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Temporal invariance of social-ecological catchments

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Abstract. Natural resources such as waterbodies, public parks, and wildlife refuges attract people from varying distances on the landscape, creating "social-ecological catchments." Catchments have provided great utility for understanding physical and social relationships within specific disciplines. Yet, catchments are rarely used across disciplines, such as its application to understand complex spatiotemporal dynamics between mobile human users and patchily distributed natural resources. We collected residence ZIP codes from 19,983 angler parties during 2014–2017 to construct seven angler–waterbody catchments in Nebraska, USA. We predicted that sizes of dense (10% utilization distribution) and dispersed (95% utilization distribution) angler–waterbody catchments would change across seasons and years as a function of diverse resource selection among mobile anglers. Contrary to expectations, we revealed that catchment size was invariant. We discuss how social (conservation actions) and ecological (low water quality, reduction in species diversity) conditions are expected to impact landscape patterns in resource use. We highlight how this simple concept and user-friendly technique can inform timely landscape-level conservation decisions within coupled social-ecological systems that are currently difficult to study and understand.

Key words: complex social-ecological systems; kernel density estimation; landscape patterns; recreational fisheries; spatiotemporal assessments.

Introduction

The oft-quoted phrase "location, location, location" describes the importance of spatial positioning, proximity, and underlying geographic-based relationships. In ecology, concepts such as central place foraging theory recognize the importance of spatial proximity to available resources. Animals that have a "home base" (e.g., nest sites, colonies) must consider distance and energy allocation to optimize foraging efficiency (Alerstam et al. 2019). In real estate, property value is often determined by proximity to other properties, and community attributes (e.g., school quality, nearby amenities) can influence a person's decision to move and purchase a home (Atack and Margo 1998, Feng and Lu 2013). Recently, within a social-ecological system, our research has demonstrated a direct link between a person's geographic residence and their interactions with natural resources (Kaemingk et al. 2020*b*). Recreational anglers residing in certain ZIP codes (U.S. Zone Improvement Plan) exhibited a greater propensity for harvesting fish, potentially affecting biodiversity and trophic dynamics through the modification of species size structure and abundance (Cooke and Schramm 2007). Changes to the underlying geographic distribution and relationships among humans and natural resources are expected to alter social-ecological dynamics. For recreational fisheries, a change in participation patterns among anglers on the landscape (e.g., via a shift in representative ZIP codes) could lead to higher or lower rates of fish harvest and lead to large ecosystem effects (Post et al. 2008).

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Recreational fisheries represent important social-ecological systems composed of diffuse angler populations that interact with patchily distributed natural resources (lakes, streams, rivers) on the landscape. Tracking and understanding these spatial and temporal relationships is a critical component for fisheries conservation (Hunt 2005, Hunt et al. 2007, Matsumura et al. 2019), but is often costly and logistically difficult. Overlooking the behavior of transient anglers and fish harvest can lead to overexploitation and the collapse of entire fisheries (Post et al. 2002, 2008). Angler populations are heterogeneous and individual anglers vary in their site selection, willingness to travel, and desire to harvest. Diverse behaviors lead to unpredictable dynamics caused by complex and cross-scale feedbacks between anglers and fish populations, creating challenges for conservation efforts (Baerenklau and Provencher 2005) that are often targeted at the waterbody level. We have gained tremendous insight into angler–fish relationships by studying angler behavior, utility, and satisfaction. Anglers often select fishing sites or waterbodies that maximize utility (Johnston et al. 2010, Hunt et al. 2011, Post and Parkinson 2012, Matsumura et al. 2019). The proximity between anglers and waterbodies is often an important and frequent attribute that factors into site selection and resource use (Hunt 2005). In general, the distance between an angler's residence and a waterbody is invariant and could contribute to structuring these social-ecological relationships. Therefore, if distance is an essential feature that factors into an angler's utility and decision-making process, it could create and lead to predictable spatial and temporal patterns between anglers and resources on the landscape.

Distance and travel costs often explain relationships between human and natural resources (Post et al. 2008, Ward et al. 2016). Thus, we could view these human–resource relationships on the landscape as social-ecological catchments. Social-ecological catchments place a greater focus on the resource (relative to the user), ultimately providing insight on how natural resources shape human behavior. Social-ecological catchments represent the spatiotemporal draw of humans to a natural resource (e.g., anglers to a waterbody, bird watchers to a field, hikers to a national park). Most notably, catchments have provided insight to physical relationships, such as the formations of rivers, lakes, and reservoirs (i.e., Freeman 1991, Şener et al. 2010). Catchments also shed insight on the formation of social relationships, such as where to build retail stores, airports and flight routes, and hospitals (i.e., Goldberg et al. 2006, Lieshout 2012, Dolega et al. 2016). Quantifying and characterizing social-ecological catchments could be useful for understanding complex and dynamic relationships between humans and natural resources. Visualizing and quantifying the catchment area for a particular resource could assist with tracking and understanding human behavior and natural-resource use. For example, social-ecological catchments could assess how the recent COVID-19 pandemic influences the distribution of visitors to national and state parks. Social-ecological catchments also allow opportunities to evaluate the risk of humans spreading invasive species from one resource to another that could vary according to catchment size, with resources with a larger catchment having a higher risk of colonization (Bossenbroek et al. 2001). Finally, social-ecological catchments provide a unique method to evaluate how conservation efforts applied to a specific resource (e.g., waterbody, field, park) may alter the spatial distribution of users on the landscape, ultimately modifying resource–user interactions.

We leveraged angler ZIP code data collected from onsite interviews to quantify the size of social-ecological catchments for seven waterbodies during 2014–2017. We employed kernel density estimation to delineate angler-waterbody catchments at two spatial and two temporal scales. Spatial scales included dense (10%) and dispersed (95%) utilization distributions (i.e., name given to describe spatial distributions; Worton 1989) and temporal scales included season (spring, summer, fall) and year (2014–2017). Dense residential patterns of anglers may uniquely change through time relative to dispersed residential patterns at both seasonal and yearly scales given these could represent different angler segments that vary in specialization, motivation, and preferences (Matsumura et al. 2019). We expected summer to have the largest catchment size at both dense and dispersed spatial scales compared to fall and spring because these months typically receive the greatest fishing effort (Kaemingk et al. 2018), putatively attracting anglers from more distant spatial sources. We also anticipated annual variation in catchment size due to high churn or turnover in yearly fishing license sales (Hinrichs et al. 2020). High angler churn rates (~30% of anglers) could lead to large residential shifts (across ZIP codes) in angler participation from year to year. Social (e.g., fishing license sales, COVID-19 pandemic, conservation actions) and ecological (e.g., low water quality, reduction in species diversity, low fish size structure) conditions are expected to shape the spatiotemporal relationships between humans and natural resources, ultimately creating unique social-ecological interactions. Therefore, social-ecological catchments could provide a practical, yet powerful tool for visualization and quantification of these important relationships that may reveal critical shifts in resource use and resource quality that are often difficult to detect.

Methods

We quantified social-ecological catchments or the spatial structure and dynamics of seven waterbodies that encompassed diverse locations, anglers, and fish communities across Nebraska, USA. Waterbodies varied in surface area, proximity to urban centers (e.g., Grand Island, Lincoln), composition of angler-access types (e.g., boat and bank; Kane et al. 2020), and speciestargeting groups (Pope et al. 2016; Appendix S1: Table S1). These waterbodies could be categorized as either "destination" or "local" fisheries according to their surface area and how far anglers are willing to travel to participate in recreational fishing (Kaemingk et al. 2019). Private second homes or cabins existed on two of the seven waterbodies and most waterbodies lacked substantial tourism amenities, such as hotels and restaurants. We conducted onsite hybrid interviews (mixture of access-point and roving) of angler parties at each waterbody during April–October 2014–2017, though not all waterbodies were sampled annually (Appendix S1: Table S1). We sampled at the party level (i.e., not individual) whereby a self-appointed spokesperson for each angler party was interviewed and asked to provide the ZIP code of their home residence to represent the entire angler party (Appendix S2: Section S1).

We constructed social-ecological catchments using angler residence ZIP codes collected onsite and kernel density estimation techniques (Worton 1989, Seaman and Powell 1996, Martin et al. 2015; Appendix S1: Fig. S1; Appendix S2: Section S2). We define a social-ecological catchment as the kernel density estimate for the spatial distribution of interviewed anglers at a waterbody for a specific time scale. We measured both the area of highest gravity (i.e., dense) and regional gravity (i.e., dispersed) to describe spatial usage patterns for each waterbody. Specifically, we quantified social-ecological catchments at dense (10%) and dispersed (95%) scales for each of the seven waterbodies as a function of season (spring, April–May; summer, June–August; fall, September–October) and year (Appendix S1: Fig. S1). Using the nlme function in R (R Core Team 2020) we then modeled dense and dispersed angler–waterbody catchments (ha) with an autoregressive linear mixed-effects model that included a simple autoregressive correlation structure of order one (i.e., AR1) to account for temporal autocorrelation among seasons. In our model, catchment area was $\log_{10}$-transformed, season and year were fixed effects, and lake identification number was a random effect. Our approach did not account for uncertainty or error generated from estimating each catchment, but focused on catchment area point estimates.

Results

We interviewed 19,983 angler parties across the seven waterbodies during 2014–2017. Most angler parties were Nebraska residents (95%), representing a majority of available Nebraska ZIP codes (79%). Social-ecological catchment area varied across individual waterbodies with some waterbodies attracting anglers from a much wider geographic area (e.g., Merritt Reservoir, Lake McConaughy) compared to other waterbodies (e.g., Branched Oak Lake, Pawnee Lake; Appendix S1: Tables S2 and S3). We determined social-ecological catchment area to be invariant at the dense and dispersed scales across season and year. In essence, population centers appear to be a high source of gravity and small changes in the distribution of anglers are difficult to detect. At the dense spatial scale, there was no difference in catchment area across spring, summer, and fall ($F_{2,67} = 0.86$, $P = 0.43$) and across 2014, 2015, 2016, and 2017 ($F_{1,67} = 0.62$, $P = 0.43$). Similarly, at the dispersed spatial scale, there was no difference in catchment area across spring, summer, and fall ($F_{2,67} = 1.24$, $P = 0.29$) and across 2014, 2015, 2016, and 2017 ($F_{1,67} = 0.15$, $P = 0.70$).

Discussion

We demonstrate that the size of social-ecological catchments could be invariant through space and time despite the complexity and dynamic properties that typify social-ecological systems (Hunt et al. 2013). In our study, the size of dense and dispersed residential patterns of anglers on the landscape did not vary seasonally or yearly. This outcome was unexpected given that anglers vary in their site selection of waterbodies (Hunt et al. 2011, Matsumura et al. 2019). At the seasonal scale, we anticipated larger catchments to occur during summer and peak fishing effort (Kaemingk et al. 2018). We hypothesized that fishing effort and catchment area were coupled processes, which would require a greater spatial area or draw of anglers on the landscape to increase onsite fishing effort. Additionally, we expected that high churn rates in angler license sales could lead to dynamic patterns in catchment area at the yearly scale.

We infer that the location and distance between humans and natural resources may be a strong structuring agent, creating predictable and invariant patterns. After all, the location of natural resources and human residences are largely fixed on the landscape, at least on seasonal and yearly scales. There are several social and ecological examples of how location of resources in relation to humans and other animals can structure human behavior and population dynamics, respectively. Selecting school building sites can increase or decrease the likelihood of children walking to school. Children were less likely to walk to school when schools were built in areas of town with low street connectivity and high traffic exposure (Giles-Corti et al. 2011), demonstrating how the placement of schools can ultimately dictate the mode of transportation (e.g., walking vs. driving) and human behavior in a social context. Beavers (*Castor canadensis*) consider provisioning energetic costs and branch size in relation to distance from the central place (McGinley and Whitham 1985). The proximity of beavers to cottonwood (*Populus fremontii*) populations ultimately shapes cottonwood reproduction and population dynamics. For social-ecological systems such as recreational fisheries, angler travel time and trip context (day vs. multi-day) can create strong coupled feedbacks between anglers and waterbodies, leading to halos of fish depletion near urban centers (Wilson et al. 2020). We provide further evidence that location and proximity between people and natural resources is a prominent and important feature that ultimately contributes to the structuring of social-ecological systems.

Several explanations exist that could account for the invariant social-ecological catchment patterns we observed, but we focus our discussion on two of the most likely explanations. The overall angler population may exhibit a high degree of site fidelity (same angler hypothesis). An extremely low percentage (7%) of the angler population visited multiple waterbodies within a small complex of Nebraska waterbodies (Chizinski et al. 2014), suggesting that anglers may prefer to participate in fishing at a small and select number of waterbodies. We know that the catchment area and location on the landscape (through visualization; see Fig. 1) does not change through time and space, but angler effort is seasonally dynamic (Kaemingk et al. 2018). It is therefore possible that similar anglers visit these waterbodies through time, yet take more frequent fishing trips or fish longer on days during the summer compared to spring and fall. Average daily trip length for these waterbodies is least during spring (4.3 h), greatest during summer (4.8 h), and intermediate during fall (4.5 h; *unpublished data*). Although most of our waterbodies did not contain second homes or lake cabins, we would expect invariant social-ecological catchments to exist within these systems as well because anglers are more "captive" given their place-based values and investments. These invariant social-ecological catchments could be ideal for applying place-based management approaches (Camp et al. 2018). An alternative explanation is that different segments (based on specialization, motivation, and preference) of the angler population participate in fishing through time, but all anglers reside in similar ZIP codes (different angler hypothesis). For example, a waterbody may attract different anglers (e.g., representing different blocks of town) through time (e.g., one block in the spring and a different block in the summer), but all anglers reside in the same ZIP code, which causes the spatial and temporal residential pattern (at the ZIP code level) to remain invariant. Therefore, travel time and distance could uniformly affect all angler segments, despite differences in specialization, motivation, and preference. It is worth noting that Papenfuss et al. (2015) found broad seasonal differences between the spatial distribution of anglers during open water fishing compared to ice fishing based on data collected from an angler fishing app. We surmise that some combination of the same angler hypothesis and the different angler hypothesis likely accounts for the invariant catchment patterns we observed. We encourage researchers to test these hypotheses by exploring in future studies the mechanisms that underlie and contribute to the development and maintenance of invariant social-ecological catchments.

Though angler-waterbody catchment areas are invariant in Nebraska for the spatiotemporal scales we assessed, it is likely that catchment areas are variable for much larger temporal scales (and perhaps much smaller temporal scales). For example, if we attempted to assess angler-waterbody catchments across centuries, we would quickly realize that none of the waterbodies (reservoirs) we sampled existed 100 yr ago and that the distribution

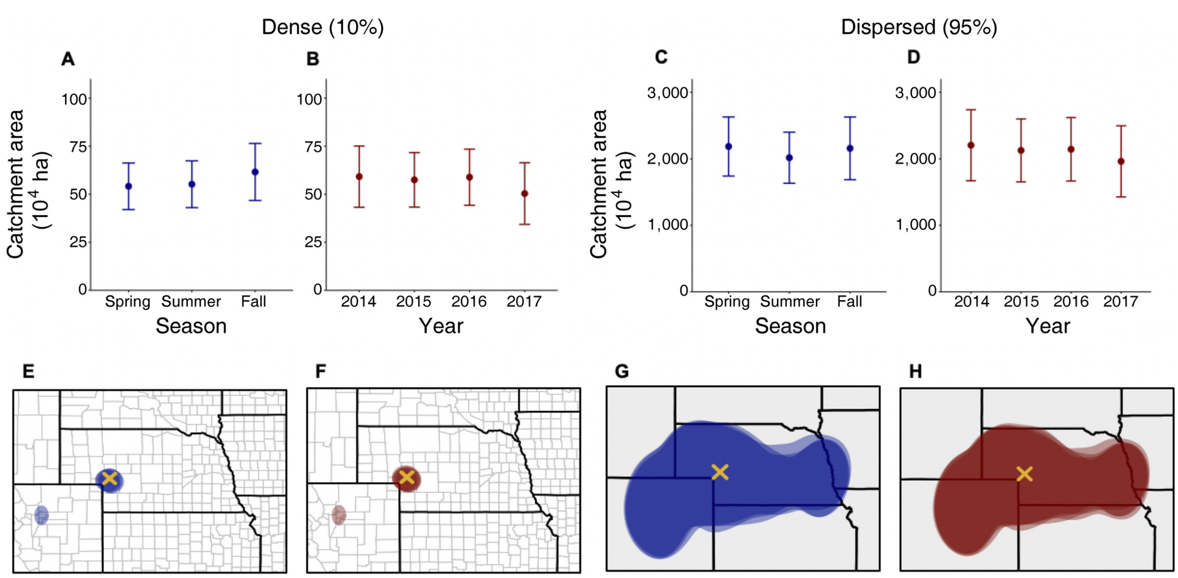

Fig. 1. Social-ecological catchment areas (10,000 ha; mean ± SE) during 2014–2017 at the dense (10%) and dispersed (95%) scales across seasons (panels A and C, respectively) and years (panel B and D, respectively). We use Lake McConaughy (depicted by yellow X; lines depict U.S. county and state boundaries) during 2016 to illustrate the seasonal and annual invariances of social-ecological catchment area at the dense (panels E and F, respectively) and dispersed (panels G and H, respectively) scales.

of people throughout Nebraska (and surrounding states) has shifted (i.e., become more urbanized). Thus, we expect angler–waterbody catchment areas to shift to a "new" invariant regime (Steele 1998) following drastic changes to the landscape, such as the removal of a resource (e.g., decommissioning a dam; Hansen et al. 2019) or a sudden change in the distribution of where people reside (e.g., influx of refugees or housing crisis of 2008; Ravuri 2016). In contrast, based on our findings, we do not anticipate that social disruptions, such as the current coronavirus (COVID-19) epidemic (Worstell 2020), to change the sizes of angler-waterbody catchments unless the disruption produces long-term changes to the distribution of angler residences on the landscape. We hope that future studies will leverage catchments as a cross-disciplinary method to evaluate spatial and temporal properties of complex social-ecological systems.

We assert that quantifying social-ecological catchments is important for conservation. This concept and technique is especially well equipped to deal with diffuse users and discrete natural resources, such as wildlife management areas, national parks, and city parks. Social-ecological catchments provide an additional piece of information to understand complex population-level patterns that stem from trade-offs experienced at the individual level, such as travel distance and cost, ultimately revealing emergent properties that appear to be at odds with patterns observed at the individual level (Johnston et al. 2010, Hunt et al. 2011). Landscape ecology techniques, such as extracting features (e.g., road density, population size, land cover) from inside and outside delineated catchment areas could lead to a better mechanistic understanding of complex social-ecological systems. We can also extract important socioeconomic ZIP code information (e.g., U.S. Census Bureau, ESRI Tapestry [ESRI, Redlands, California, USA]) such as household income, age demographics, household size, and gender information and link it to onsite participation patterns (Schlechte et al., *in press*). Changes in spatiotemporal participation patterns could ultimately impact resource abundance and quality, such as overfishing in recreational fisheries (Post et al. 2008, Kaemingk et al. 2020*b*). This study provides a springboard to facilitate future work and novel ideas that will guide efforts geared toward conserving patchily distributed resources that are used by diffuse and mobile users on the landscape.

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Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.2272/full

Data Availability

Data available from the University of Nebraska-Lincoln Data Repository (Kaemingk et al. 2020*a*): *https://doi.org/10.32873/unl.dr.20201125*