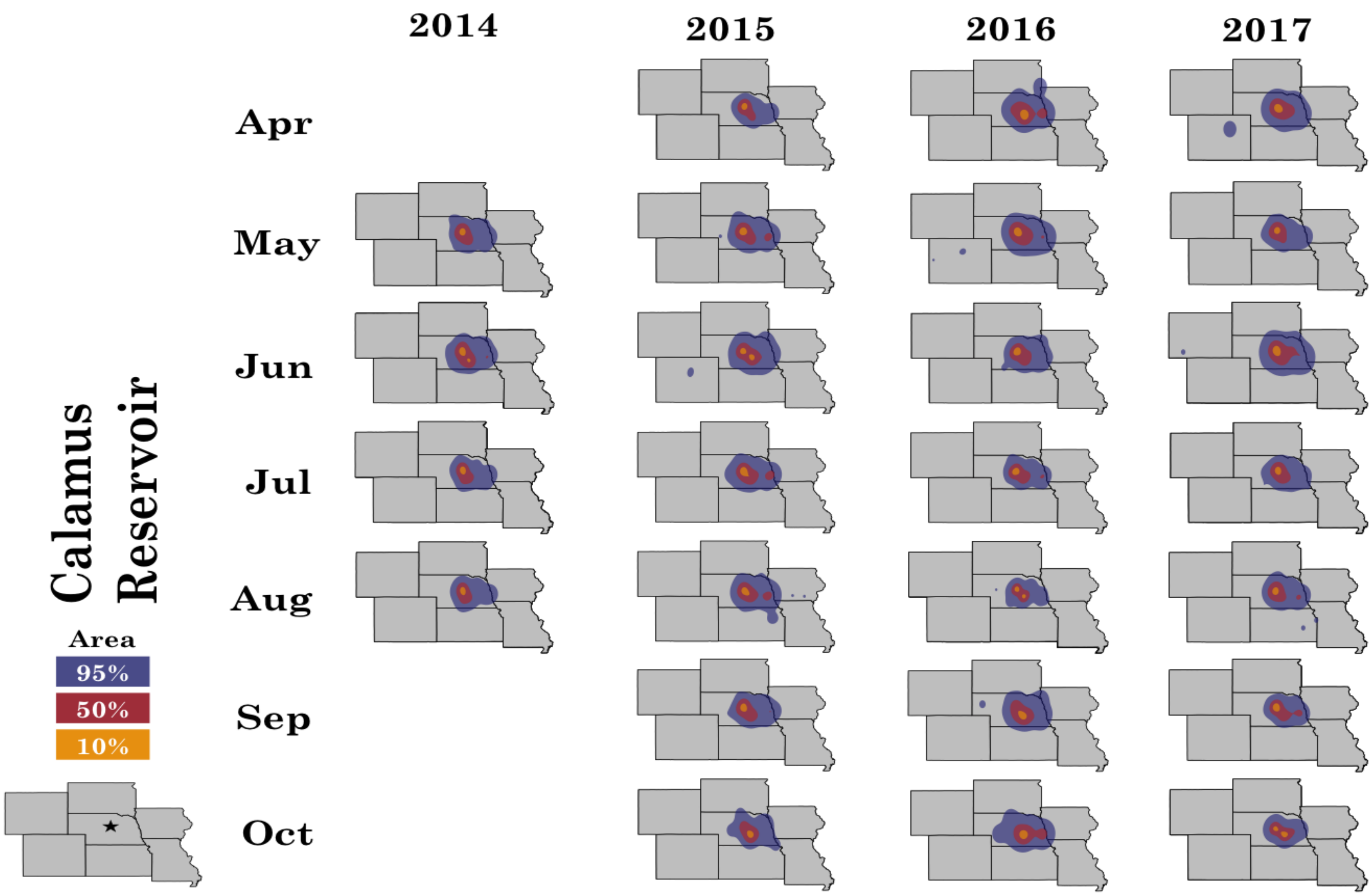
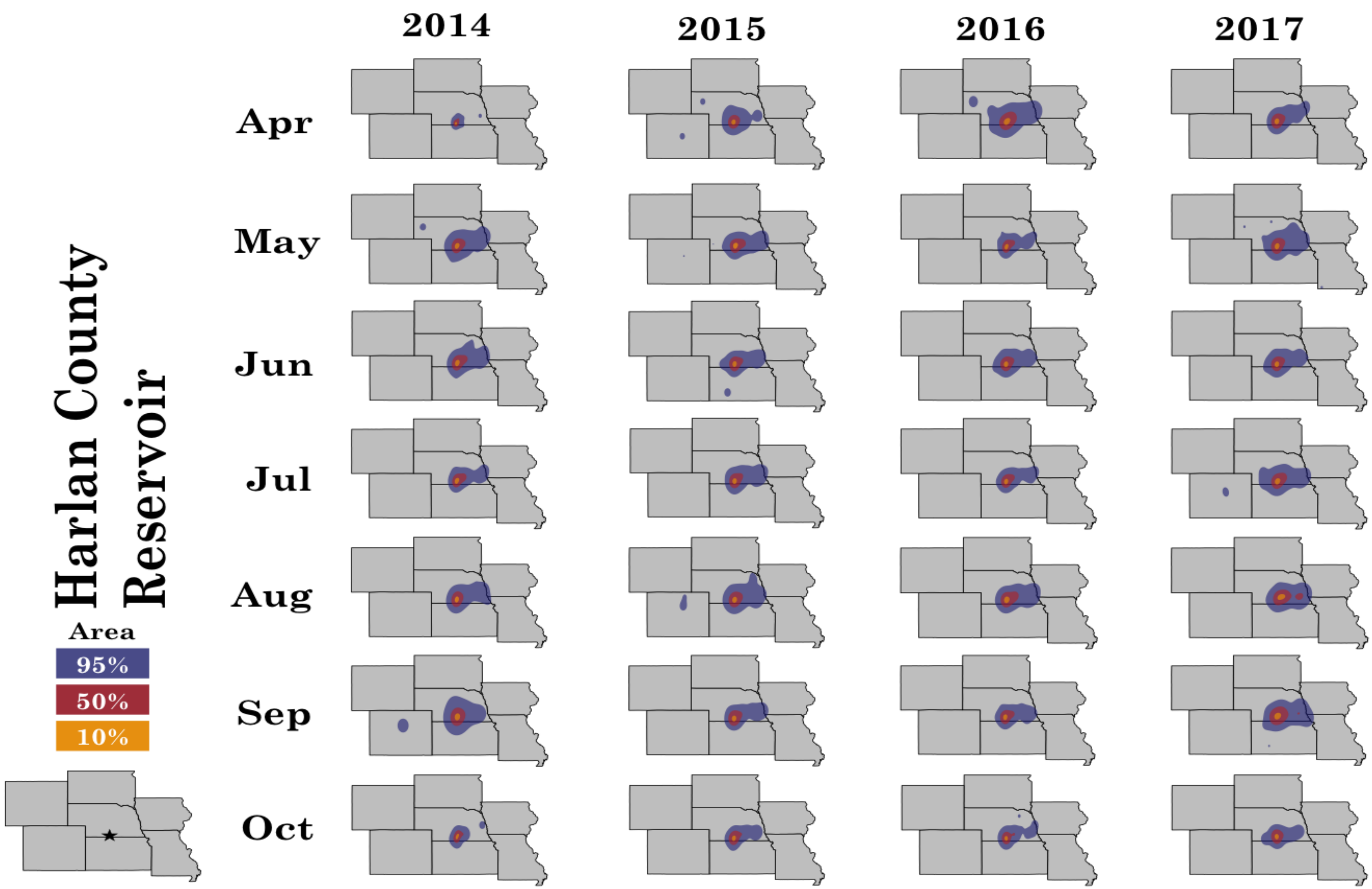


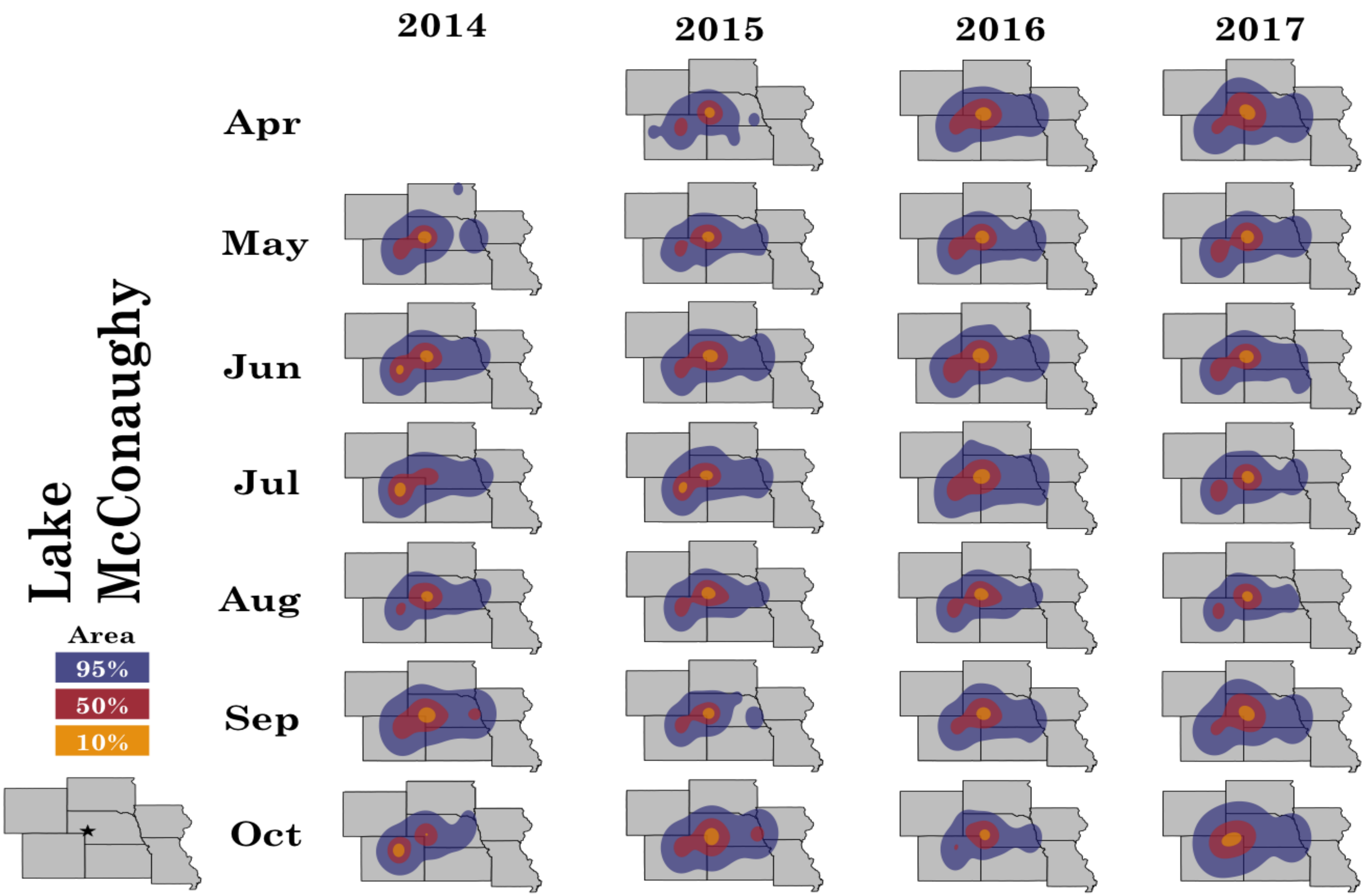
Figure 4-3. Anglersheds can be instrumental in monitoring and preventing the spread of invasive species. (A) illustrates two anglersheds that show an overlap with a known invasion (indicated by the red burst with zebra mussel graphic). (B) illustrates the ability to track this overlap through time, in particular during times where reproduction is occurring among zebra mussels (grey box).

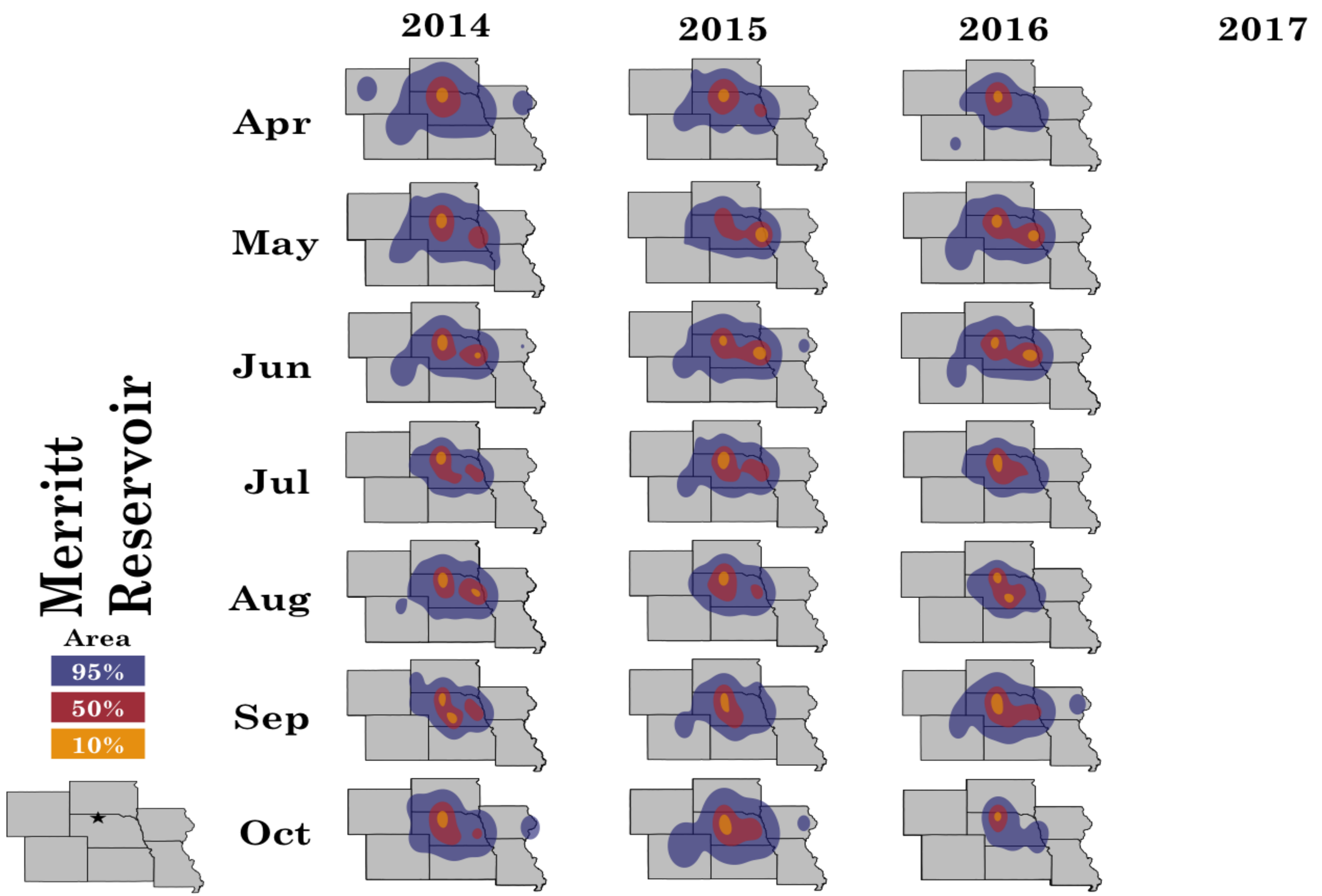
Appendix 1. Maps of the primary (10% UD), median (50% UD), and total (95% UD) anglersheds on a monthly scale for each reservoir.

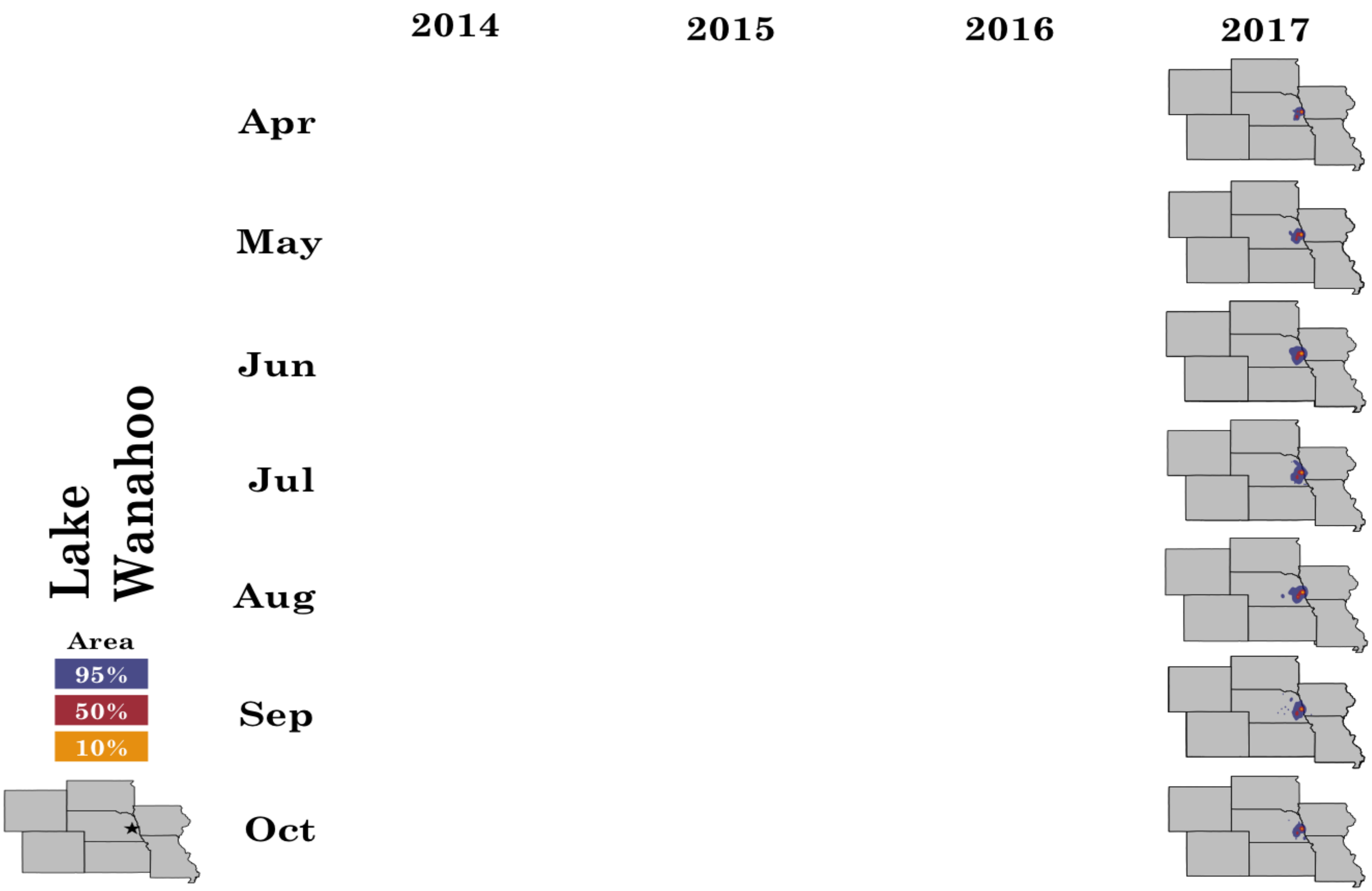

2014
2015
2016
2017
Apr
May
Jun
Jul
Aug
Sep
Oct
Branched Oak Reservoir
Area
95%
50%
10%

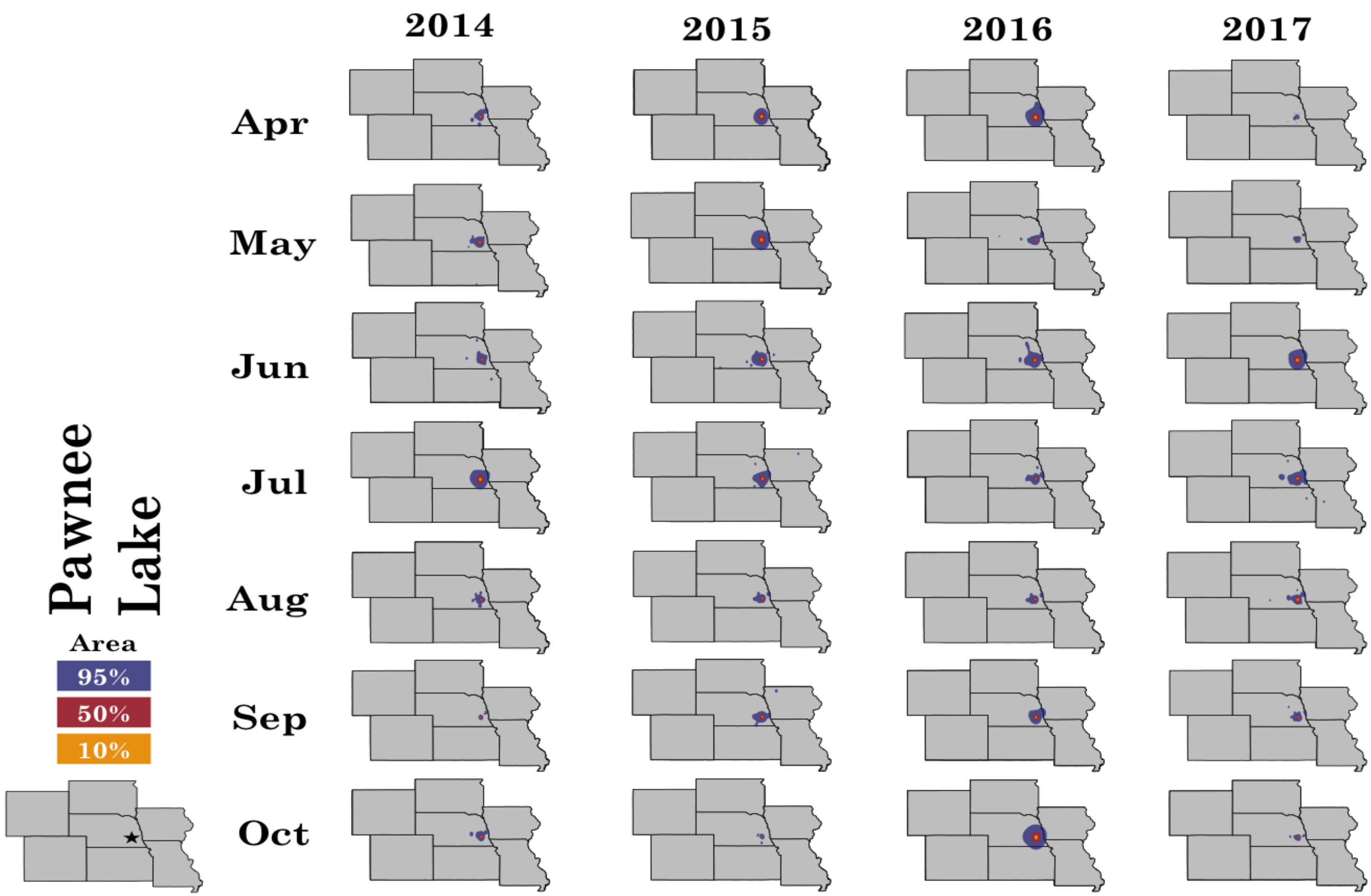

Calamus
Reservoir
2014
2015
2016
2017
Apr
May
Jun
Jul
Aug
Sep
Oct
Area
95%
50%
10%

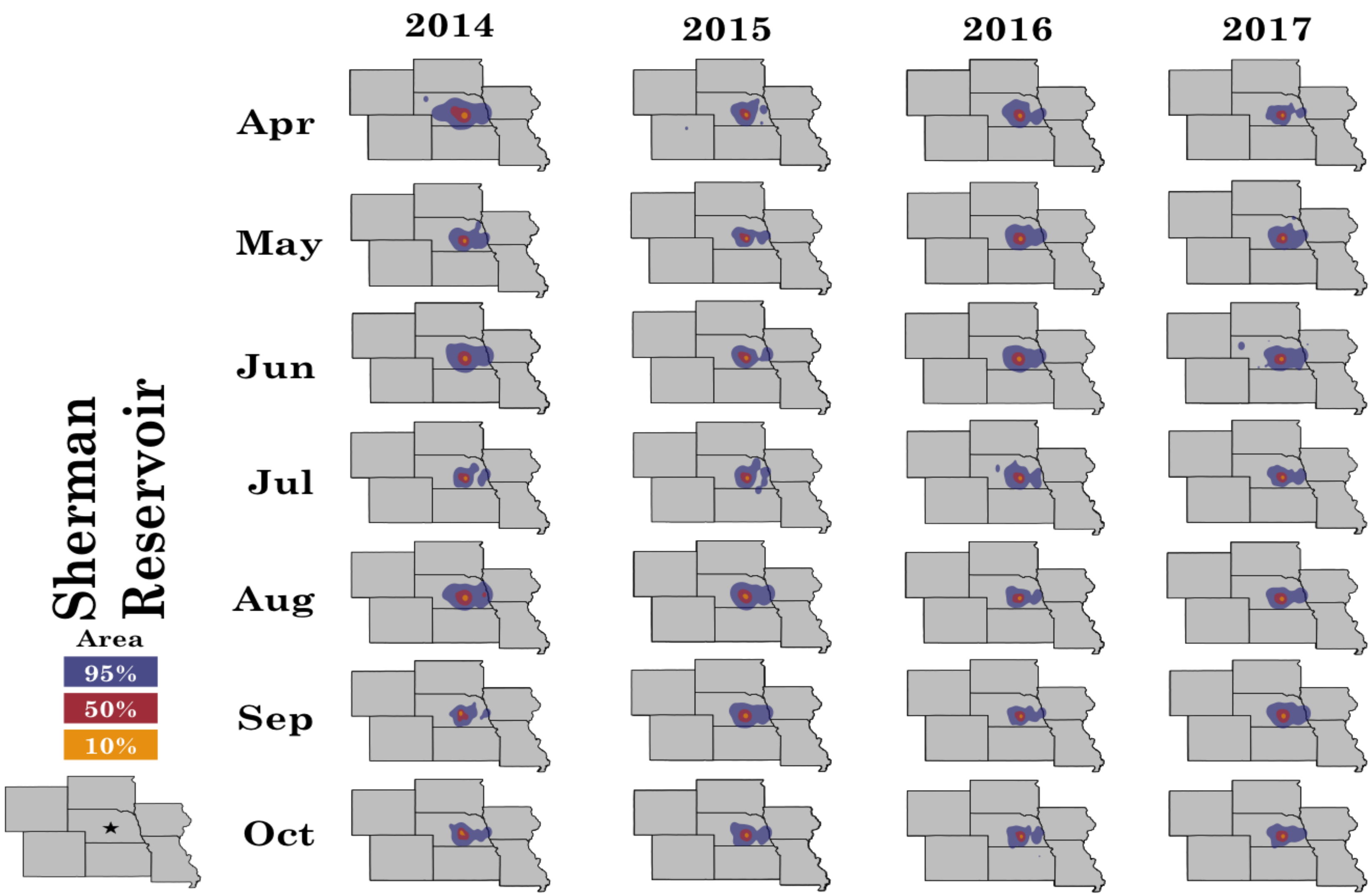

Harlan County Reservoir
Area
95%
50%
10%
2014
2015
2016
2017
Apr
May
Jun
Jul
Aug
Sep
Oct


Lake McConaughy
2014
2015
2016
2017
Apr
May
Jun
Jul
Aug
Sep
Oct
Area
95%
50%
10%

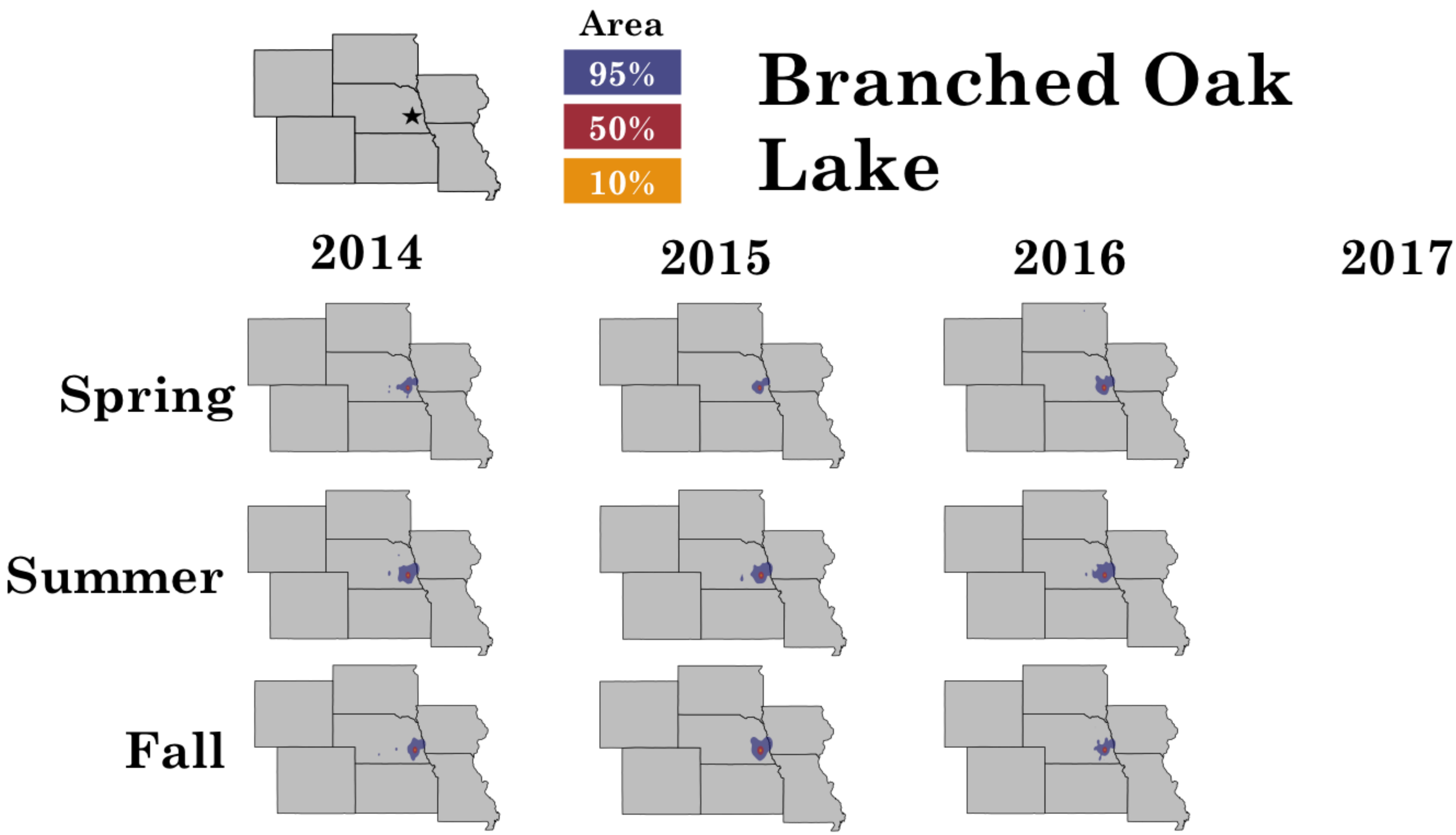

Merritt Reservoir
2014
2015
2016
2017
Apr
May
Jun
Jul
Aug
Sep
Oct
Area
95%
50%
10%

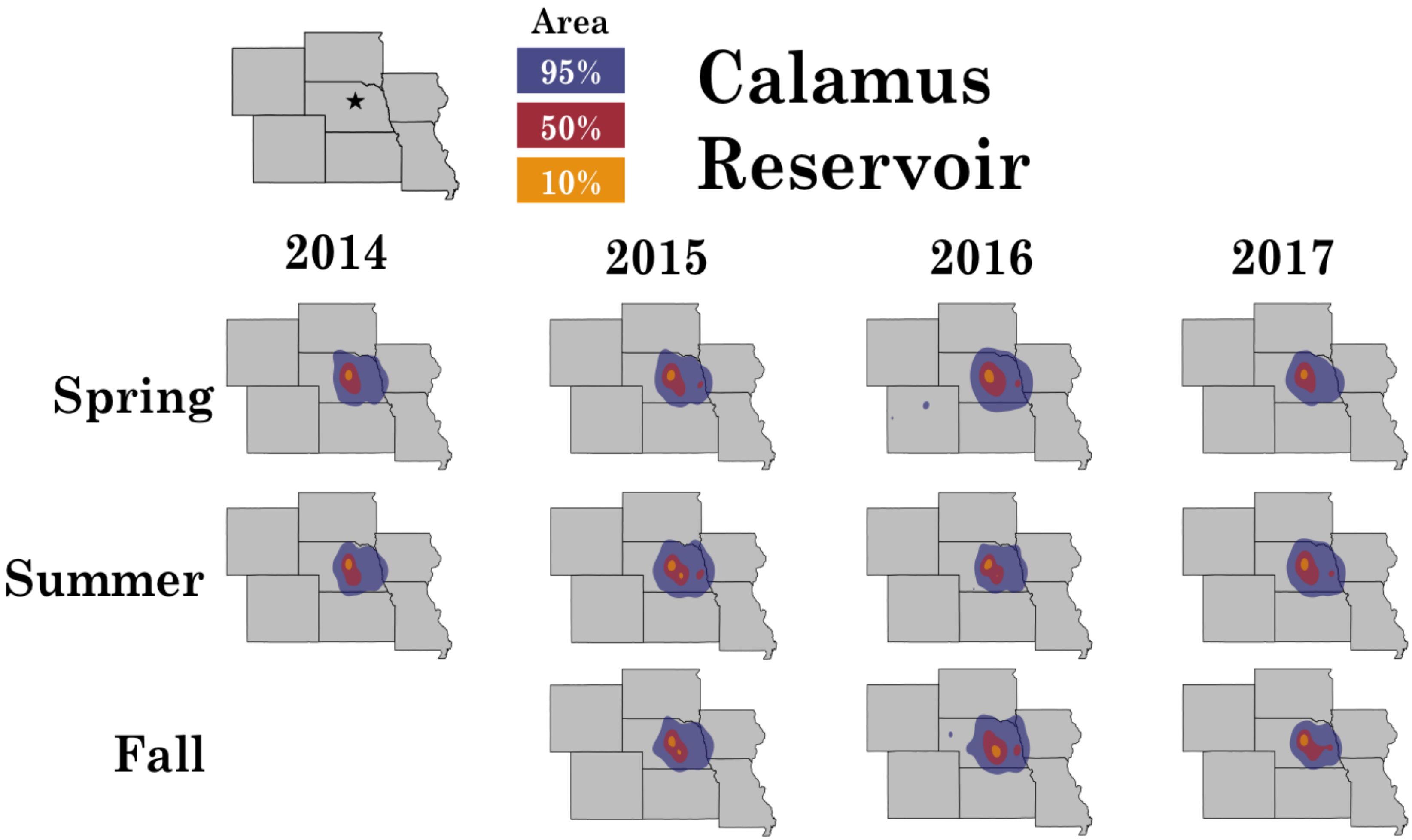

2014
2015
2016
2017
Apr
May
Jun
Jul
Aug
Sep
Oct
Lake Wanahoo
Area
95%
50%
10%

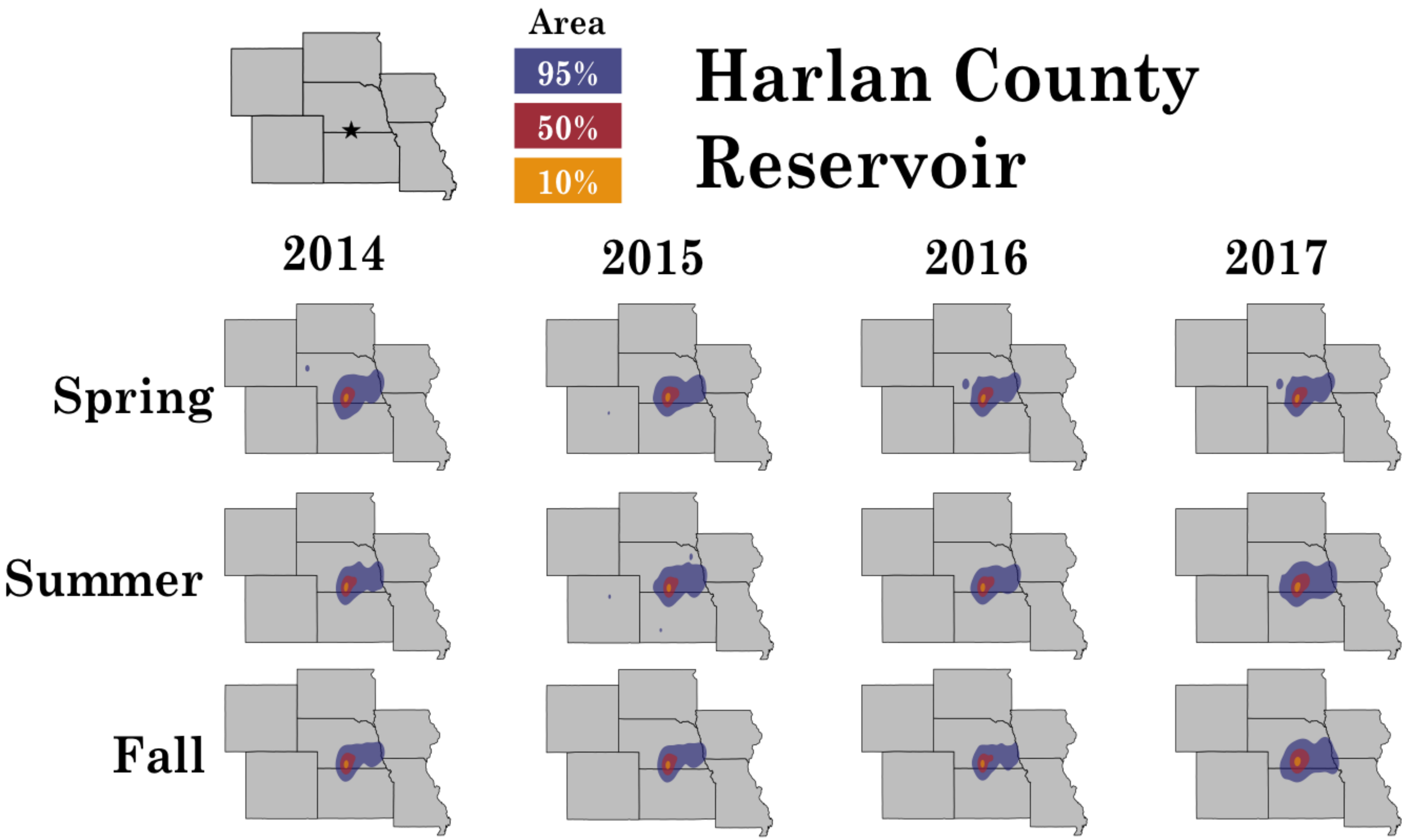

2014
2015
2016
2017
Apr
May
Jun
Jul
Aug
Sep
Oct
Pawnee Lake
Area
95%
50%
10%

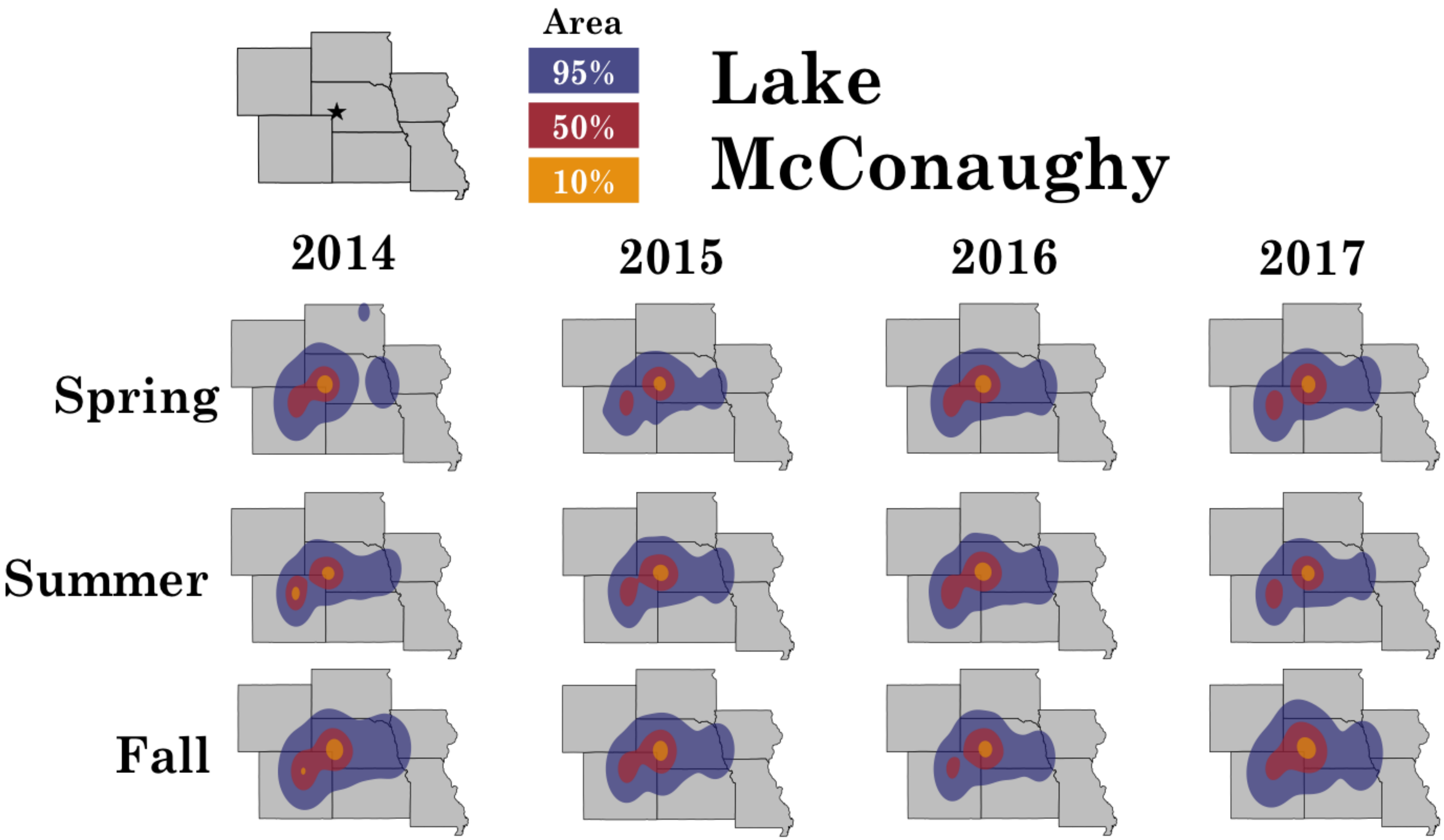

2014
2015
2016
2017
Apr
May
Jun
Jul
Aug
Sep
Oct
Sherman Reservoir
Area
95%
50%
10%

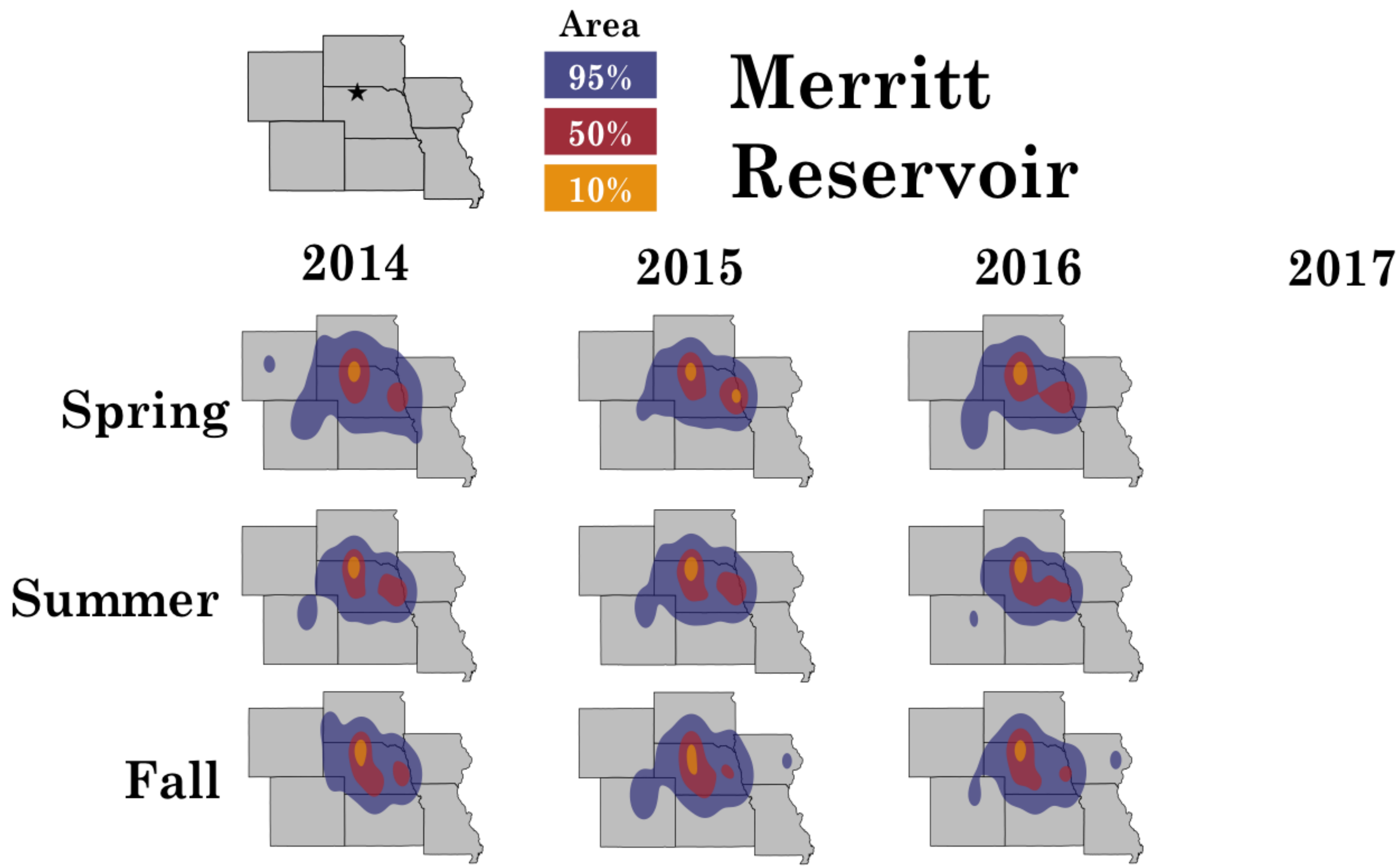
Appendix 2. Maps of the primary (10% UD), median (50% UD), and total (95% UD) anglersheds on a seasonal scale for each reservoir.

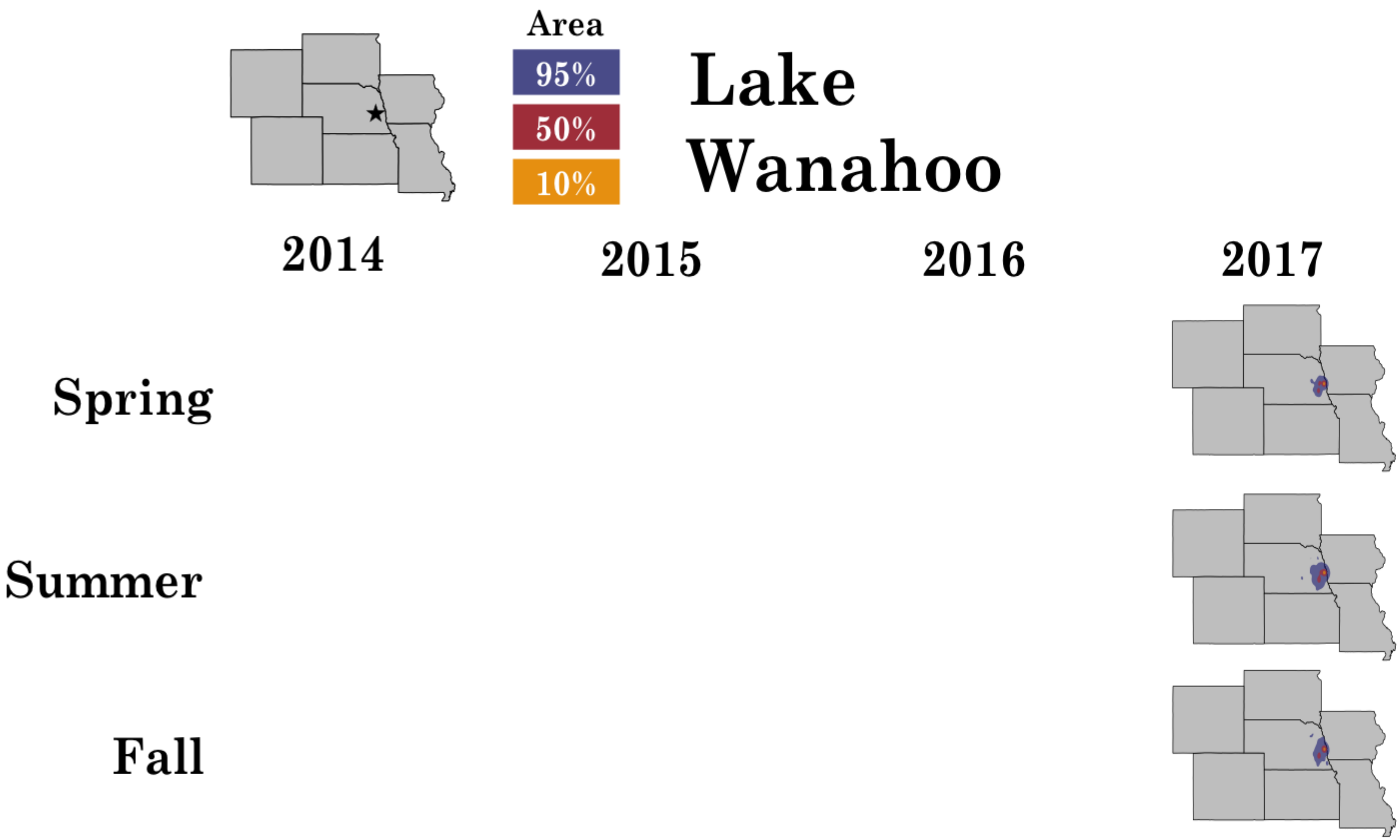

Area
95%
50%
10%
Branched Oak Lake
2014
2015
2016
2017
Spring
Summer
Fall

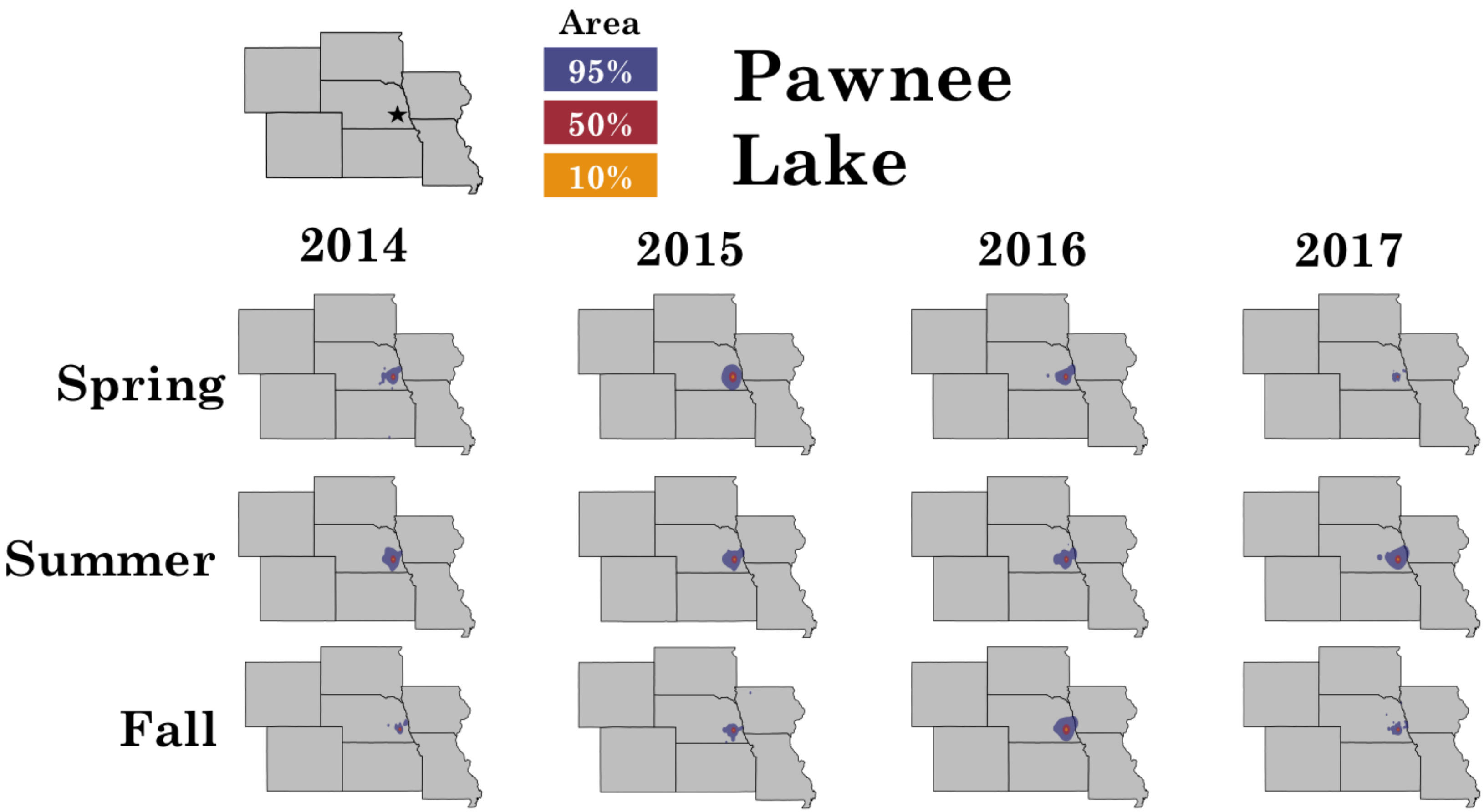

Area
95%
50%
10%
Calamus
Reservoir
2014
2015
2016
2017
Spring
Summer
Fall

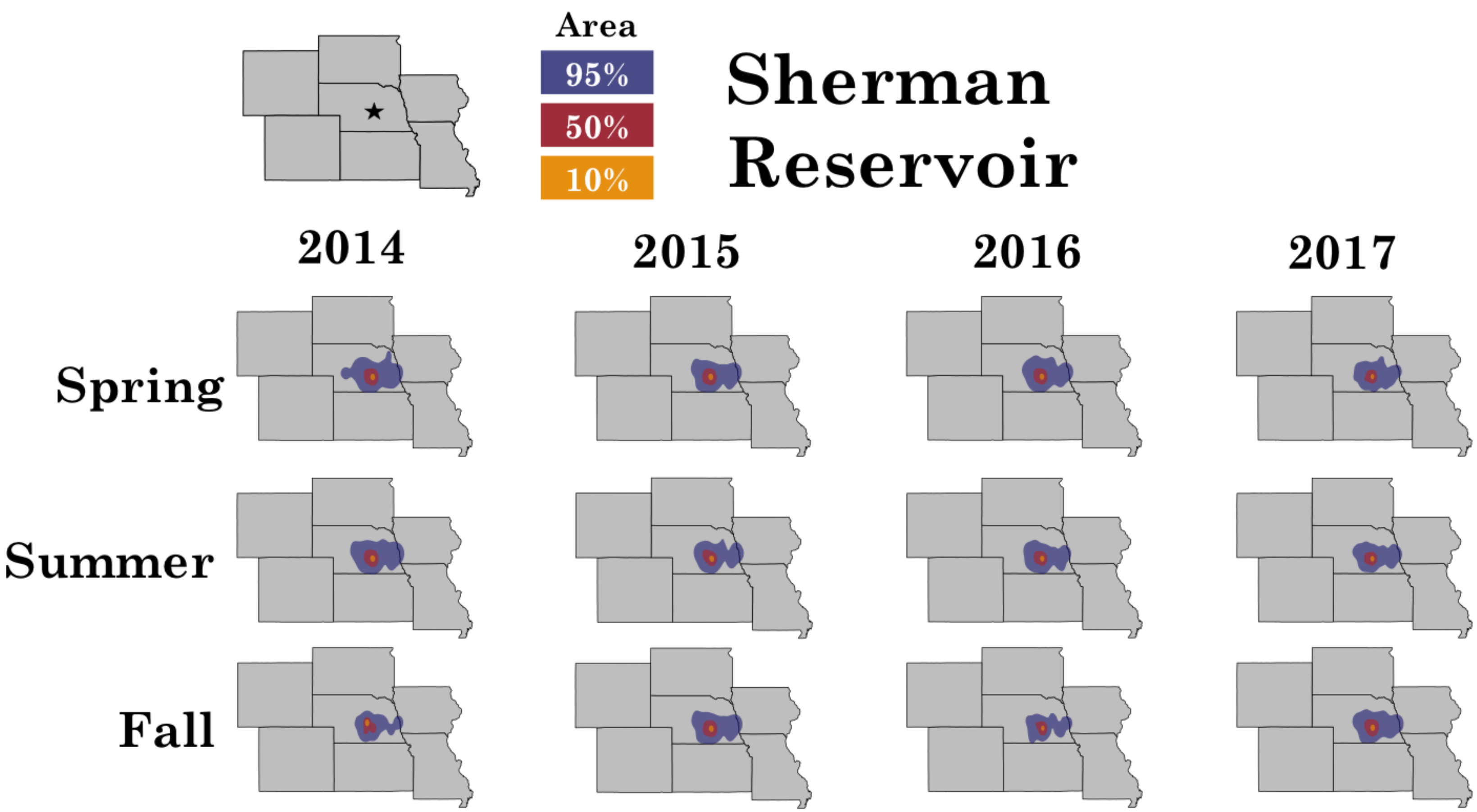

Area
95%
50%
10%
Harlan County Reservoir
2014
2015
2016
2017
Spring
Summer
Fall


Area
95%
50%
10%
Lake McConaughy
2014
2015
2016
2017
Spring
Summer
Fall

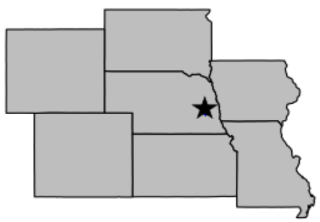

Area
95%
50%
10%
Merritt
Reservoir
2014
2015
2016
2017
Spring
Summer
Fall


Area
95%
50%
10%
Lake Wanahoo
2014
2015
2016
2017
Spring
Summer
Fall


Area
95%
50%
10%
Pawnee
Lake
2014
2015
2016
2017
Spring
Summer
Fall


Area
95%
50%
10%
Sherman Reservoir
2014
2015
2016
2017
Spring
Summer
Fall

Appendix 3. Maps of the primary (10% UD), median (50% UD), and total (95% UD) anglersheds on an annual scale for each reservoir.



Area

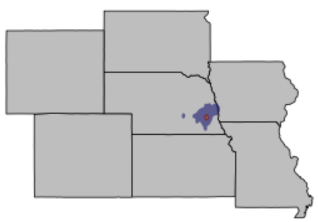
95%

50%

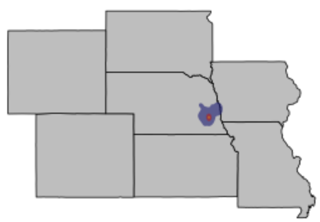
10%

Branched Oak Lake

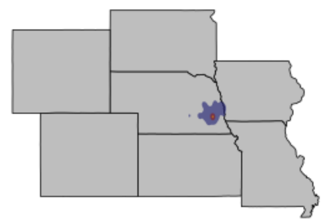
2014



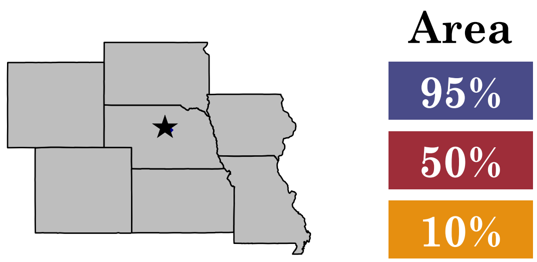
2015



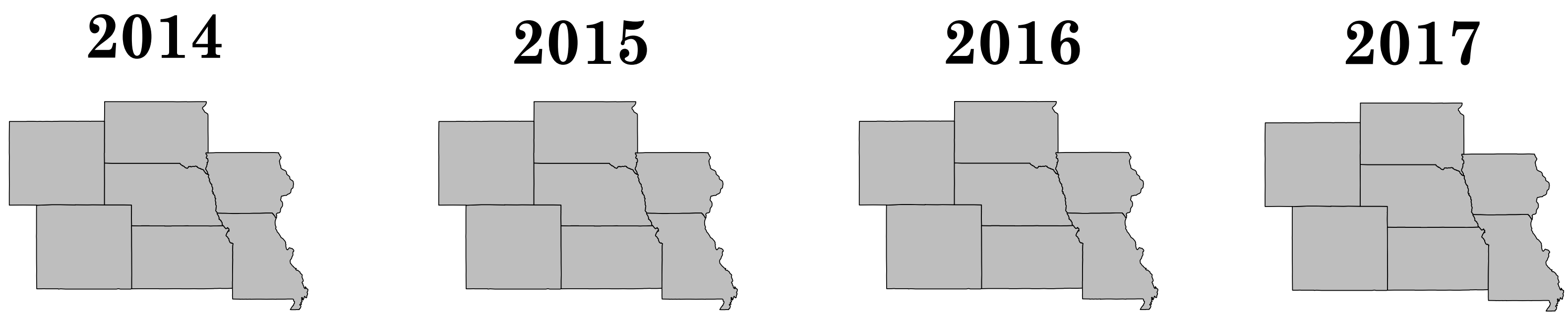
2016

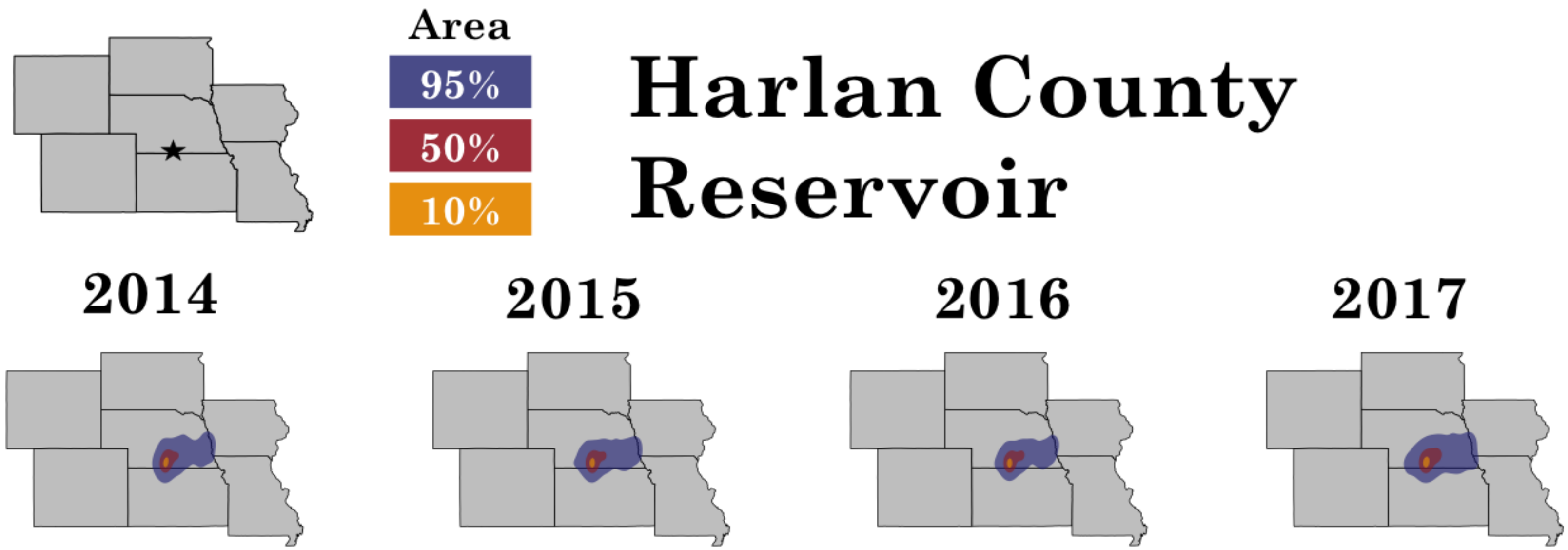


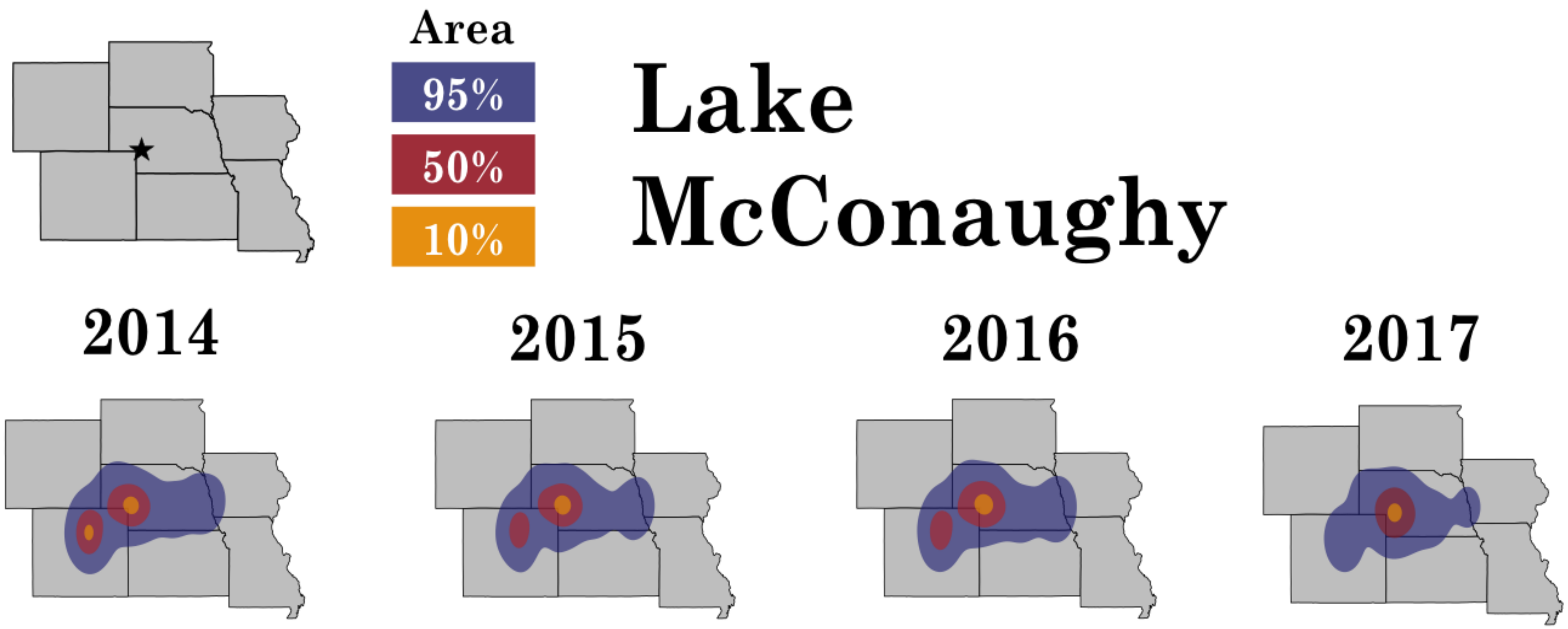
2017

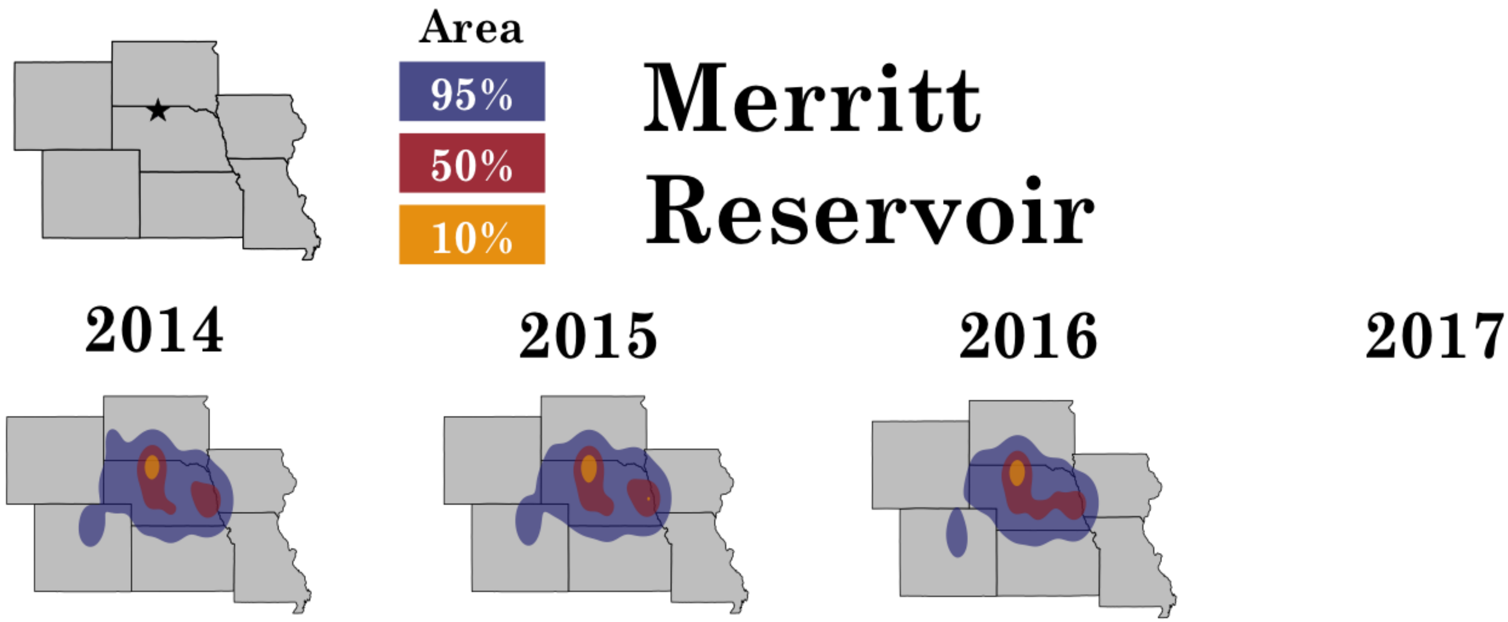


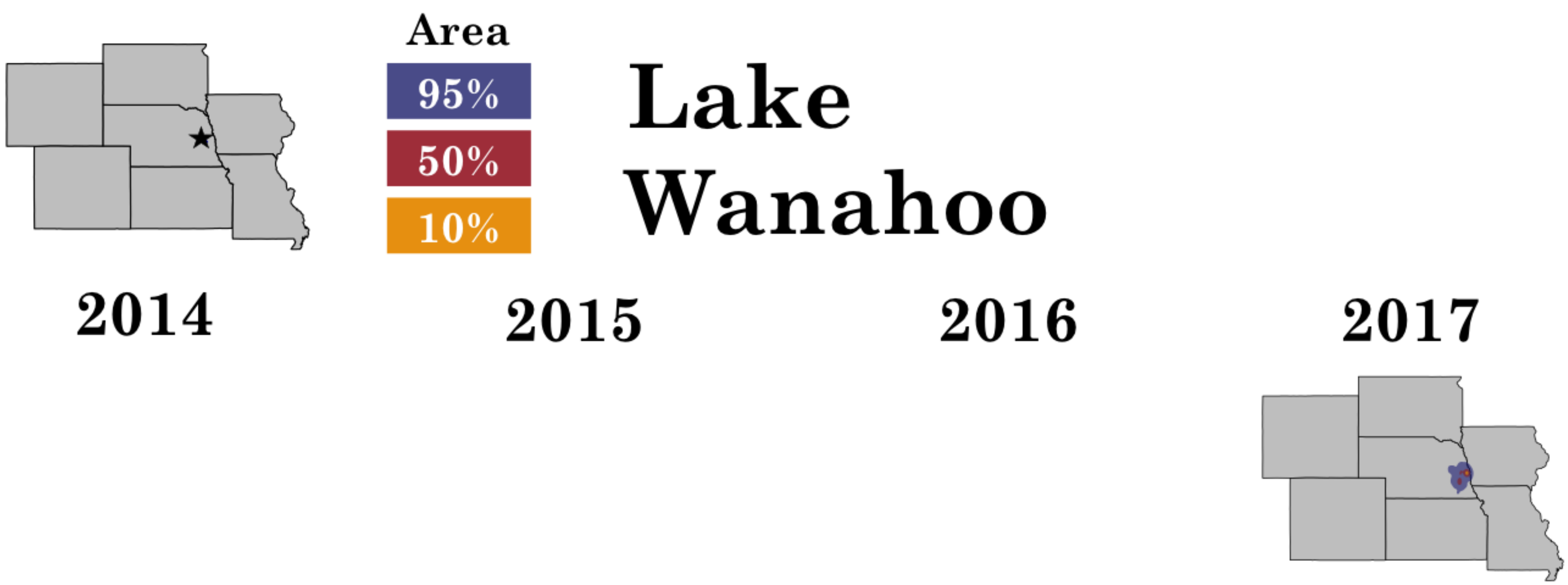
Calamus Reservoir

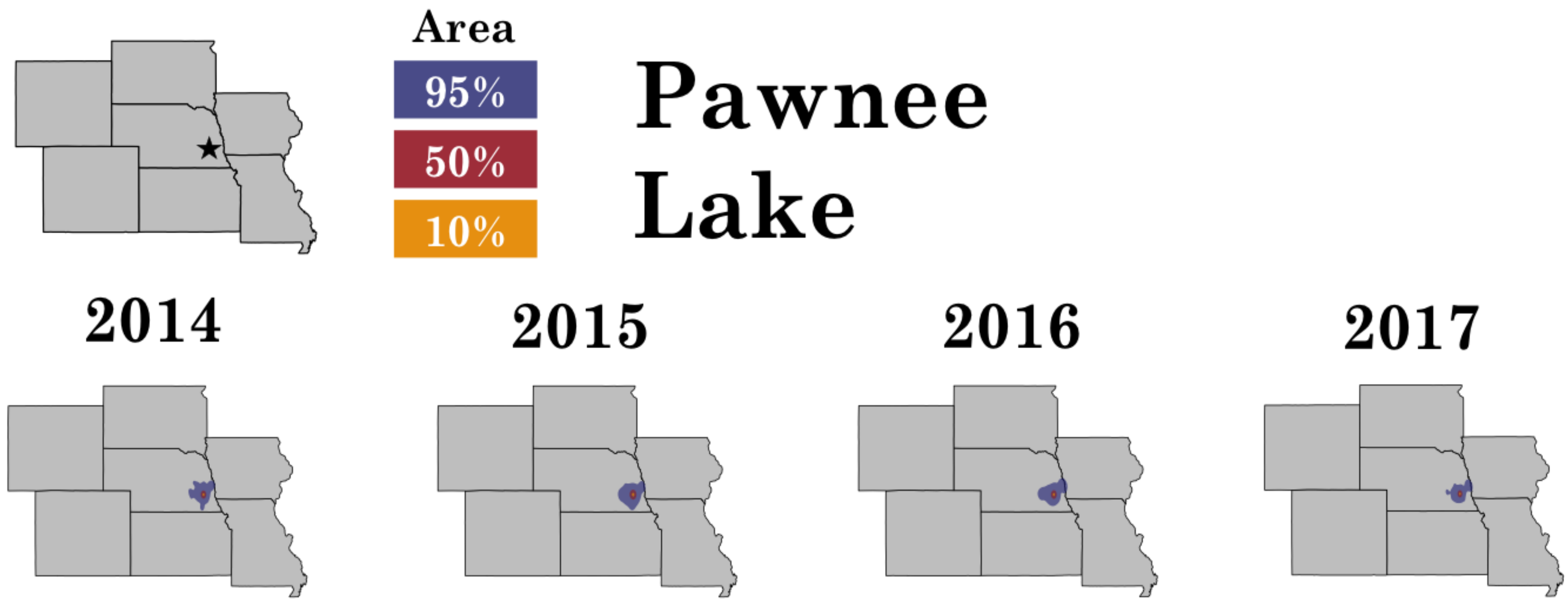


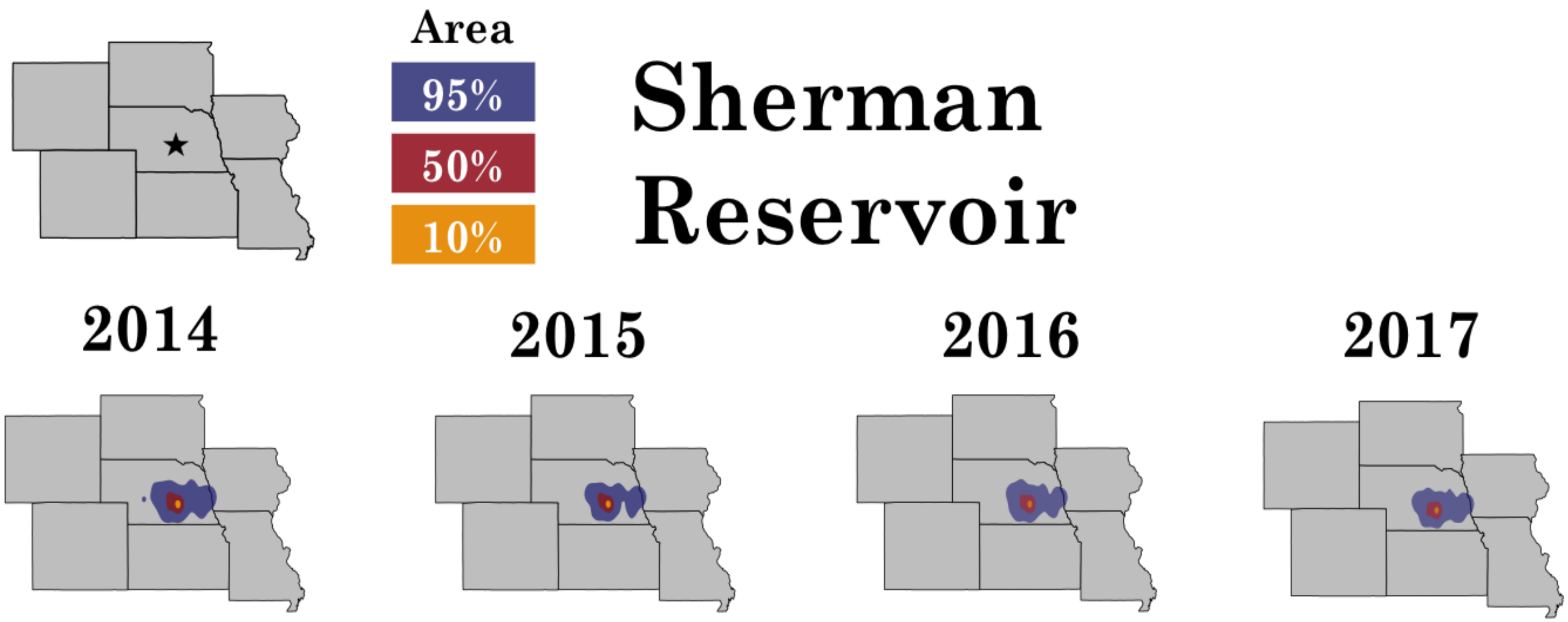

Area
95%
50%
10%
Harlan County
Reservoir
2014
2015
2016
2017


Area
95%
50%
10%
Lake McConaughy
2014
2015
2016
2017


Area
95%
50%
10%
Merritt
Reservoir
2014
2015
2016
2017


Area
95%
50%
10%
Lake Wanahoo
2014
2015
2016
2017


Area
95%
50%
10%
Pawnee
Lake
2014
2015
2016
2017


Area
95%
50%
10%
Sherman Reservoir
2014
2015
2016
2017

Appendix 4. Anglershed metrics quantified for eight Nebraska waterbodies.

Appendix 4-1. Area (A; ha), number of patches (P), and compactness (C; %) of primary (10% UD), median (50% UD), and total (95% UD) anglersheds for Branched Oak Lake. Sample size is number of angler parties.

				Primary		Median			Total		
Year	Month	Season	Sample Size	A	P	A	P	C	A	P	C
2014			1031	13,511	1	109,214	1	1	1,762,060	2	12
		Spring	399	13,431	1	104,925	1	1	1,482,386	3	13
		Summer	417	22,518	1	174,517	1	1	2,229,315	3	13
		Fall	215	21,560	1	162,964	1	1	1,744,813	3	13
	Apr		121	18,612	1	145,011	1	1	1,618,300	4	13
	May		278	14,894	1	113,835	1	1	1,471,216	1	13
	Jun		179	21,997	1	162,777	1	1	1,881,558	4	14
	Jul		126	55,443	1	420,718	1	2	2,725,863	1	13
	Aug		112	24,275	1	175,589	1	1	2,105,284	3	14
	Sep		118	43,840	1	335,631	1	2	2,894,547	3	13
	Oct		97	7,556	1	54,595	1	1	675,050	4	14
2015			1155	17,405	1	137,312	1	1	1,671,920	1	13
		Spring	417	15,231	1	114,236	1	1	1,198,936	1	13
		Summer	521	26,108	1	199,199	1	1	2,221,169	2	13
		Fall	217	38,745	1	292,806	1	2	2,490,241	1	13
	Apr		142	38,895	1	283,414	1	2	2,331,506	2	14
	May		275	9,393	1	70,891	1	1	803,164	2	13
	Jun		196	39,646	1	289,129	1	2	2,162,182	1	14
	Jul		183	37,245	1	285,547	1	1	2,969,116	4	13
	Aug		142	25,596	1	200,253	1	1	1,969,381	4	13
	Sep		133	54,652	1	409,887	1	2	2,557,696	1	13
	Oct		84	34,550	1	256,218	1	1	2,511,955	4	13

Appendix 4-1. Continued.

				Primary		Median			Total		
Year	Month	Season	Sample Size	A	P	A	P	C	A	P	C
2016			1260	15,107	1	120,108	1	1	1,915,685	2	13
		Spring	533	21,037	1	161,407	1	1	1,840,776	2	13
		Summer	551	18,701	1	149,308	1	1	2,332,837	2	13
		Fall	176	17,582	1	143,996	1	1	1,594,569	4	12
	Apr		202	47,878	1	348,569	1	2	2,533,923	2	14
	May		331	13,664	1	105,171	1	1	1,558,440	2	13
	Jun		235	20,950	1	164,303	1	1	2,037,777	2	13
	Jul		187	29,142	1	224,844	1	1	2,817,369	7	13
	Aug		129	30,564	1	236,141	1	1	2,209,567	1	13
	Sep		113	20,484	1	165,693	1	1	1,604,140	2	12
	Oct		63	20,668	1	166,581	1	1	1,445,490	2	12

Appendix 4-2. Area (A; ha), number of patches (P), and compactness (C; %) of primary (10% UD), median (50% UD), and total (95% UD) anglersheds for Calamus Reservoir. Sample size is number of angler parties.

				Primary		Median			Total		
Year	Month	Season	Sample Size	A	P	A	P	C	A	P	C
2014			412	373,142	1	3,070,896	1	2	15,866,681	1	12
		Spring	124	425,509	1	3,609,714	1	2	17,903,411	1	12
		Summer	288	424,131	1	3,184,461	1	3	16,242,141	1	13
	May		124	425,509	1	3,609,714	1	2	17,903,411	1	12
	Jun		107	669,197	2	4,744,822	2	3	20,403,072	1	14
	Jul		106	456,095	1	3,316,624	1	3	15,796,702	1	14
	Aug		75	444,208	1	3,111,932	1	3	15,653,078	1	14
2015			876	451,747	1	3,528,358	2	3	17,275,668	1	13
		Spring	327	487,920	1	3,925,651	2	3	18,008,460	1	12
		Summer	400	591,236	2	4,175,839	2	3	20,527,802	1	13
		Fall	149	521,372	2	3,734,480	1	3	17,578,630	1	12
	Apr		88	402,984	1	3,157,240	1	3	14,757,276	1	13
	May		239	599,374	1	4,673,630	2	3	21,094,492	2	13
	Jun		183	702,420	2	4,658,156	1	3	23,569,901	2	15
	Jul		113	743,166	1	5,105,073	2	4	20,540,976	1	15
	Aug		104	604,636	1	4,512,437	2	3	21,880,163	3	13
	Sep		115	535,170	1	4,124,339	2	3	18,318,449	1	13
	Oct		34	468,100	1	3,621,588	1	3	18,167,184	1	13

Appendix 4-2. Continued.

				Primary		Median			Total		
Year	Month	Season	Sample Size	A	P	A	P	C	A	P	C
2016			701	487,293	2	3,648,896	2	3	16,997,243	1	13
		Spring	219	711,926	1	5,249,744	2	3	23,718,268	3	14
		Summer	405	450,485	2	3,343,715	1	3	15,962,529	2	13
		Fall	77	601,155	1	4,789,862	2	3	21,412,729	2	13
	Apr		22	705,715	1	4,881,900	2	3	23,358,189	1	14
	May		197	402,378	1	3,441,715	2	2	17,119,690	3	12
	Jun		199	780,530	1	5,894,055	1	3	25,968,437	1	13
	Jul		130	494,798	1	3,913,313	2	3	17,885,945	1	13
	Aug		76	476,604	2	3,786,220	1	3	17,993,856	2	13
	Sep		57	555,650	1	4,129,906	1	4	15,064,119	2	13
	Oct		20	605,082	1	3,714,264	1	4	13,866,129	1	16
2017			647	402,231	1	3,627,395	2	2	16,620,686	1	11
		Spring	211	396,643	1	3,425,467	1	2	17,063,300	1	12
		Summer	370	531,433	1	4,409,918	2	3	19,860,476	1	12
		Fall	66	525,138	1	3,824,544	1	4	14,110,113	1	14
	Apr		29	705,715	1	4,881,900	1	3	23,358,189	2	14
	May		182	402,378	1	3,441,715	1	2	17,119,690	1	12
	Jun		196	780,530	1	5,894,055	1	3	25,968,437	2	13
	Jul		97	494,798	1	3,913,313	1	3	17,885,945	1	13
	Aug		77	476,604	1	3,786,220	2	3	17,993,856	3	13
	Sep		56	555,650	1	4,129,906	1	4	15,064,119	1	13
	Oct		10	605,082	2	3,714,264	1	4	13,866,129	1	16

Appendix 4-3. Area (A; ha), number of patches (P), and compactness (C; %) of primary (10% UD), median (50% UD), and total (95% UD) anglersheds for Harlan County Reservoir. Sample size is number of angler parties.

				Primary		Median			Total		
Year	Month	Season	Sample Size	A	P	A	P	C	A	P	C
2014			732	188,059	1	1,403,213	1	2	9,990,300	2	13
		Spring	283	227,557	1	1,626,169	1	2	12,306,719	2	14
		Summer	392	216,282	1	1,637,836	1	2	10,190,980	2	13
		Fall	59	231,321	1	1,598,862	1	2	10,120,515	2	14
	Apr		39	63,331	1	465,439	1	3	2,396,304	2	14
	May		244	271,472	1	1,917,602	1	2	14,518,415	1	14
	Jun		158	289,319	1	2,180,129	1	2	12,874,246	1	13
	Jul		122	262,132	1	1,807,025	1	3	9,404,409	1	15
	Aug		112	244,931	1	1,800,245	1	2	12,353,959	2	14
	Sep		30	377,409	1	2,638,536	1	2	16,020,751	2	14
	Oct		27	158,520	1	1,056,318	1	3	4,866,972	1	15
2015			1074	185,085	1	1,498,244	1	2	10,203,438	2	12
		Spring	413	251,993	1	1,889,428	1	2	11,604,248	4	13
		Summer	511	206,920	1	1,637,156	1	2	12,026,246	1	13
		Fall	150	215,024	1	1,731,585	1	2	9,140,372	3	12
	Apr		69	220,146	1	1,593,010	1	2	10,648,230	3	14
	May		344	281,271	1	2,075,548	1	2	12,091,505	2	14
	Jun		160	239,002	1	1,844,083	1	2	11,231,324	1	13
	Jul		149	251,506	1	1,973,940	1	2	11,919,268	2	13
	Aug		202	281,288	1	2,093,306	1	2	15,086,756	1	13
	Sep		103	260,237	1	2,070,507	1	2	10,502,543	1	13
	Oct		47	213,364	1	1,657,982	1	3	8,195,544	1	13

Appendix 4-3. Continued.

				Primary		Median			Total		
Year	Month	Season	Sample Size	A	P	A	P	C	A	P	C
2016			862	251,372	1	1,446,532	1	2	9,051,602	1	13
		Spring	157	223,351	1	1,593,380	1	3	10,783,366	2	14
		Summer	521	229,768	1	1,791,770	1	3	10,242,602	1	13
		Fall	184	176,628	1	1,399,808	1	3	8,712,251	1	13
	Apr		44	649,748	1	2,982,644	1	3	18,883,313	2	22
	May		113	315,744	1	1,431,482	1	4	8,678,673	1	22
	Jun		114	387,866	1	1,865,549	1	3	11,232,292	1	21
	Jul		163	348,247	1	1,640,675	1	3	9,373,645	1	21
	Aug		244	541,007	1	2,587,014	1	4	12,862,370	1	21
	Sep		106	369,077	1	1,822,153	1	4	9,876,955	1	20
	Oct		78	255,334	1	1,265,447	1	3	8,223,099	2	20
2017			621	251,372	1	1,929,393	1	2	13,056,661	1	13
		Spring	156	247,855	1	1,896,556	1	2	13,555,048	1	13
		Summer	361	318,978	1	2,290,845	1	2	14,340,294	1	14
		Fall	104	340,167	1	2,650,444	1	2	13,952,338	1	13
	Apr		37	423,617	1	2,017,263	1	4	10,840,194	1	21
	May		119	439,033	1	2,130,031	1	3	15,338,250	4	21
	Jun		127	500,140	1	2,319,854	1	3	16,795,241	1	22
	Jul		101	514,874	1	2,356,614	1	3	15,689,145	2	22
	Aug		133	672,912	1	3,163,501	2	5	13,690,994	1	21
	Sep		72	699,251	1	3,459,326	2	4	16,499,431	2	20
	Oct		32	346,126	1	1,701,323	1	4	9,051,816	1	20

Appendix 4-4. Area (A; ha), number of patches (P), and compactness (C; %) of primary (10% UD), median (50% UD), and total (95% UD) anglersheds for Lake McConaughy. Sample size is number of angler parties.

				Primary		Median			Total		
Year	Month	Season	Sample Size	A	P	A	P	C	A	P	C
2014			580	1,360,759	2	9,770,847	2	3	46,382,841	1	14
		Spring	63	1,567,219	1	10,531,604	1	3	53,069,515	3	15
		Summer	375	1,488,285	1	10,440,484	2	3	48,089,190	1	14
		Fall	142	2,197,904	2	15,510,176	2	3	65,097,115	1	14
	May		63	2,466,312	1	10,531,604	1	5	53,069,515	3	23
	Jun		87	3,427,153	2	14,875,283	1	6	60,341,362	1	23
	Jul		140	2,487,971	1	12,826,237	1	4	62,223,810	1	20
	Aug		148	1,909,383	1	10,040,929	2	4	49,801,551	1	20
	Sep		92	4,119,914	1	19,684,036	2	5	75,986,451	1	21
	Oct		50	2,495,006	2	11,194,195	2	5	51,550,435	1	22
2015			587	1,042,128	1	8,501,950	2	2	44,931,109	1	12
		Spring	173	989,568	1	7,989,041	2	2	46,013,109	1	12
		Summer	307	1,392,713	1	10,949,552	1	3	52,073,011	1	13
		Fall	107	1,666,442	1	12,770,318	1	3	56,234,526	1	13
	Apr		61	1,666,604	1	8,434,070	2	4	44,927,149	2	20
	May		112	1,912,263	1	9,489,511	2	4	50,957,034	1	20
	Jun		149	2,896,241	2	14,687,760	1	5	64,197,770	1	20
	Jul		105	3,296,145	1	13,592,676	1	5	63,835,349	1	24
	Aug		53	1,021,968	1	5,279,031	1	4	29,165,927	1	19
	Sep		55	1,989,024	1	9,049,641	1	5	41,270,159	2	22
	Oct		52	3,920,618	1	19,615,843	2	5	73,257,139	1	20

Appendix 4-4. Continued.

				Primary		Median			Total		
Year	Month	Season	Sample Size	A	P	A	P	C	A	P	C
2016			497	749,652	1	6,313,053	2	2	30,487,073	1	12
		Spring	140	1,606,893	1	12,088,339	1	3	54,121,391	1	13
		Summer	233	1,735,931	1	13,133,942	1	3	57,904,119	1	13
		Fall	124	1,268,117	1	10,697,781	2	3	50,675,297	1	12
	Apr		50	3,322,394	1	15,835,496	1	5	65,828,573	1	21
	May		90	2,752,083	1	12,507,148	1	5	57,836,964	1	22
	Jun		100	3,780,768	1	16,957,521	1	5	71,349,811	1	22
	Jul		73	3,790,470	1	18,096,397	1	5	77,217,254	1	21
	Aug		60	2,574,282	1	12,187,751	1	5	51,167,814	1	21
	Sep		74	2,811,706	1	14,044,280	1	5	61,964,866	1	20
	Oct		50	1,738,855	1	9,175,860	2	4	46,949,980	1	19
2017			594	1,031,377	1	8,393,961	2	2	44,419,600	1	12
		Spring	166	1,333,092	1	11,208,189	2	2	53,548,009	1	12
		Summer	385	1,138,516	1	8,923,341	2	2	47,373,582	1	13
		Fall	43	2,251,819	1	16,572,973	1	3	70,392,717	1	14
	Apr		29	1,340,411	1	6,528,298	1	3	41,988,091	1	21
	May		137	2,635,183	1	13,212,387	1	4	60,242,650	1	20
	Jun		133	2,819,164	1	12,709,795	1	5	61,221,986	1	22
	Jul		148	2,357,503	1	11,130,333	2	4	55,943,744	1	21
	Aug		104	1,710,173	1	8,972,957	2	4	43,924,671	1	20
	Sep		34	3,612,606	1	17,925,680	1	5	76,462,587	1	20
	Oct		9	4,051,417	1	17,307,026	1	5	81,625,390	1	23

Appendix 4-5. Area (A; ha), number of patches (P), and compactness (C; %) of primary (10% UD), median (50% UD), and total (95% UD) anglersheds for Merritt Reservoir. Sample size is number of angler parties.

				Primary		Median			Total		
Year	Month	Season	Sample Size	A	P	A	P	C	A	P	C
2014			857	1,130,156	1	10,107,239	2	2	1,130,157	1	11
		Spring	217	1,357,604	1	12,273,913	2	2	72,494,735	2	11
		Summer	471	1,395,820	1	10,933,412	2	3	47,918,040	2	13
		Fall	167	1,658,439	1	11,774,003	2	3	48,802,096	1	14
	Apr		49	1,664,370	1	13,370,439	1	2	86,619,036	3	12
	May		168	1,524,607	1	13,027,502	2	2	73,054,948	1	12
	Jun		173	1,989,712	2	13,543,361	2	3	61,446,852	2	15
	Jul		170	1,230,675	1	11,050,764	2	2	43,221,703	1	11
	Aug		128	2,038,341	2	13,355,184	2	4	57,666,276	2	15
	Sep		101	1,898,400	2	12,382,698	2	4	45,590,781	1	15
	Oct		68	1,751,875	1	13,360,725	2	3	62,983,465	2	13
2015			752	1,419,627	2	11,413,115	1	3	49,538,138	1	12
		Spring	218	1,733,604	2	12,862,457	2	3	54,602,216	1	13
		Summer	387	1,680,125	1	12,915,812	2	3	54,641,762	1	13
		Fall	147	1,664,415	1	12,113,244	2	2	57,197,461	2	14
	Apr		57	1,386,718	1	12,061,619	2	2	61,581,612	1	11
	May		161	1,799,716	1	13,640,060	1	3	55,453,277	1	13
	Jun		150	2,370,421	2	15,922,465	1	3	70,450,408	2	15
	Jul		147	1,968,816	1	14,458,978	1	3	58,516,272	1	14
	Aug		90	1,404,193	1	12,049,035	2	3	50,267,444	1	12
	Sep		93	1,595,065	1	10,940,588	1	3	54,932,007	1	15
	Oct		54	2,429,677	1	16,837,376	1	3	77,175,702	2	14

Appendix 4-5. Continued.

				Primary		Median			Total		
Year	Month	Season	Sample Size	A	P	A	P	C	A	P	C
2016			638	1,277,658	1	11,074,660	1	3	45,993,243	2	12
		Spring	193	1,775,917	1	13,869,426	1	3	61,888,026	1	13
		Summer	301	1,721,308	1	12,103,456	1	4	44,864,779	2	14
		Fall	144	1,276,388	1	11,015,270	2	2	51,903,162	2	12
	Apr		53	1,050,903	1	8,630,026	1	2	45,198,389	2	12
	May		140	2,456,748	2	16,794,245	1	3	71,179,365	1	15
	Jun		117	2,443,828	2	15,871,404	1	4	63,306,668	1	15
	Jul		100	1,586,698	1	11,506,111	1	3	45,371,999	1	13
	Aug		84	1,641,697	2	10,955,437	1	4	38,377,764	1	15
	Sep		88	2,424,347	1	16,201,832	1	4	69,118,596	2	15
	Oct		56	626,763	1	4,975,919	1	2	29,204,137	1	13

Appendix 4-6. Area (A; ha), number of patches (P), and compactness (C; %) of primary (10% UD), median (50% UD), and total (95% UD) anglersheds for Lake Wanahoo. Sample size is number of angler parties.

				Primary		Median			Total		
Year	Month	Season	Sample Size	A	P	A	P	C	A	P	C
2017			1609	41,124	1	347,798	2	2	2,328,840	1	12
		Spring	510	44,308	1	364,893	2	3	1,759,308	1	13
		Summer	790	61,246	1	460,026	1	2	3,005,140	4	13
		Fall	309	42,769	1	356,935	2	2	2,373,221	3	12
	Apr		192	35,847	1	302,568	3	3	1,404,922	1	12
	May		318	60,598	1	450,904	1	3	2,174,374	1	13
	Jun		303	92,637	1	605,530	1	3	3,047,985	1	15
	Jul		287	60,265	1	471,786	2	2	3,154,480	4	13
	Aug		200	79,703	2	532,774	1	3	3,002,928	2	15
	Sep		204	55,663	1	433,196	2	2	2,743,050	9	13
	Oct		105	38,527	1	338,993	3	2	1,879,611	3	11

Appendix 4-7. Area (A; ha), number of patches (P), and compactness (C; %) of primary (10% UD), median (50% UD), and total (95% UD) anglersheds for Pawnee Lake. Sample size is number of angler parties.

				Primary		Median			Total		
Year	Month	Season	Sample Size	A	P	A	P	C	A	P	C
2014			344	20,513	1	148,719	1	1	1,887,200	1	14
		Spring	113	23,768	1	170,271	1	1	1,818,274	3	14
		Summer	178	33,049	1	235,900	1	1	2,258,715	3	14
		Fall	53	10,861	1	76,834	1	1	739,232	3	14
	Apr		30	35,727	1	175,520	1	2	1,599,007	3	20
	May		83	44,873	1	201,211	1	3	1,657,428	3	22
	Jun		78	34,728	1	159,969	1	2	1,586,976	4	22
	Jul		61	138,832	1	617,855	1	4	3,734,685	1	22
	Aug		39	26,982	1	133,645	1	2	1,346,380	1	20
	Sep		32	12,630	1	55,978	1	3	401,576	2	23
	Oct		31	34,915	1	165,892	1	3	1,259,644	2	21
2015			476	31,298	1	167,366	1	1	2,196,224	1	14
		Spring	155	67,362	1	459,468	1	2	2,929,737	1	15
		Summer	230	31,930	1	239,476	1	1	2,340,986	1	13
		Fall	91	20,328	1	145,318	1	1	1,448,071	3	14
	Apr		45	111,791	1	484,772	1	5	2,503,196	1	23
	May		110	129,697	1	574,084	1	4	3,648,598	1	23
	Jun		108	65,175	1	307,880	1	2	2,690,955	6	21
	Jul		87	75,361	1	349,549	1	3	2,777,415	4	22
	Aug		35	32,908	1	161,721	1	2	1,337,573	2	20
	Sep		55	53,791	1	248,000	1	3	2,091,369	2	22
	Oct		36	13,205	1	59,117	1	3	405,528	3	22

Appendix 4-7. Continued.

Year	Month	Season	Sample Size	Primary A	Primary P	Median A	Median P	Median C	Total A	Total P	Total C
2016			1213	23,602	1	167,366	1	1	2,126,409	1	14
		Spring	372	25,055	1	181,650	1	1	1,988,123	2	14
		Summer	586	24,986	1	180,778	1	1	2,331,013	2	14
		Fall	255	61,830	1	430,603	1	2	3,087,094	1	14
	Apr		82	137,564	1	612,338	1	3	4,160,090	1	22
	May		290	28,063	1	129,919	1	2	1,577,740	3	22
	Jun		200	68,478	1	312,151	1	2	3,286,923	2	22
	Jul		246	30,629	1	140,172	1	2	1,844,222	2	22
	Aug		140	83,773	1	373,826	1	3	2,508,687	2	22
	Sep		170	71,251	1	322,884	1	3	2,445,080	1	22
	Oct		85	227,447	1	1,004,741	1	4	5,756,833	1	23
2017			817	15,610	1	114,678	1	1	1,492,622	1	14
		Spring	336	5,596	1	40,521	1	1	545,872	3	14
		Summer	351	39,177	1	278,291	1	1	3,062,547	2	14
		Fall	130	12,358	1	90,682	1	1	1,157,043	4	14
	Apr		149	7,681	1	34,885	1	2	383,774	7	22
	May		187	12,253	1	57,018	1	2	618,519	2	21
	Jun		137	128,498	1	569,560	1	3	3,826,297	1	23
	Jul		121	61,348	1	288,200	1	2	3,384,783	5	21
	Aug		93	35,831	1	164,953	1	2	1,714,094	3	22
	Sep		90	24,022	1	113,199	1	2	1,329,800	4	21
	Oct		40	18,307	1	84,849	1	3	666,906	3	22

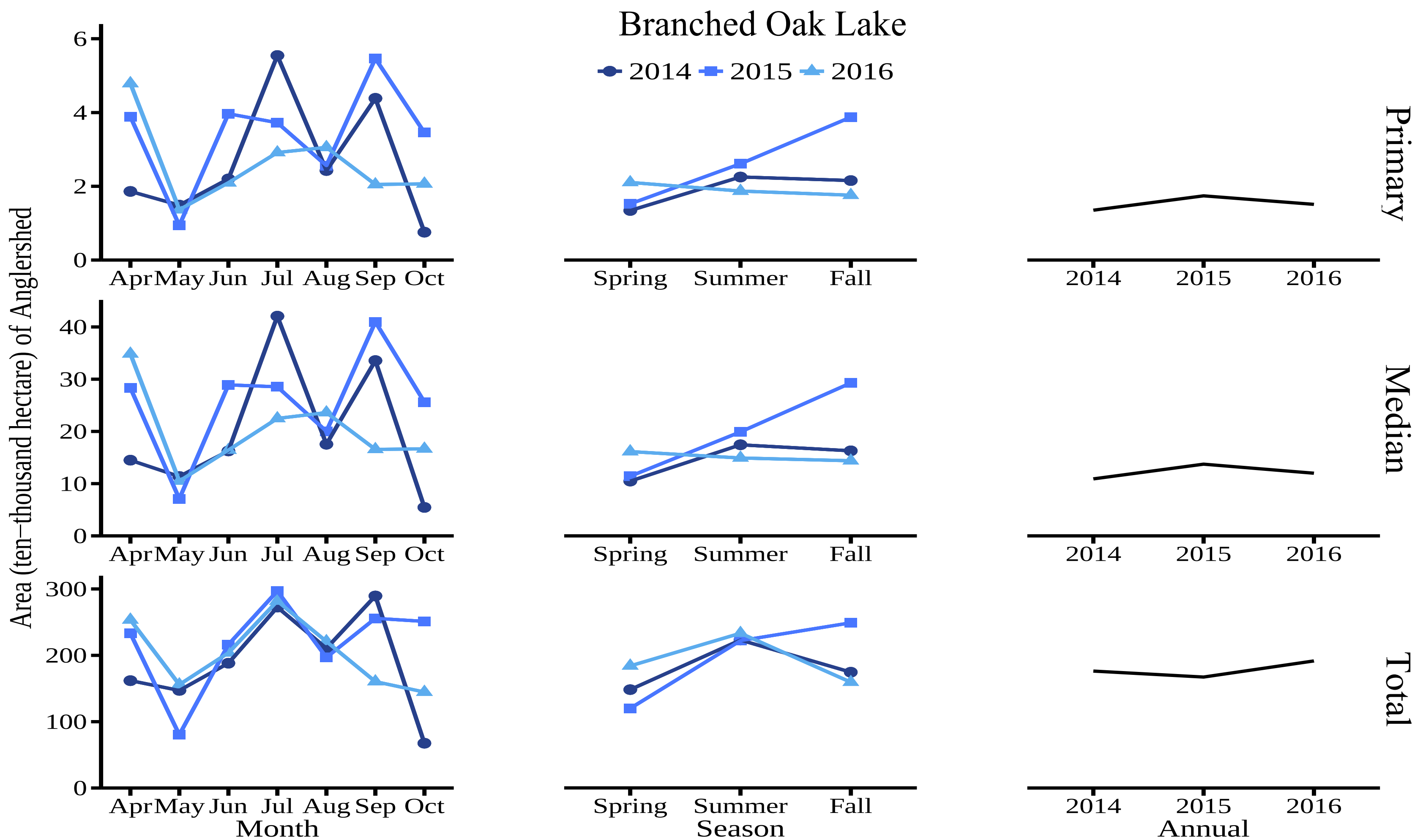
Appendix 4-8. Area (A; ha), number of patches (P), and compactness (C; %) of primary (10% UD), median (50% UD), and total (95% UD) anglersheds for Sherman Reservoir. Sample size is number of angler parties.

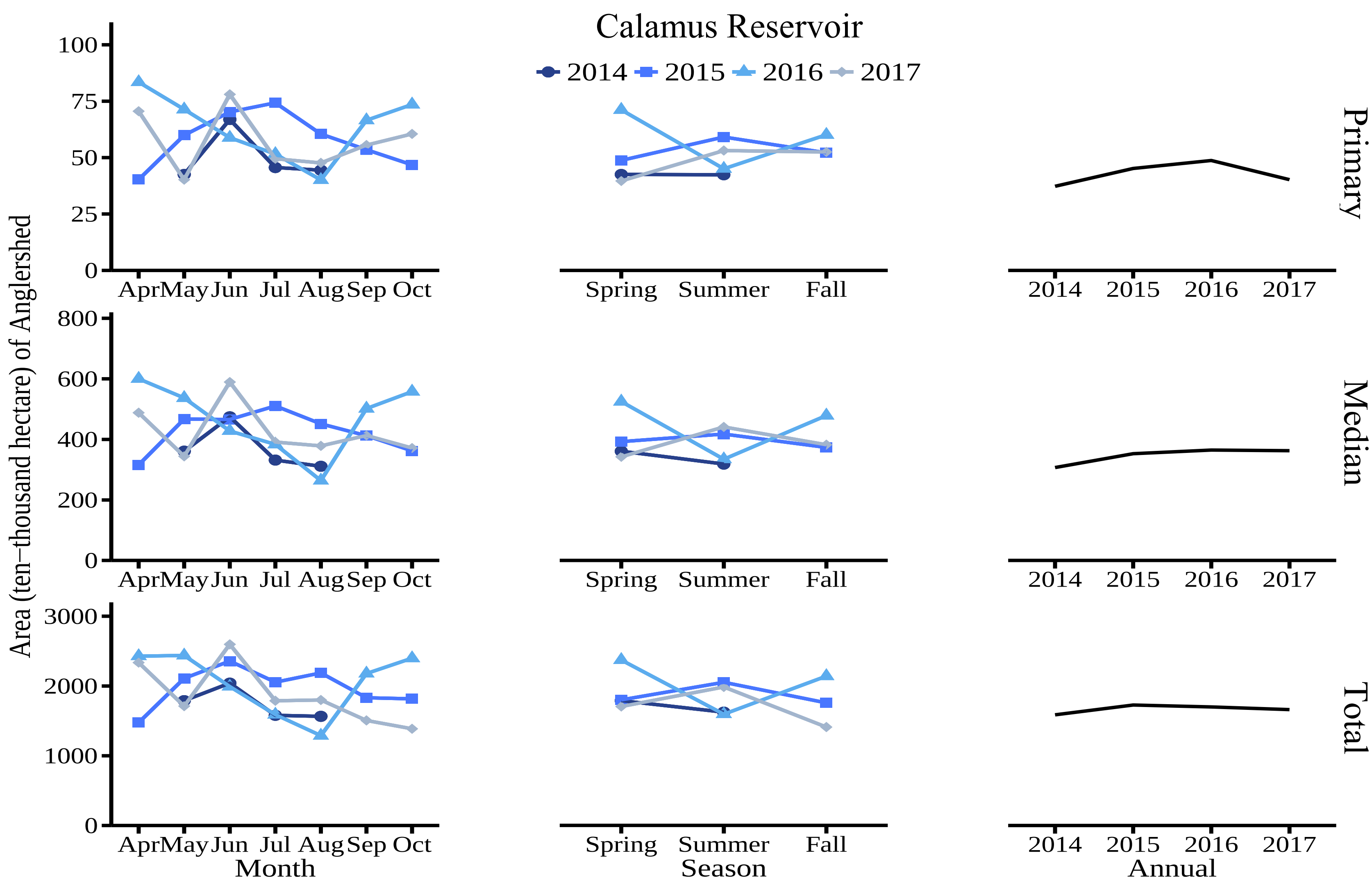
				Primary		Median			Total		
Year	Month	Season	Sample Size	A	P	A	P	C	A	P	C
2014			661	145,374	1	1,223,958	1	2	9,041,346	2	12
		Spring	223	173,036	1	1,502,463	1	2	11,065,896	1	12
		Summer	290	184,453	1	1,480,317	1	2	10,399,736	1	12
		Fall	148	161,453	1	1,101,080	1	2	6,765,233	1	15
	Apr		64	388,712	1	145,011	1	2	16,322,526	2	13
	May		159	144,713	1	2,919,705	1	2	9,324,859	1	12
	Jun		128	264,175	1	1,205,755	1	2	13,386,944	1	13
	Jul		88	145,480	1	1,983,656	1	2	7,232,816	2	13
	Aug		74	319,682	1	1,099,672	1	2	13,319,336	1	12
	Sep		84	165,904	1	2,704,944	2	3	6,566,977	2	15
	Oct		64	207,307	1	1,138,393	1	3	7,920,837	1	16
2015			608	118,696	1	1,336,516	1	2	7,197,776	1	12
		Spring	225	117,341	1	895,550	1	2	6,664,992	1	13
		Summer	187	171,671	1	1,265,184	1	2	8,478,077	1	14
		Fall	196	182,985	1	1,437,001	1	2	9,077,301	1	13
	Apr		92	166,093	1	1,148,320	1	2	7,802,170	4	14
	May		133	117,121	1	916,262	1	2	6,348,011	1	13
	Jun		68	185,629	1	1,368,357	1	2	7,583,836	1	13
	Jul		46	160,027	1	1,197,081	1	2	8,695,970	1	13
	Aug		73	273,015	1	1,914,671	1	2	11,485,350	1	14
	Sep		115	235,019	1	1,732,726	1	2	10,453,595	1	14
	Oct		81	181,056	1	1,461,953	1	2	9,113,130	1	12

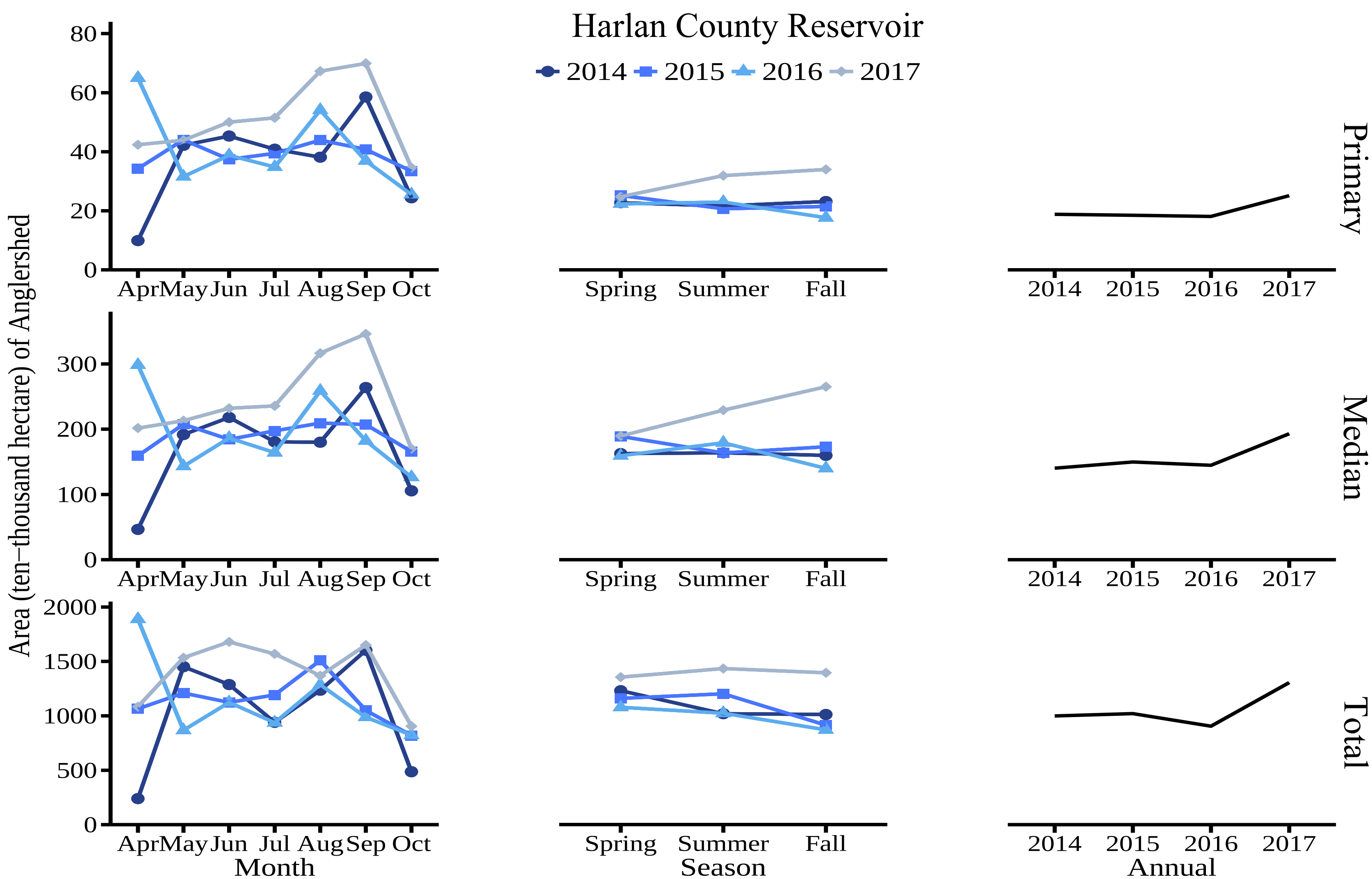
Appendix 4-8. Continued.

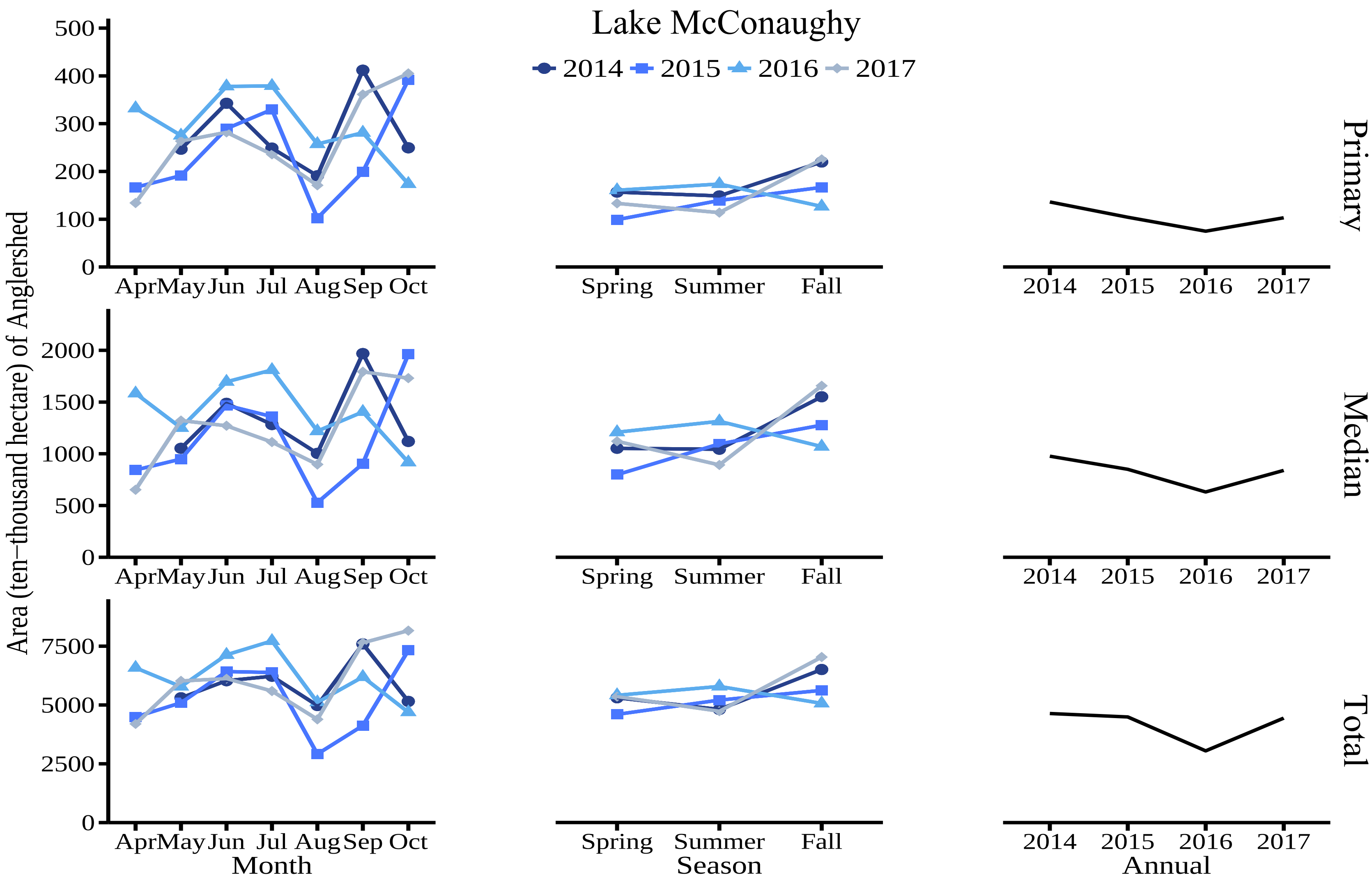
				Primary		Median			Total		
Year	Month	Season	Sample Size	A	P	A	P	C	A	P	C
2016			1019	111,731	1	991,012	1	1	7,755,645	1	11
		Spring	393	165,168	1	1,316,492	1	2	9,565,215	1	13
		Summer	406	147,954	1	1,150,101	1	2	8,366,346	1	13
		Fall	220	101,001	1	891,444	1	1	6,747,716	1	11
	Apr		131	192,010	1	1,394,315	1	2	10,165,761	2	14
	May		262	195,328	1	1,534,212	1	1	10,157,051	2	13
	Jun		147	230,809	1	1,704,438	1	1	10,883,549	2	14
	Jul		154	164,741	1	1,206,236	1	1	9,275,730	2	14
	Aug		105	155,190	1	1,145,965	1	1	6,928,460	2	14
	Sep		119	124,096	1	1,034,082	1	1	6,862,704	2	12
	Oct		101	119,814	1	999,615	1	1	7,605,612	2	12
2017			969	100,009	1	940,092	1	1	7,555,982	1	11
		Spring	336	111,467	1	958,623	1	1	8,264,619	1	12
		Summer	417	126,996	1	1,051,314	1	2	7,904,320	1	12
		Fall	216	174,016	1	1,463,682	1	2	9,073,592	1	12
	Apr		112	125,134	1	984,313	1	2	6,983,773	1	13
	May		224	132,046	1	1,100,958	1	1	9,381,583	2	12
	Jun		170	176,117	1	1,308,900	1	2	11,427,269	5	13
	Jul		153	131,195	1	1,061,569	1	2	7,243,297	1	12
	Aug		94	191,853	1	1,461,329	1	2	8,249,159	1	13
	Sep		130	225,250	1	1,796,698	1	2	10,766,057	1	13
	Oct		86	166,955	1	1,380,304	1	2	8,206,757	1	12

Appendix 5. Dynamics of area (ha) of the primary (10%), median (50%), total (95%) anglersheds across three time scales: monthly, seasonal (Spring = April-May, Summer = June-August, Fall = September-October), and annual.

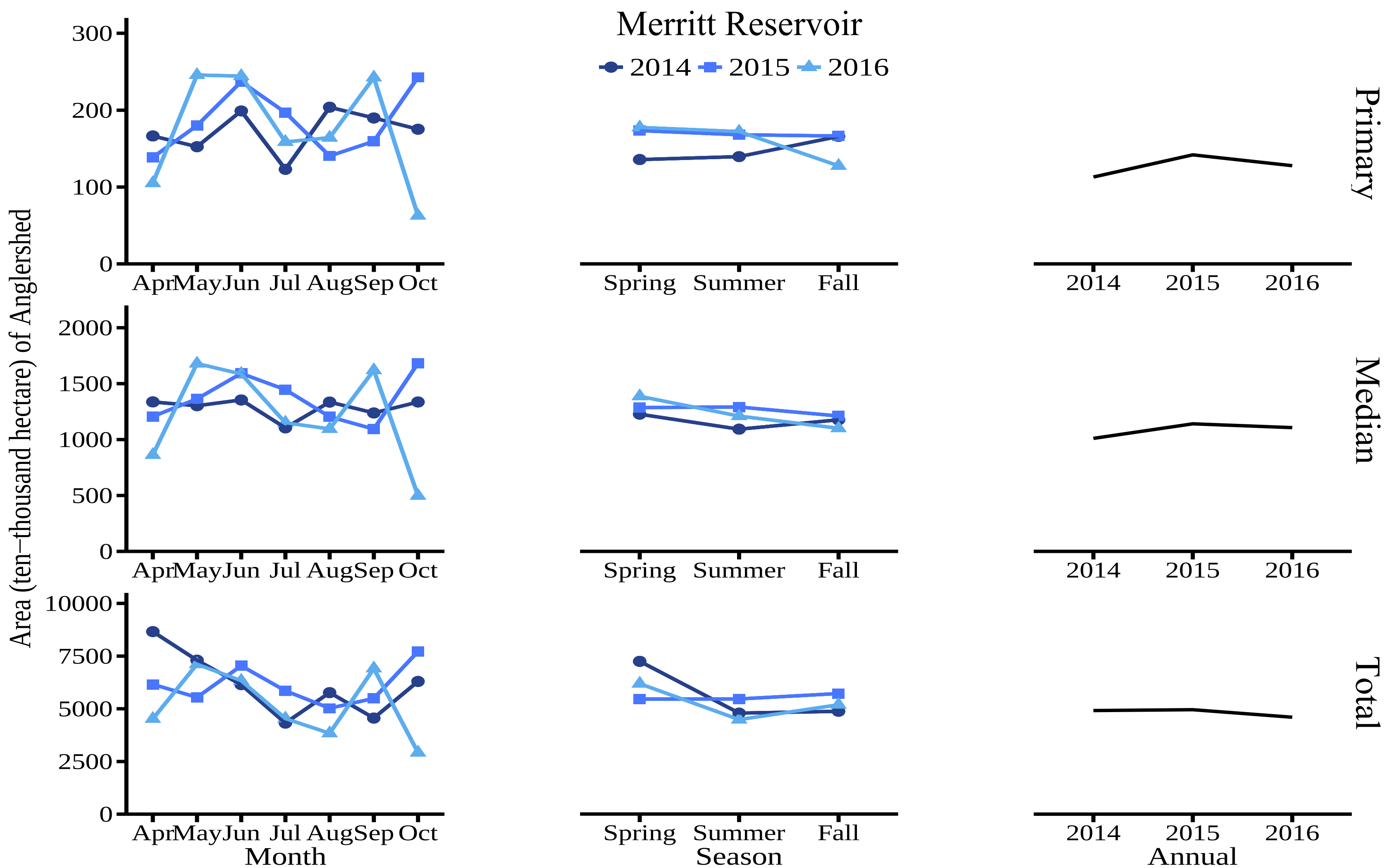

Branched Oak Lake
2014
2015
2016
Area (ten–thousand hectare) of Anglershed
Primary
Median
Total
0
2
4
6
10
20
30
40
100
200
300
Apr
May
Jun
Jul
Aug
Sep
Oct
Month
Spring
Summer
Fall
Season
2014
2015
2016
Annual

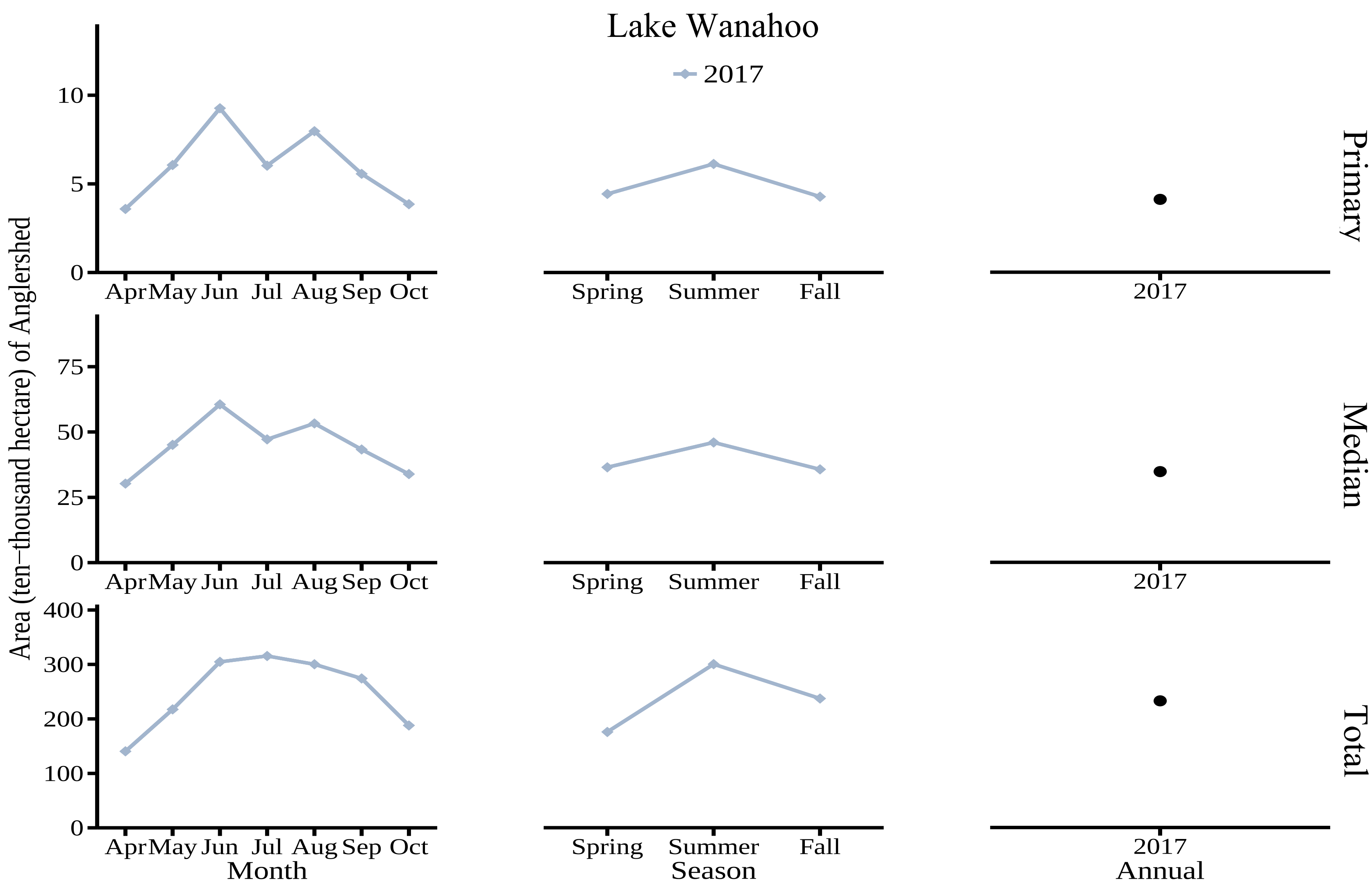

Calamus Reservoir
2014 2015 2016 2017
Area (ten−thousand hectare) of Anglershed
Primary
Median
Total
0 25 50 75 100
0 200 400 600 800
0 1000 2000 3000
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014 2015 2016 2017
Annual


Harlan County Reservoir
2014 2015 2016 2017
Area (ten−thousand hectare) of Anglershed
Primary
Median
Total
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014 2015 2016 2017
Annual
0 20 40 60 80
0 100 200 300
0 500 1000 1500 2000

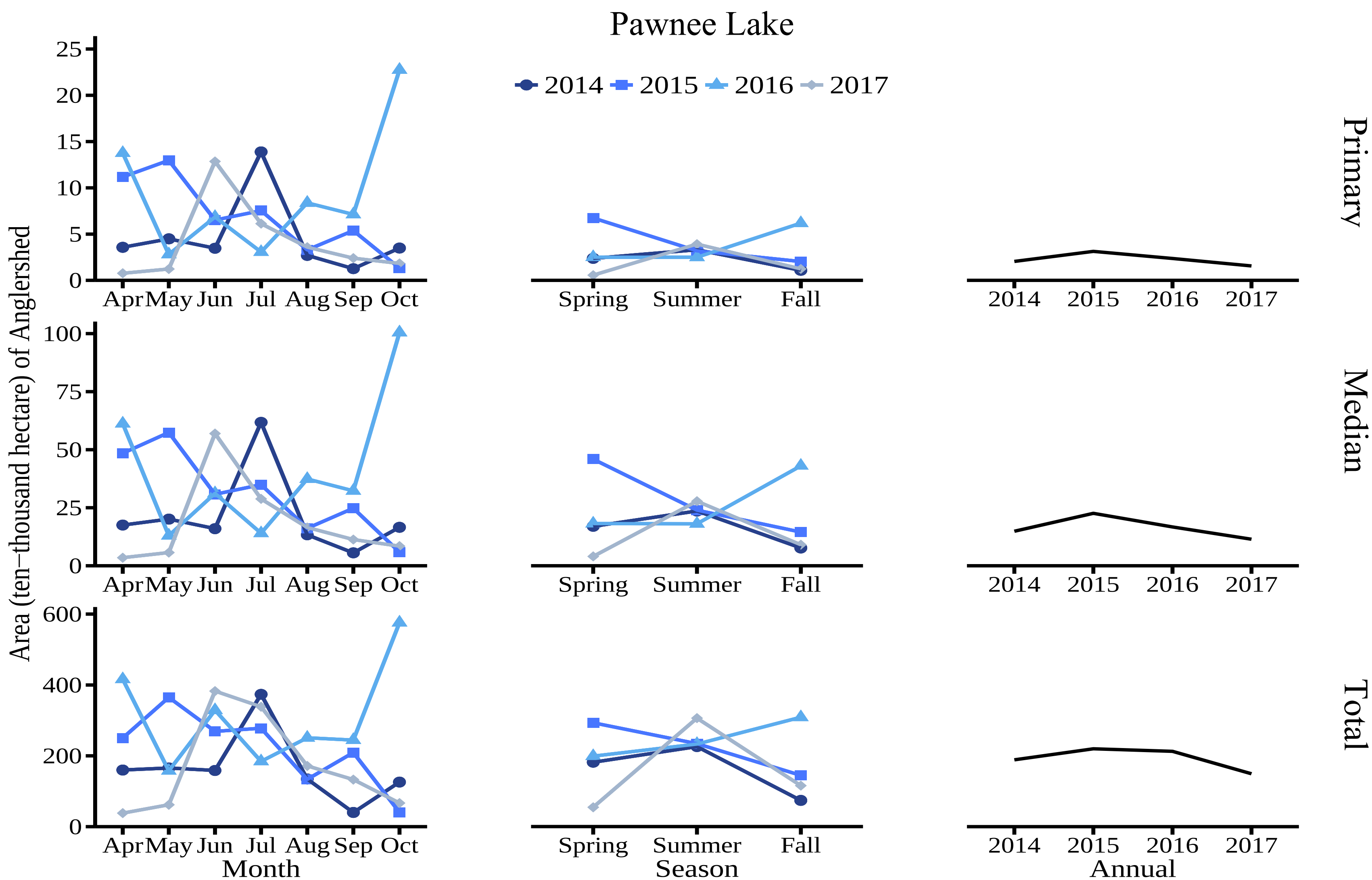


Lake McConaughy
2014 2015 2016 2017
Area (ten−thousand hectare) of Anglershed
Primary
Median
Total
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014 2015 2016 2017
Annual

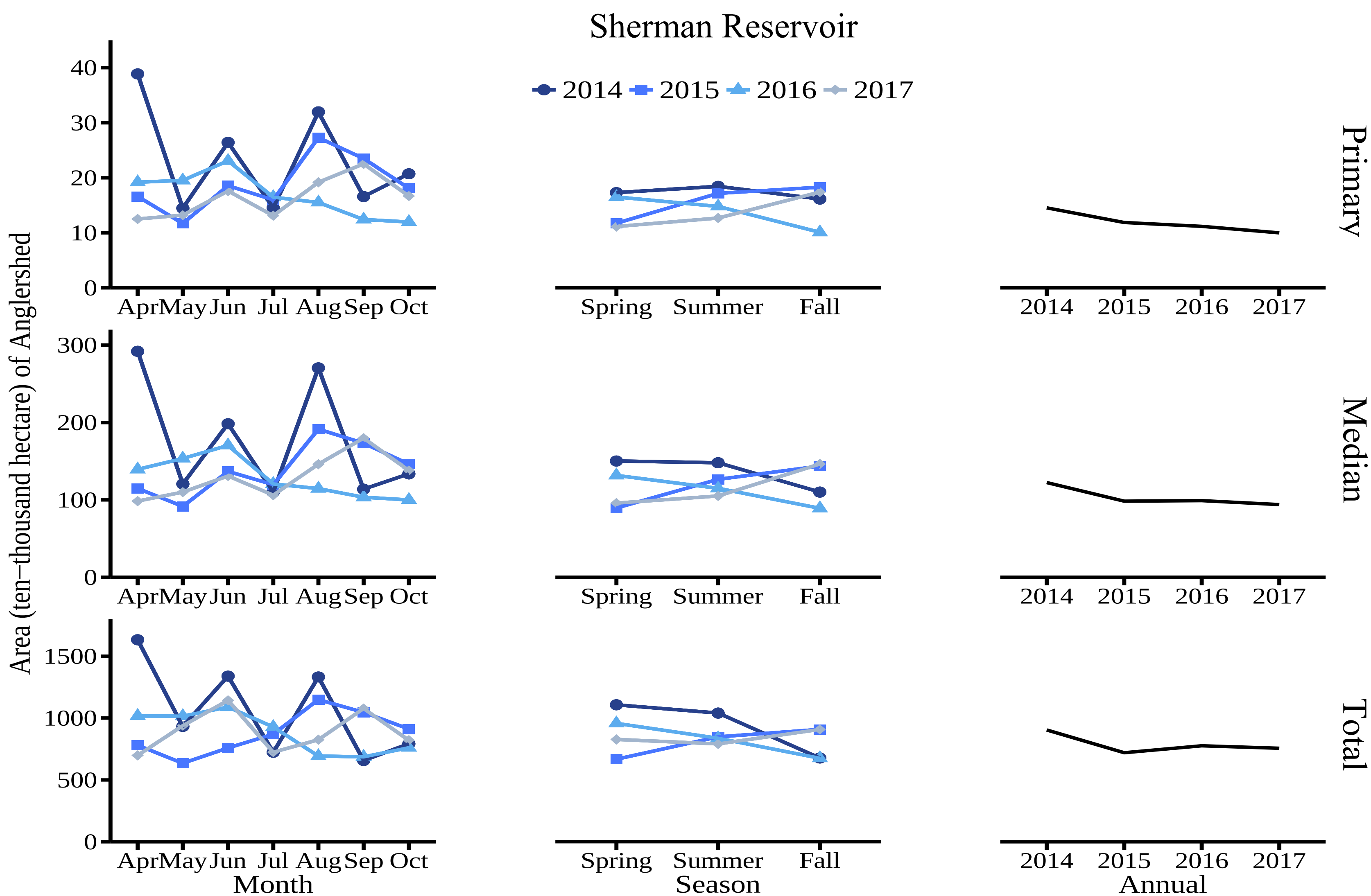

Merritt Reservoir
2014
2015
2016
Area (ten−thousand hectare) of Anglershed
Primary
Median
Total
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014 2015 2016
Annual



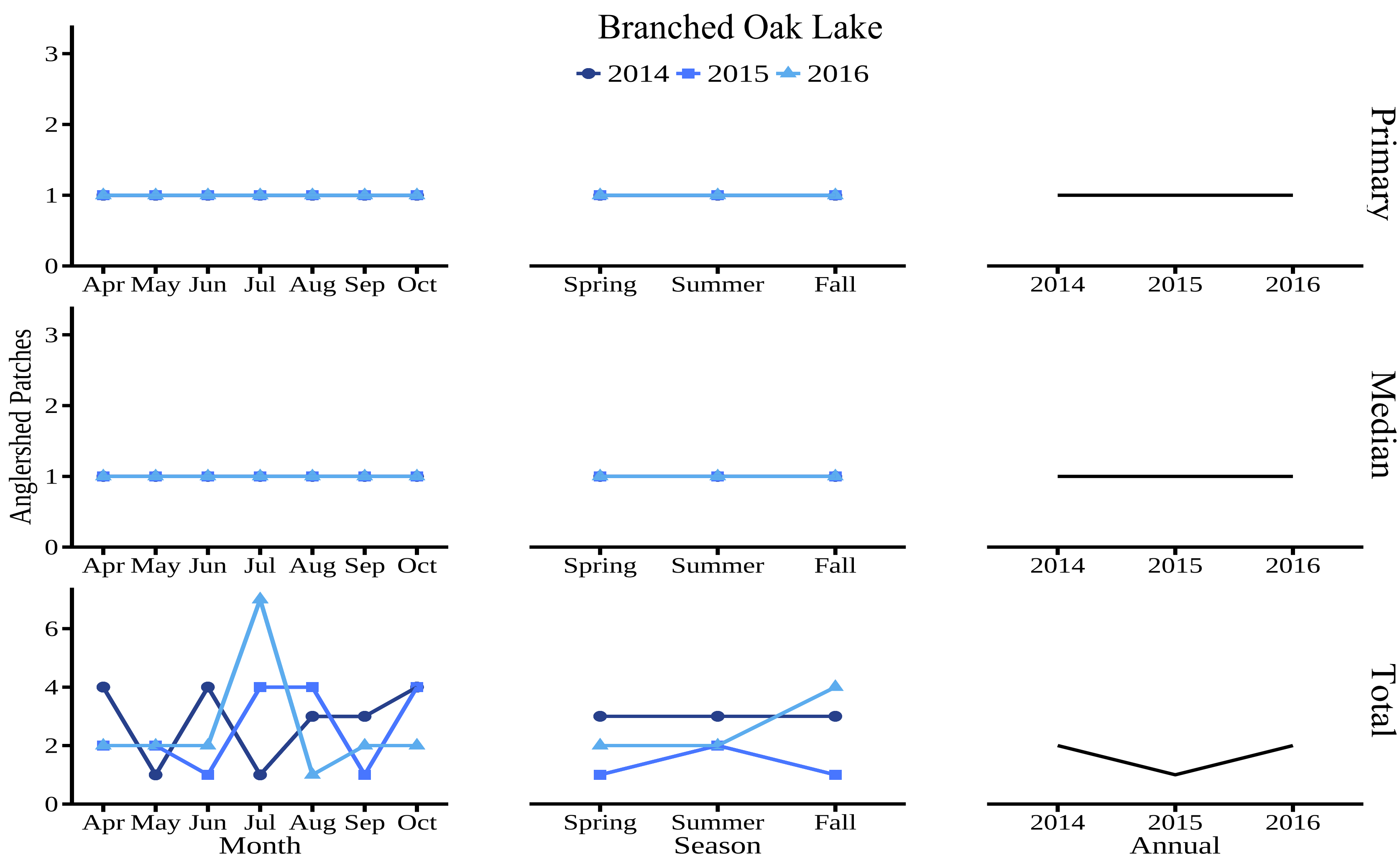
Lake Wanahoo
2017
Area (ten−thousand hectare) of Anglershed
Primary
Median
Total
Apr May Jun Jul Aug Sep Oct
Spring Summer Fall
2017
Month
Season
Annual

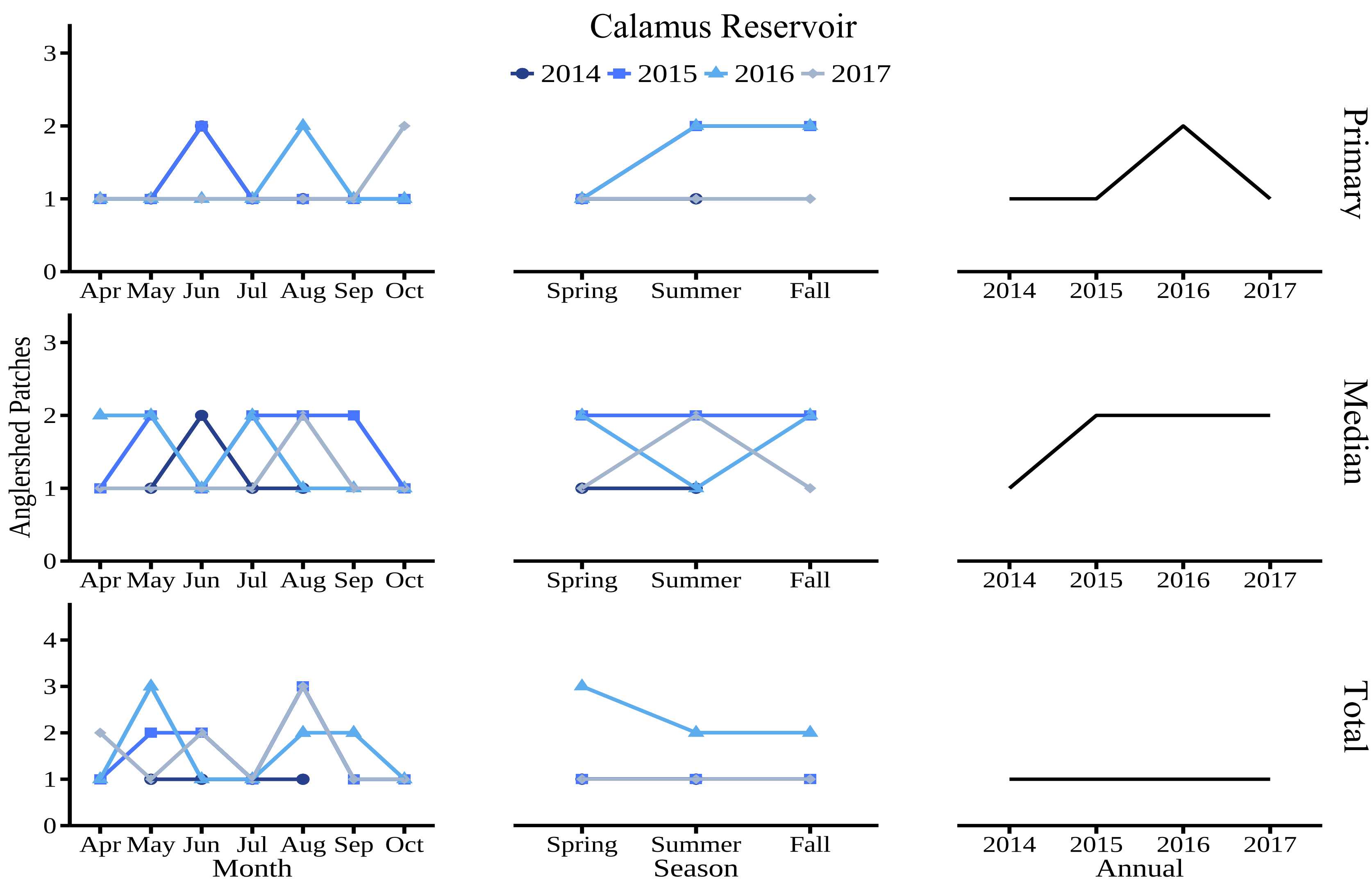


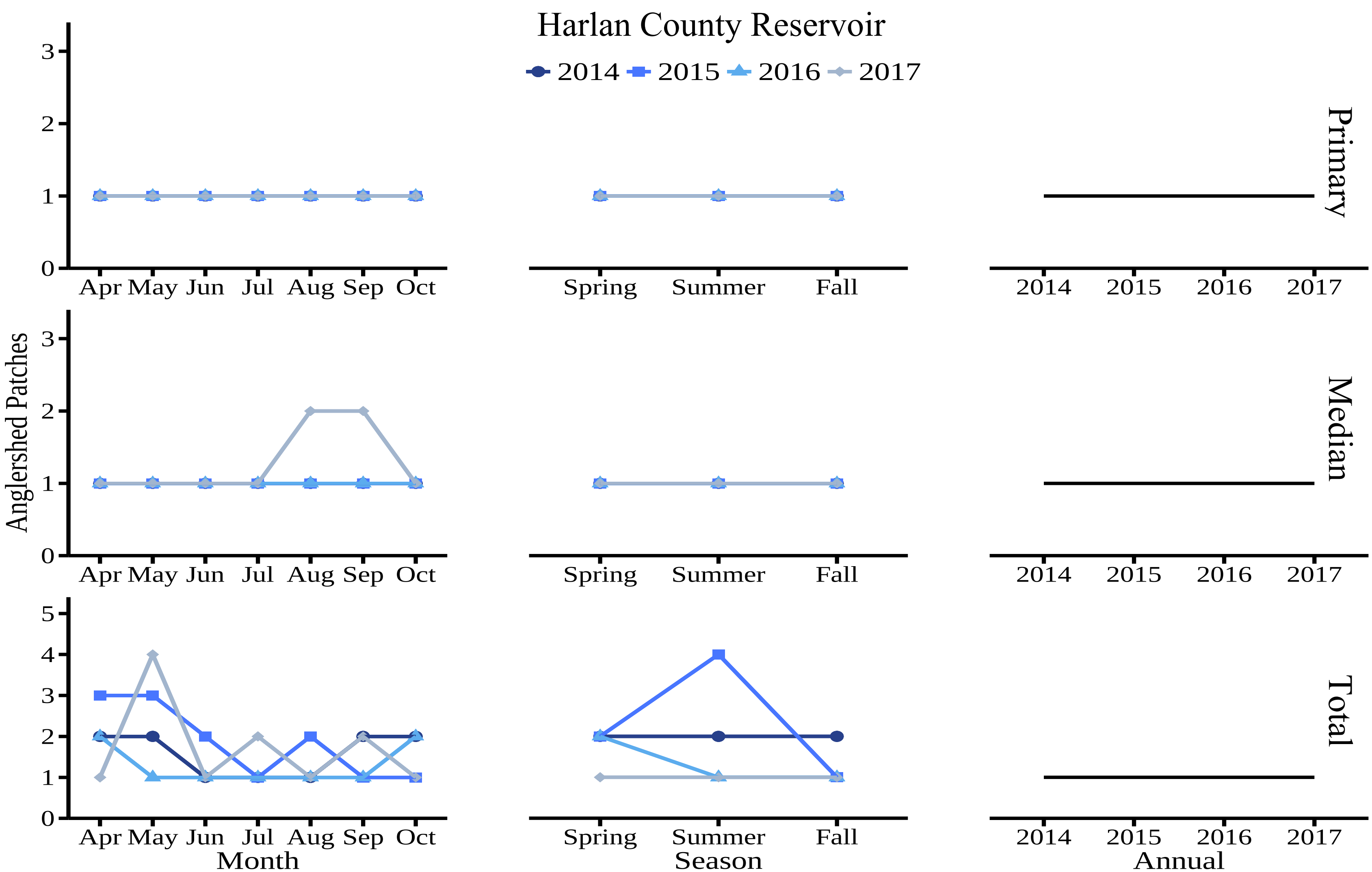
Pawnee Lake
2014 2015 2016 2017
Area (ten−thousand hectare) of Anglershed
Primary
Median
Total
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014 2015 2016 2017
Annual
0
5
10
15
20
25
0
25
50
75
100
0
200
400
600


Sherman Reservoir
2014 2015 2016 2017
Area (ten−thousand hectare) of Anglershed
Primary
Median
Total
0 10 20 30 40
0 100 200 300
0 500 1000 1500
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014 2015 2016 2017
Annual

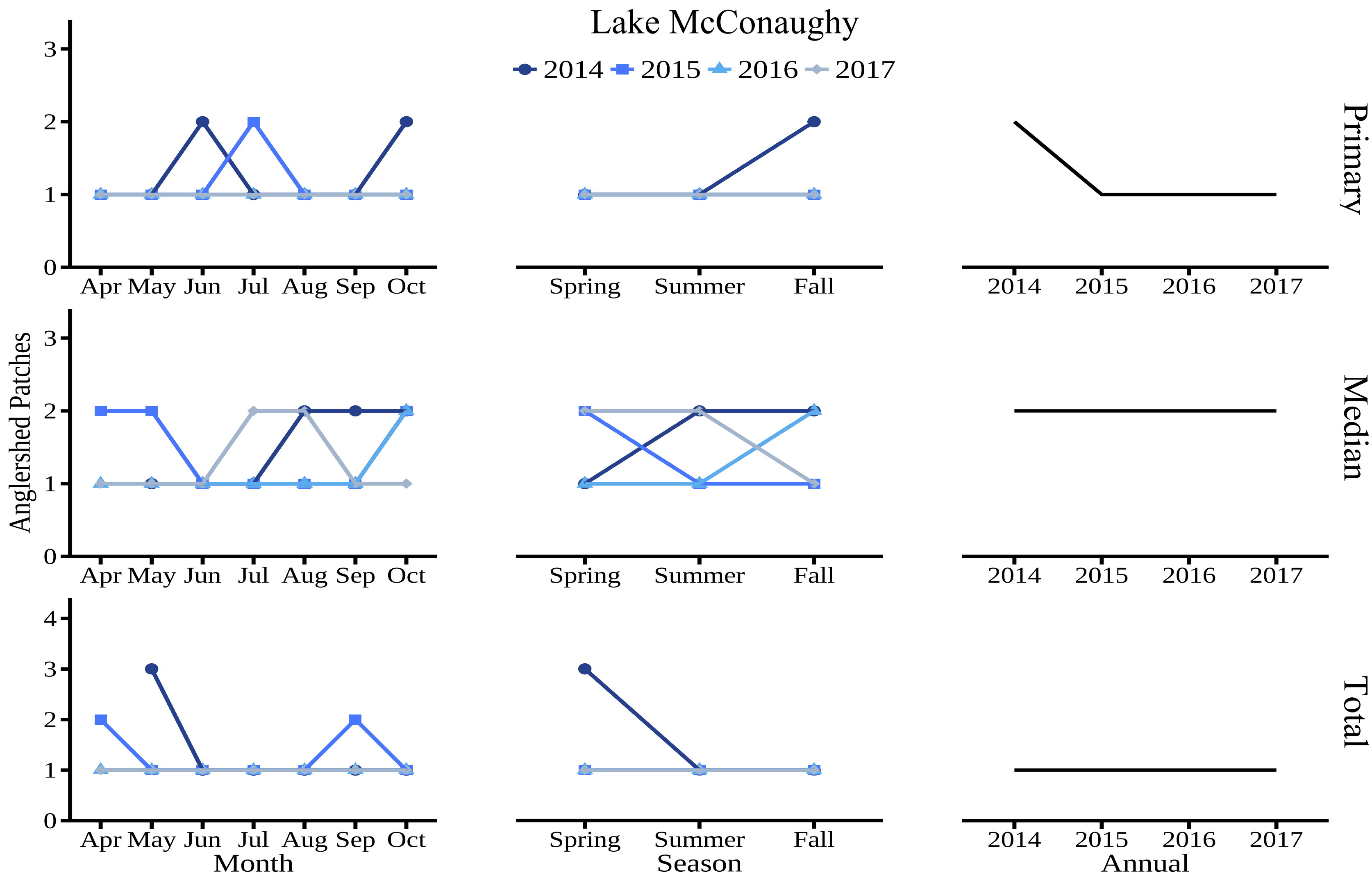
Appendix 6. Dynamics of patches of the primary (10% UD), median (50% UD), total (95% UD) anglersheds across three time scales: monthly, seasonal (Spring = April-May, Summer = June-August, Fall = September-October), and annual.

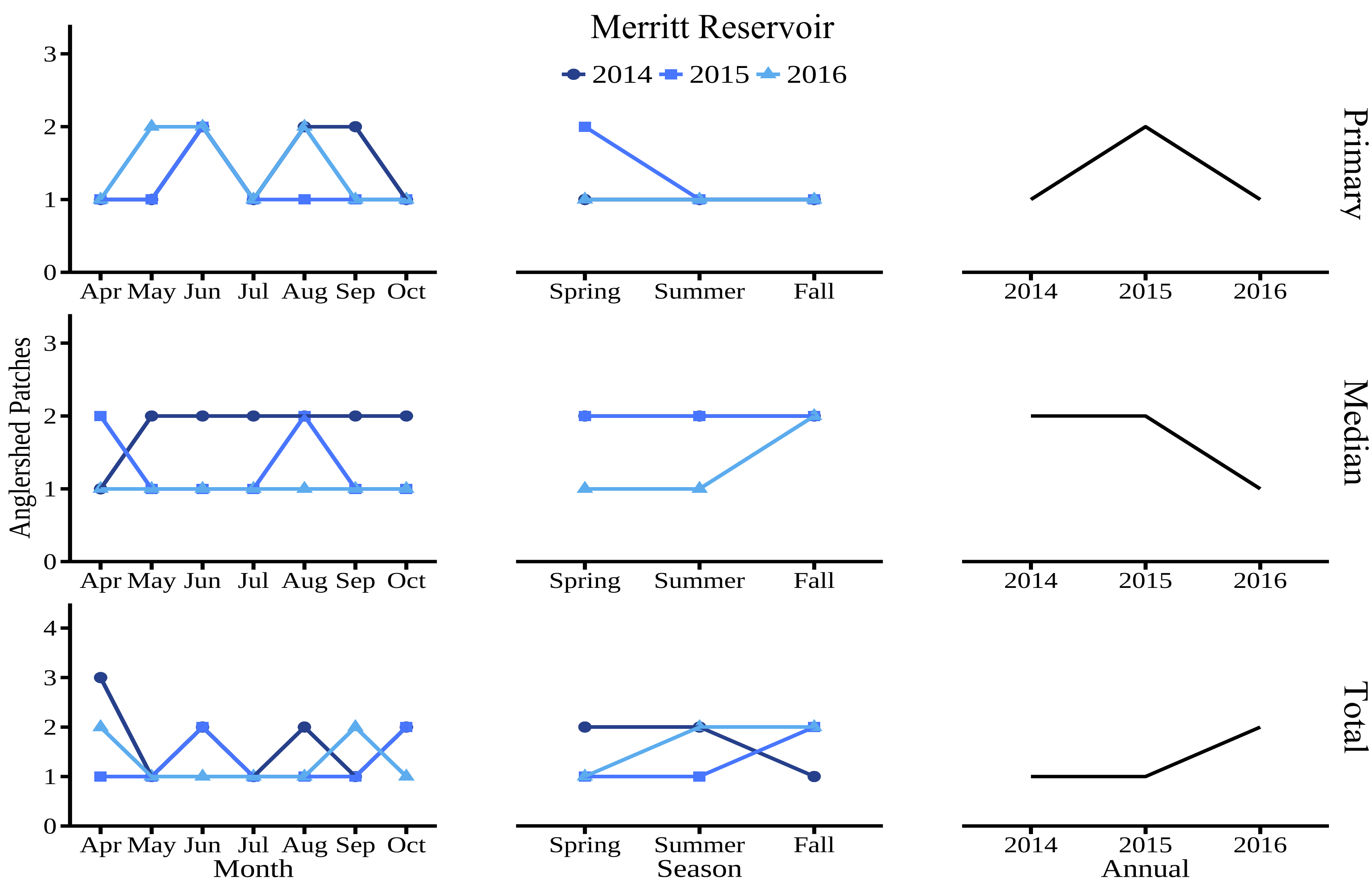

Branched Oak Lake
2014 2015 2016
Anglershed Patches
Primary
Median
Total
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014 2015 2016
Annual
0 1 2 3
0 2 4 6


Calamus Reservoir
2014
2015
2016
2017
Anglershed Patches
Primary
Median
Total
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014 2015 2016 2017
Annual
0
1
2
3
4

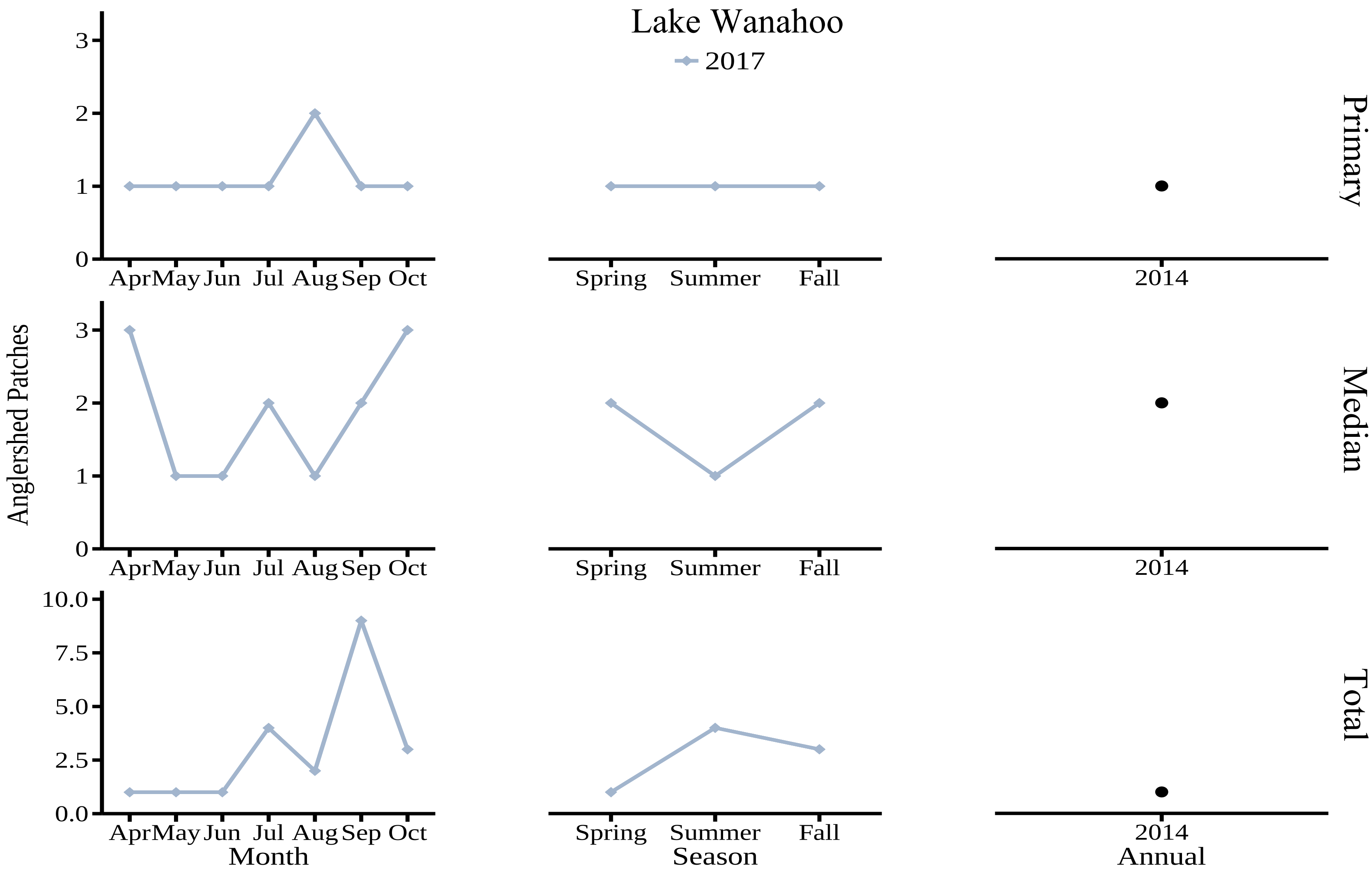


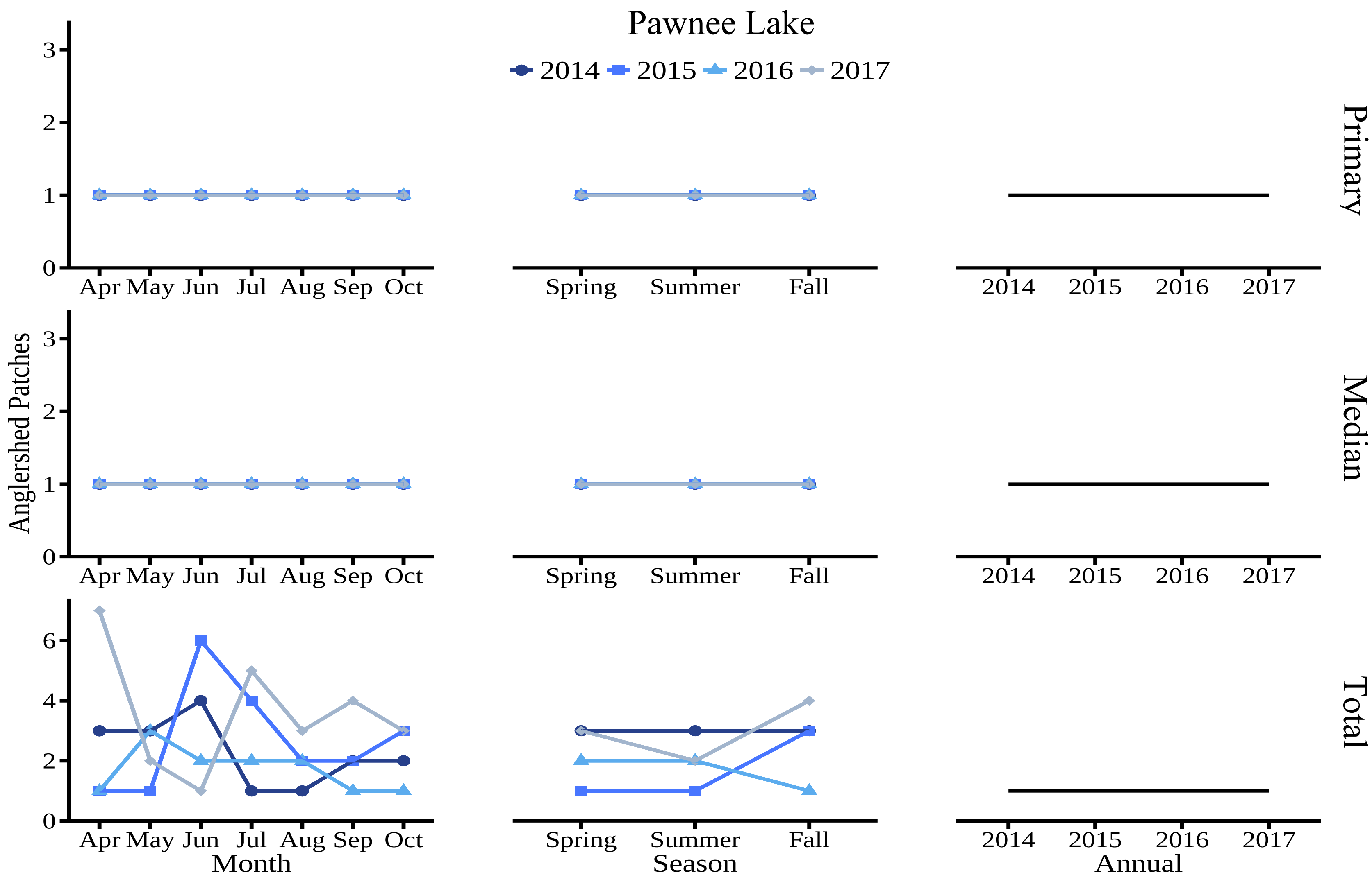
Harlan County Reservoir
2014
2015
2016
2017
Primary
Median
Total
Anglershed Patches
Apr May Jun Jul Aug Sep Oct
Spring Summer Fall
2014 2015 2016 2017
Month
Season
Annual

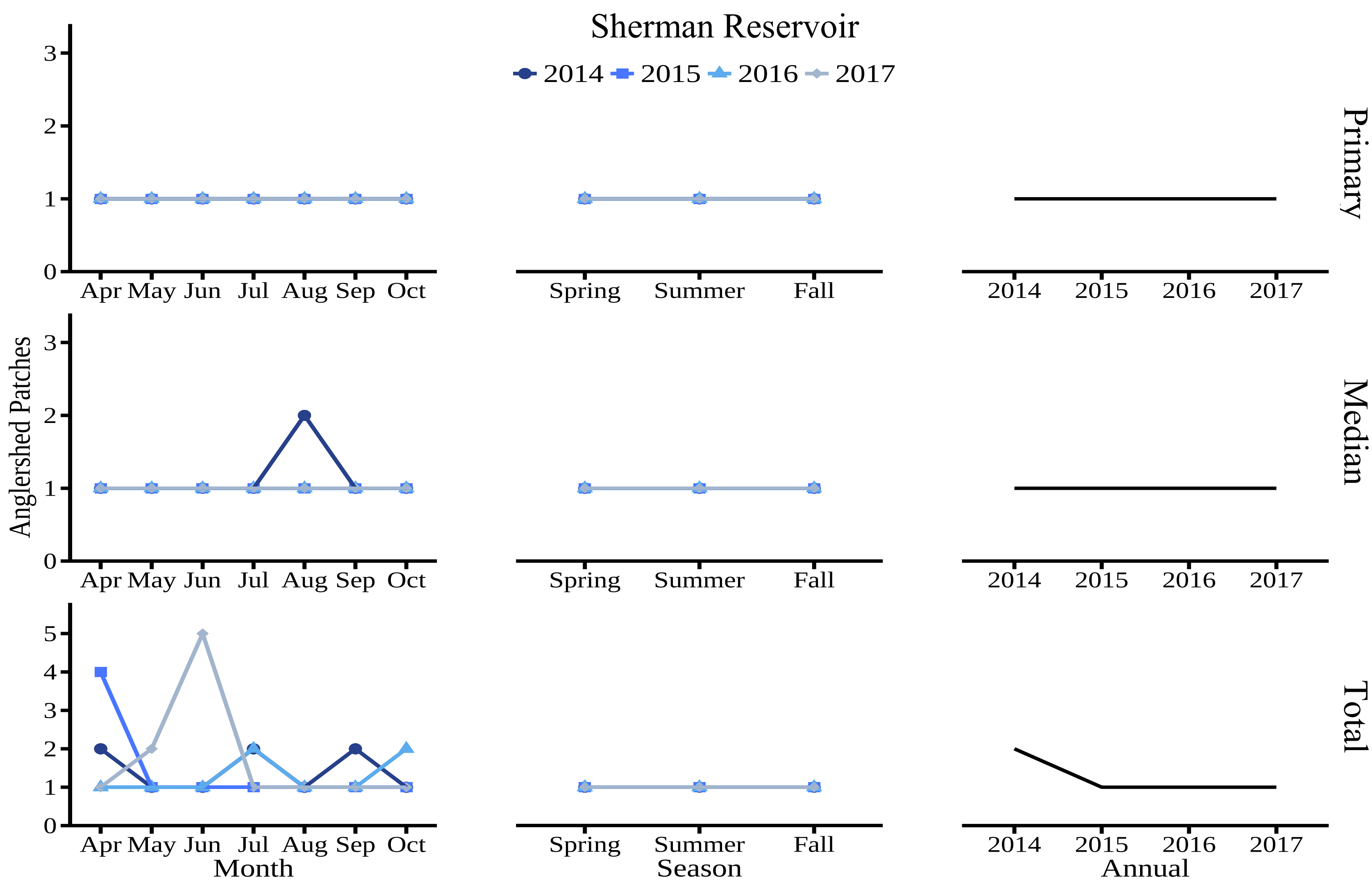

Lake McConaughy
2014 2015 2016 2017
Anglershed Patches
Primary
Median
Total
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014 2015 2016 2017
Annual



Merritt Reservoir
2014
2015
2016
Primary
Median
Total
Anglershed Patches
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014 2015 2016
Annual


Lake Wanahoo
2017
Anglershed Patches
Primary
Median
Total
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014
Annual
0
1
2
3
0.0
2.5
5.0
7.5
10.0

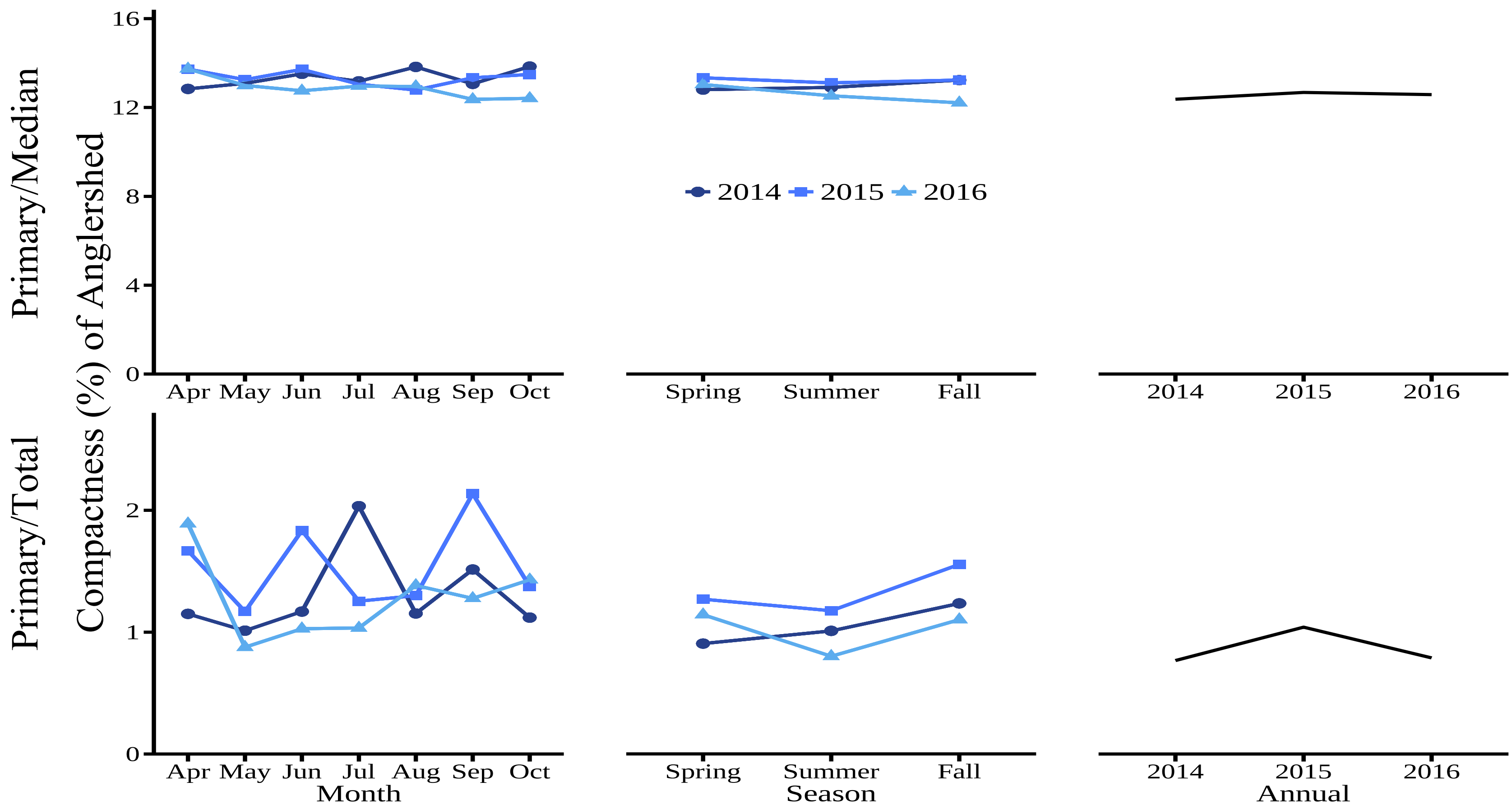

Pawnee Lake
2014
2015
2016
2017
Anglershed Patches
Primary
Median
Total
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014 2015 2016 2017
Annual

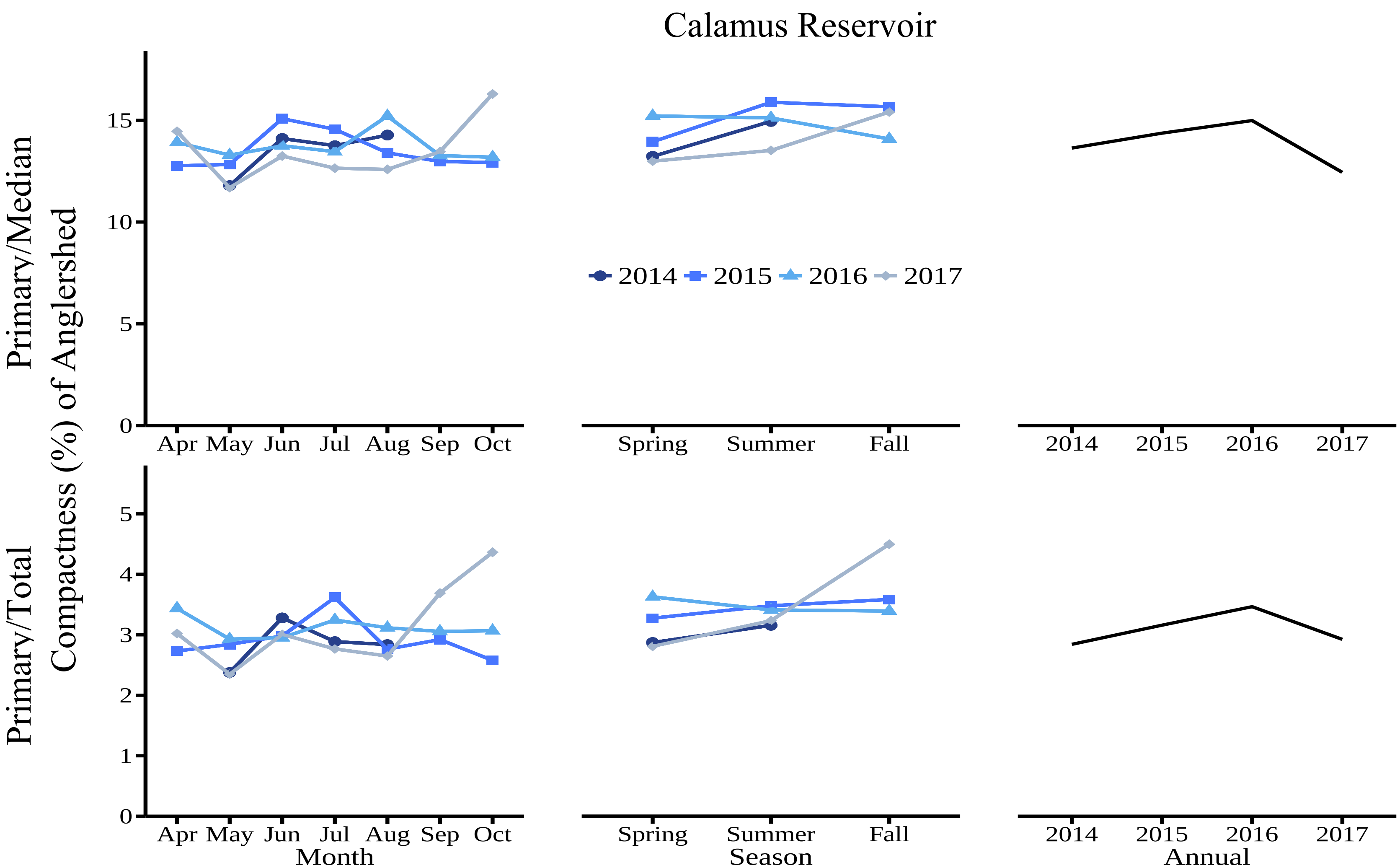


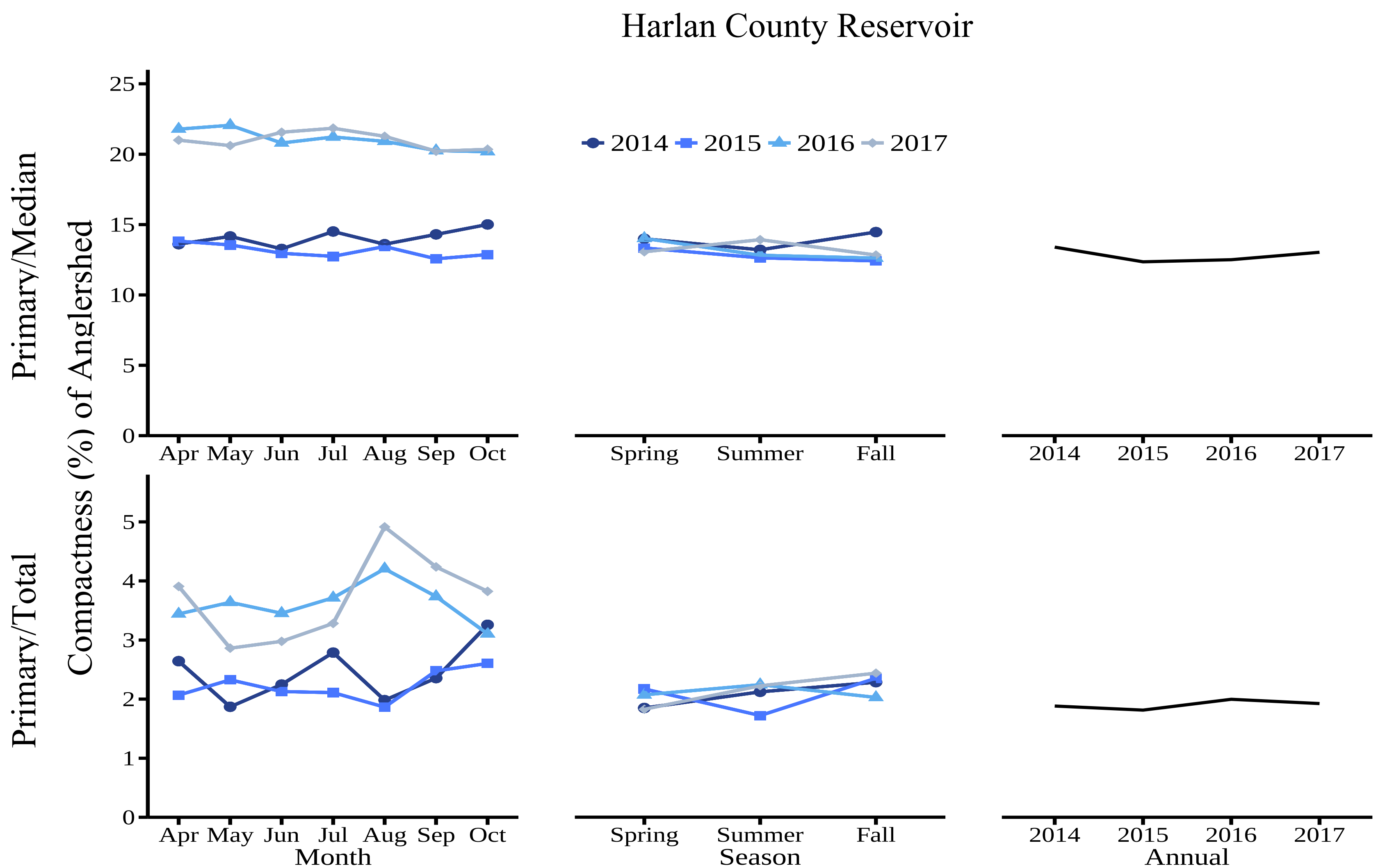
Sherman Reservoir
2014 2015 2016 2017
Anglershed Patches
Primary
Median
Total
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014 2015 2016 2017
Annual

Appendix 7. Dynamics of compactness of the median (50% UD) anglershed represented by primary (10% UD)/median (50% UD) and compactness of the total (95% UD) anglershed represented by primary (10% UD)/total (95% UD) across three time scales: monthly, seasonal (Spring = April-May, Summer = June-August, and Fall = September-October).

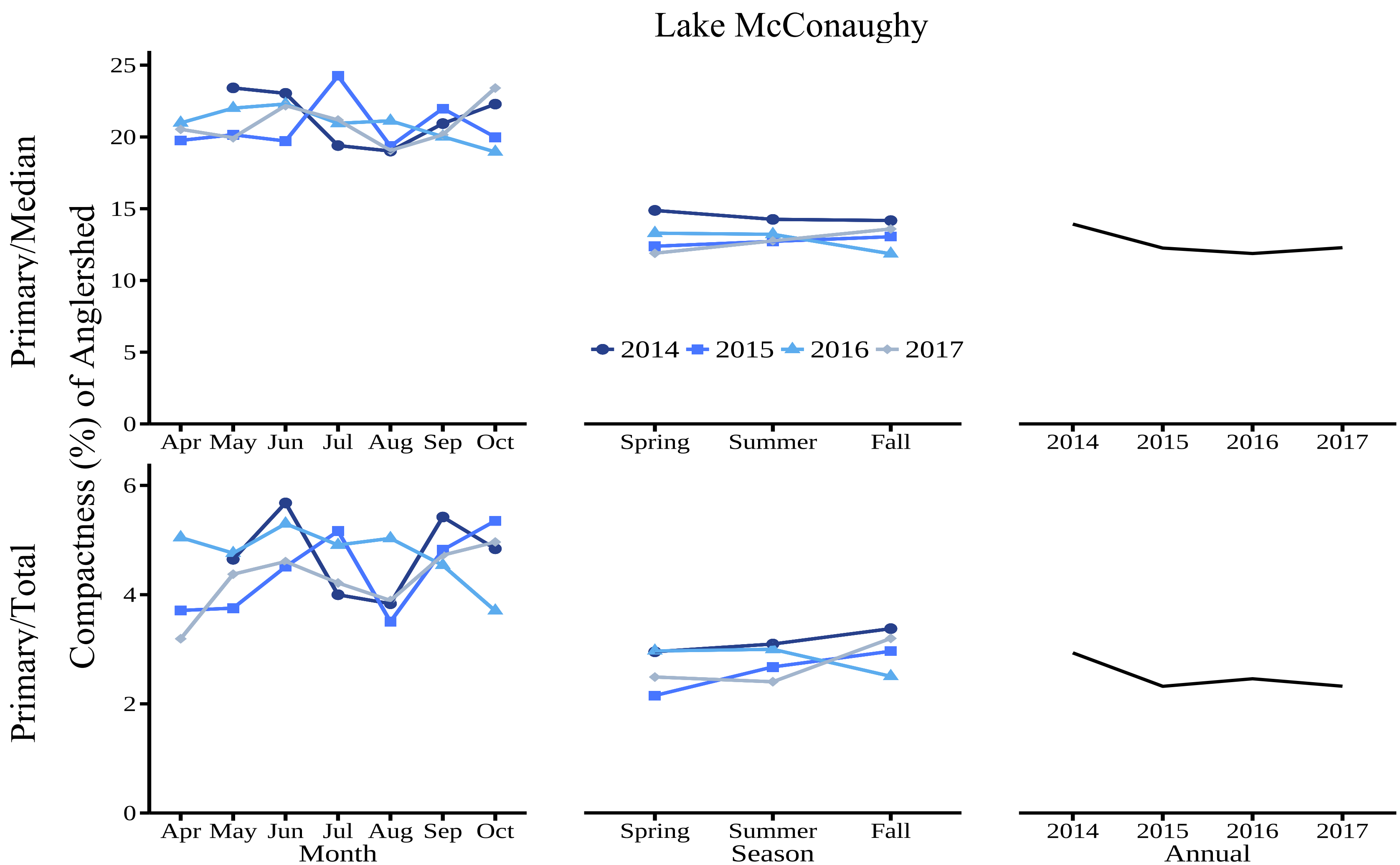
Branched Oak Lake



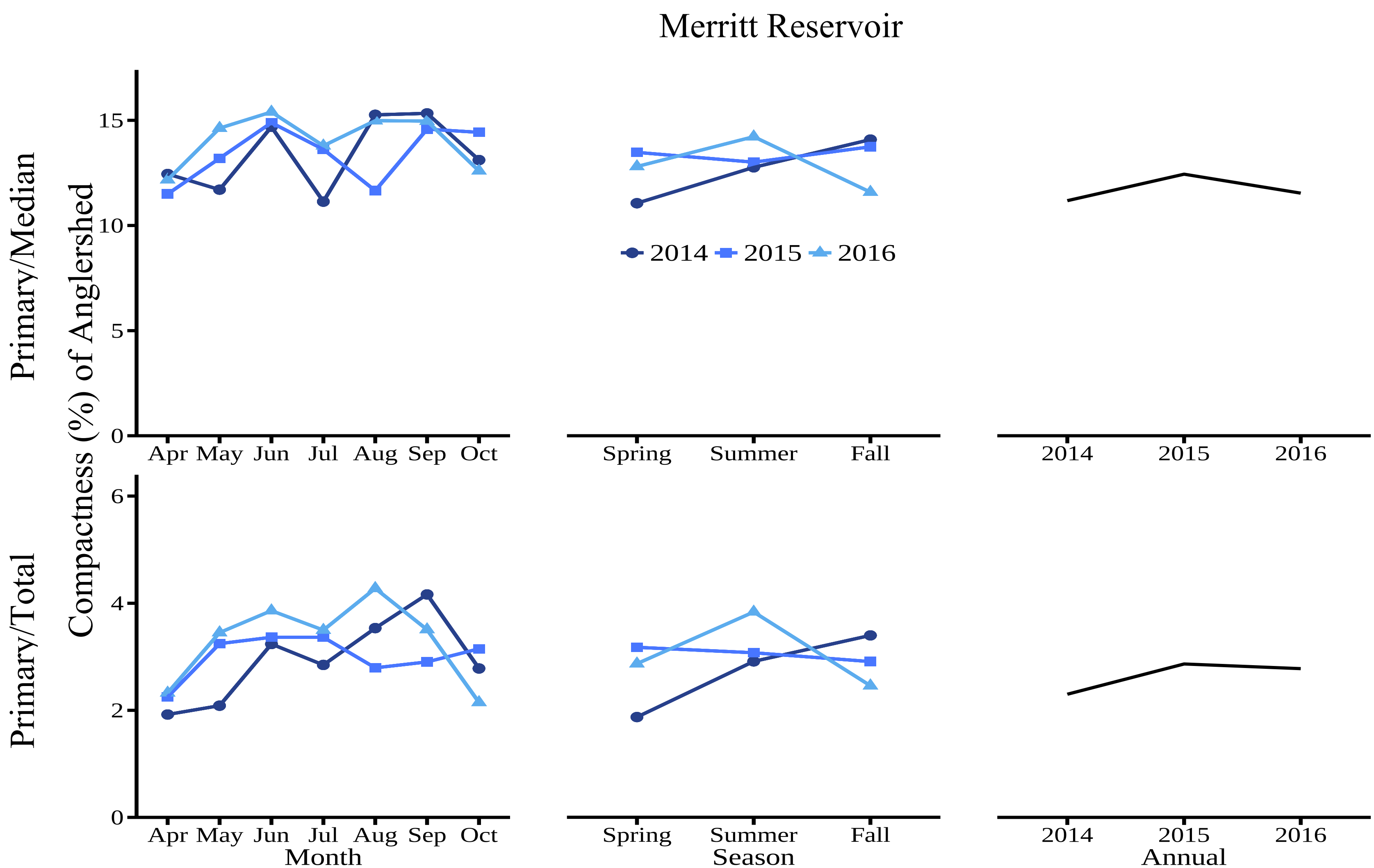

Calamus Reservoir
Primary/Median
Primary/Total
Compactness (%) of Anglershed
2014 2015 2016 2017
0
5
10
15
0
1
2
3
4
5
Apr May Jun Jul Aug Sep Oct
Spring Summer Fall
2014 2015 2016 2017
Month
Season
Annual

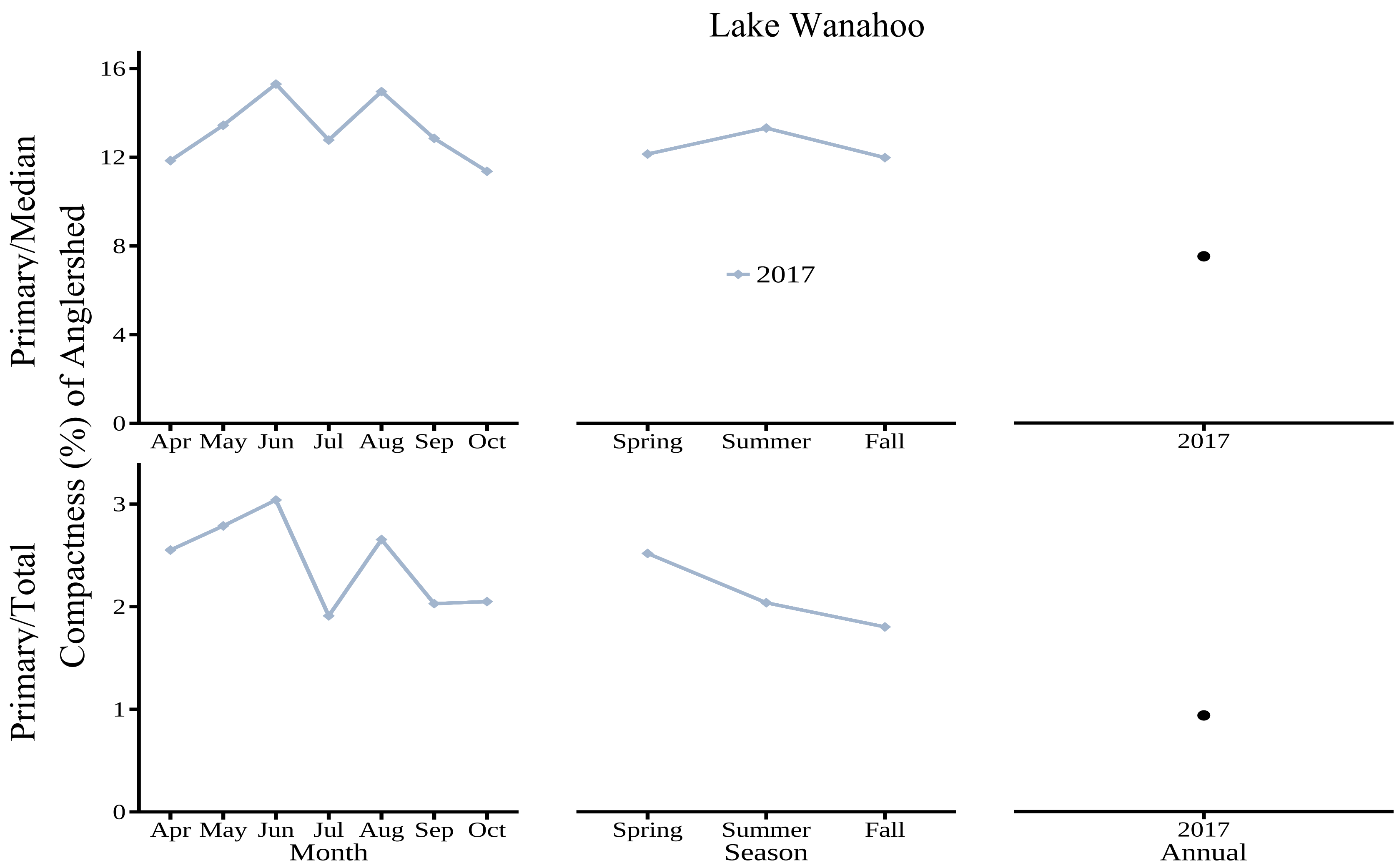


Harlan County Reservoir
Primary/Median
Primary/Total
Compactness (%) of Anglershed
2014
2015
2016
2017
0
5
10
15
20
25
0
1
2
3
4
5
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014 2015 2016 2017
Annual

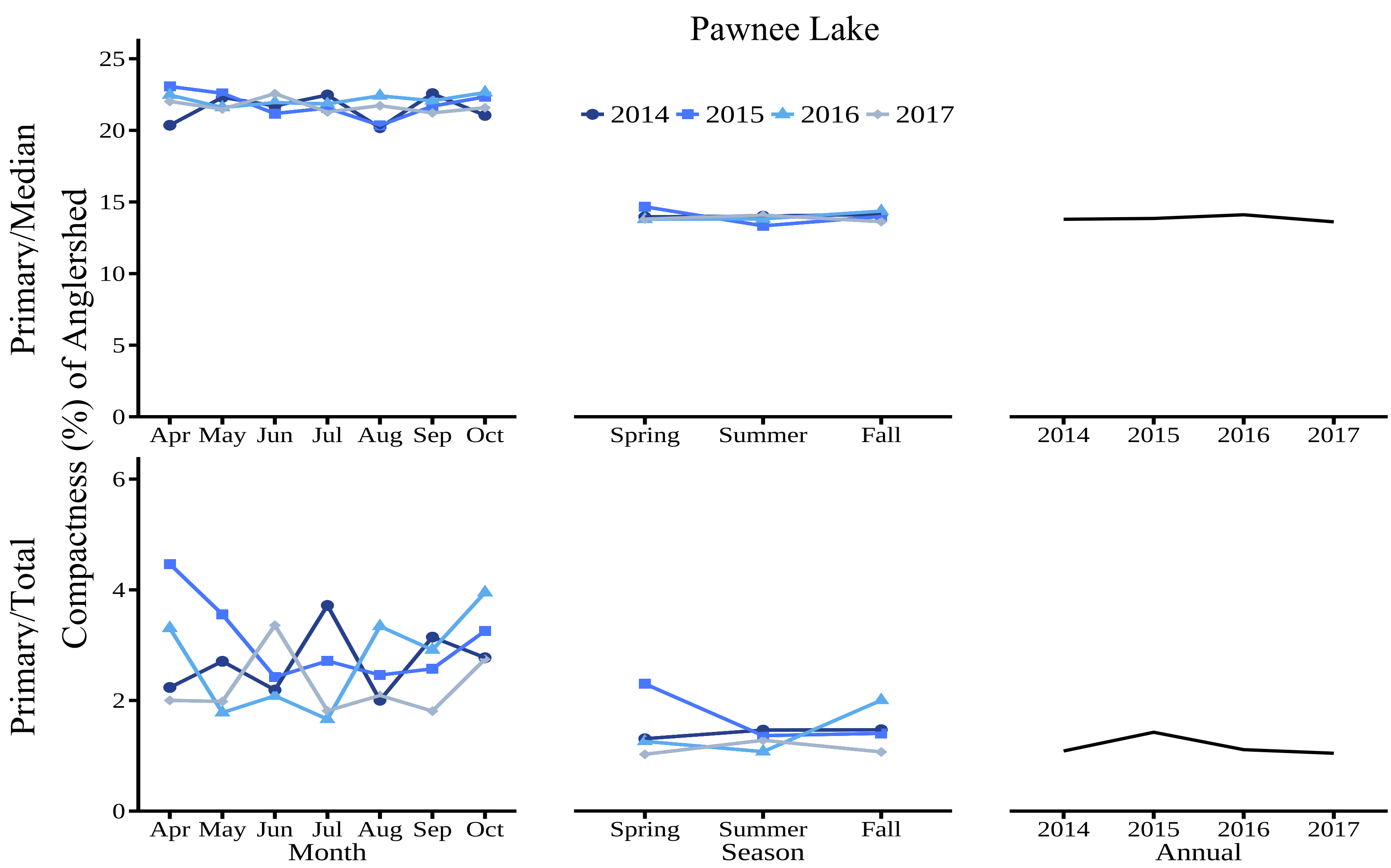


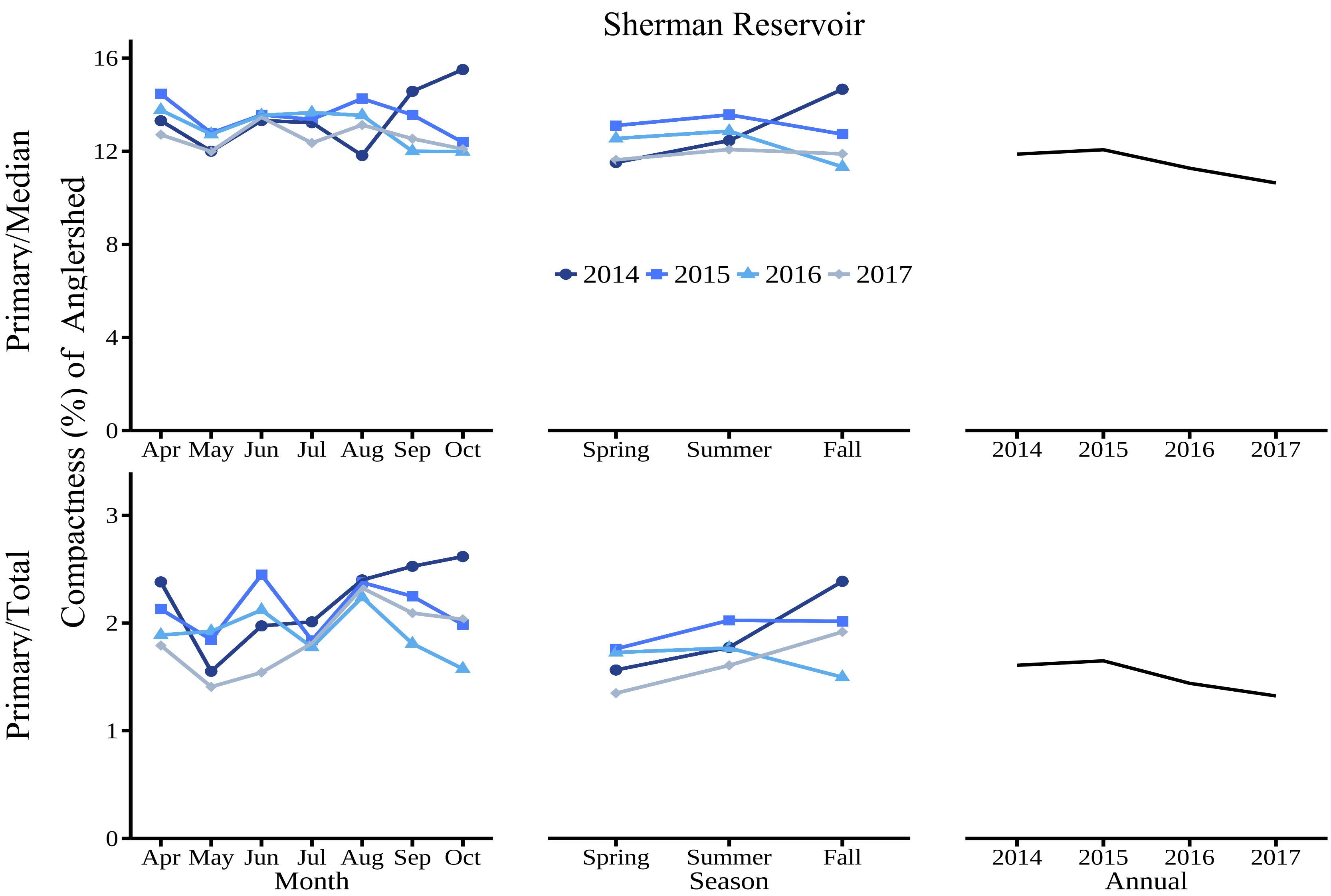
Lake McConaughy
Primary/Median
Primary/Total
Compactness (%) of Anglershed
2014 2015 2016 2017
25
20
15
10
5
0
6
4
2
0
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2014 2015 2016 2017
Annual


Merritt Reservoir
Primary/Median
Primary/Total
Compactness (%) of Anglershed
0
5
10
15
0
2
4
6
2014
2015
2016
Apr
May
Jun
Jul
Aug
Sep
Oct
Month
Spring
Summer
Fall
Season
2014
2015
2016
Annual



Lake Wanahoo
Primary/Median
Compactness (%) of Anglershed
Primary/Total
16
12
8
4
0
3
2
1
0
2017
Apr May Jun Jul Aug Sep Oct
Month
Spring Summer Fall
Season
2017
Annual


Pawnee Lake
2014
2015
2016
2017
Primary/Median
Primary/Total
Compactness (%) of Anglershed
25
20
15
10
5
0
6
4
2
0
Apr
May
Jun
Jul
Aug
Sep
Oct
Spring
Summer
Fall
Month
Season
Annual


Sherman Reservoir
Primary/Median
Primary/Total
Compactness (%) of Anglershed
2014
2015
2016
2017
16
12
8
4
0
3
2
1
0
Apr
May
Jun
Jul
Aug
Sep
Oct
Spring
Summer
Fall
2014
2015
2016
2017
Month
Season
Annual