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Matching of resource use and investment according to waterbody size in recreational fisheries

Mark A. Kaemingk[a,*], Robert Arlinghaus[b,c], Max H. Birdsong[b,c], Christopher J. Chizinski[d], Roman Lyach[e], Kyle L. Wilson[f,1], Kevin L. Pope[g]

[a] Department of Biology, University of North Dakota, Grand Forks, ND 58202, USA
[b] Department of Fish Biology, Fisheries and Aquaculture, Leibniz Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany
[c] Division of Integrative Fisheries Management, Faculty of Life Sciences and Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), Humboldt-Universität zu Berlin, Berlin, Germany
[d] School of Natural Resources, University of Nebraska-Lincoln, Lincoln, NE 68583, USA
[e] Institute for Evaluations and Social Analyses, Sokolovská 351/25, 186 00 Prague, Czech Republic
[f] Earth to Ocean Research Group, Simon Fraser University, Burnaby, BC, Canada
[g] US Geological Survey—Nebraska Cooperative Fish and Wildlife Research Unit, and School of Natural Resources, University of Nebraska-Lincoln, Lincoln, NE 68583, USA

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ABSTRACT

The size of an ecosystem affects ecological interactions, but less is known about how ecosystem size may affect social interactions. We posit that ecosystem size could serve as a basis for understanding and contextualizing social interactions, connecting how ecosystem size influences natural resource investment decisions and the use of ecosystem services. We leverage international (Canada, Czech Republic, Germany, United States of America) inland recreational fishery data to explore whether certain ecosystem sizes receive a disproportionate amount of fish stocked (a measure of resource investment) and attract more angler effort – our measure of an ecosystem service. We find that smaller lentic waterbodies receive a disproportionate amount of fish stocked per area and also attract more angler effort per area consistently in all four countries. Therefore, we find that resource use and resource investment is matched by ecosystem size. We conclude that small waterbodies are prioritized by both managers and users and contribute more (per area) to recreational fisheries compared to large and more visible waterbodies on the landscape. An increasing focus on smaller-sized lakes and rivers, also those anthropogenically created, in science, assessment, and management is warranted.

1. Introduction

Successfully managing ecosystems to support and sustain a multitude of ecosystem services is challenging. Managers often face the difficult decision of where to distribute limited resources to increase, retain, or sustain certain ecosystem services (Keeler et al., 2019). It is unlikely that all management units (e.g., plots, land sections, lakes, districts) receive the same amount of resource investment. How then are resource investments distributed across management units that vary in size and frequency across the landscape? Furthermore, do these policy decisions shape and reflect which ecosystem services are supported, retained, and ultimately used? We posit that the allocation of investment resources is unevenly distributed and that this inherent bias is likely reflected in the ecosystems chosen to be managed. Patterns in how limited resources are allocated may further affect and contribute to the value and use of these resources, for example by attracting users to fisheries that are stocked (Arlinghaus et al., 2022; Mee et al., 2016). Therefore, through "co-evolution" of coupled social-ecological systems we would anticipate a strong coupling between the allocation of resource investments and ecosystem services (Egoh et al., 2009). Charting and linking resource investments to ecosystem services can reveal critical matches or mismatches in priorities between managers and users.

An opportunity exists to explore the potential matches in management investment and ecosystem services across ecosystem sizes, ultimately allowing for the ability to track the flow of ecological resources from decision makers to natural resource users. It would be useful to

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[*] Corresponding author.
E-mail address: mark.kaemingk@und.edu (M.A. Kaemingk).
[1] Current Address: Central Coast Indigenous Resource Alliance, Campbell River, British Columbia, Canada.

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understand how decision makers and natural resource users collectively prioritize and view resources based on ecosystem size. In part, understanding these relationships can provide actionable information to managers as they struggle to manage complex social-ecological dynamics, such as recreational fisheries (Arlinghaus et al., 2017). Smaller ecosystems, such as small lakes, have historically been viewed as less important with respect to their contribution to global processes and cycles (Downing, 2010), perhaps as a function of their low visibility on the landscape. However, several studies have shown that small waterbodies contribute more, on a per unit area basis, than their larger counterparts with respect to carbon sequestration, regional biodiversity, fish production, and recreational use of lakes (Downing et al., 1990; Kelly et al., 2001; Reed-Andersen et al., 2000; Scheffer et al., 2006). We therefore expect that decision makers and natural resource users follow similar ecosystem-size dependencies within social-ecological systems and focus on smaller, rather than larger, lakes (Meyerhoff et al., 2019). A social match should exist whereby small ecosystems will receive the most conservation and enhancement resources and ecosystem services (e.g., angling activity) per area (Fig. 1). Herein, we used inland recreational fisheries that span two continents and four countries (hereafter regions) to explore relationships among ecosystem size, resource investment, and ecosystem services. We test whether a social match existed between managers and anglers by evaluating fish stocking (i.e., investment resource) and angler effort (i.e., ecosystem service) across waterbody sizes.

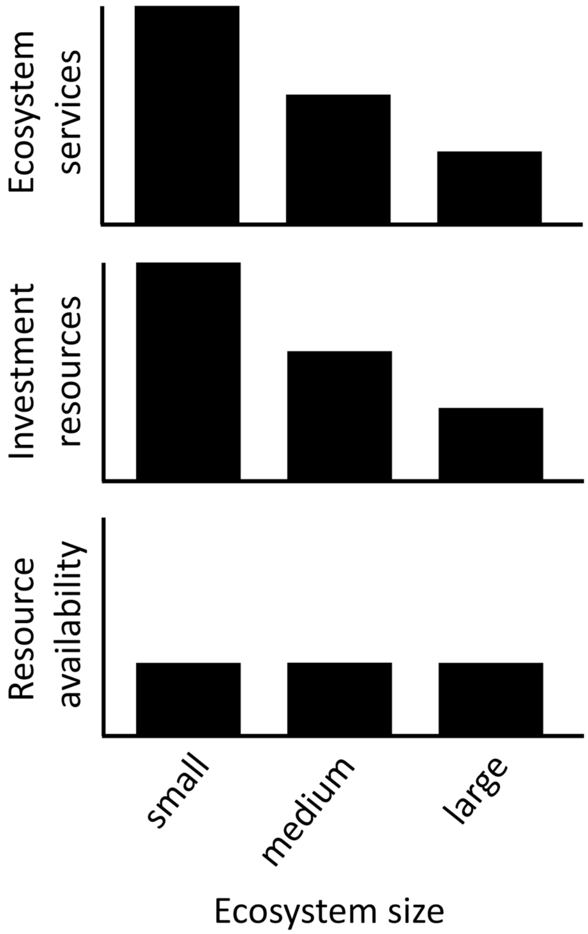

Fig. 1. Conceptual diagram for recreational fisheries representing a social match of investment resources and ecosystem services between managers and anglers as a function of ecosystem size, assuming constant resource availability across ecosystem-size groups.

2. Materials and methods

2.1. Study sites and data collection

We collated data sets pertaining to lentic waterbody size, fish stocking, and angler behavior from Canada (Freshwater Fisheries Society of British Columbia), Czech Republic (Czech fishing union), Germany (Angler Association of Saxony), and United States of America (Nebraska Game and Parks Commission and University of Nebraska-Lincoln). We used surface area (ha), fish-biomass stocked (kg/ha), and angler effort (hrs/ha, number of anglers/ha, or angling days/ha) as indices for ecosystem size, resource investment, and ecosystem services, respectively. Fish culture and production often represent a substantial cost to management agencies and the decision on where and how much fish biomass to stock can reveal important resource allocation patterns (Fujitani et al., 2020; Varkey et al., 2016). Likewise, we interpret angler effort as an indication of the level of ecosystem services generated; ecosystems that are more valued putatively receive greater use by anglers per unit area (Villamagna et al., 2014).

2.2. Sampling methods

Canada – We evaluated 545 public waterbodies in British Columbia (Canada) that are managed and monitored by the Freshwater Fisheries Society of British Columbia (FFSBC) and British Columbia Ministry of Forests, Lands, Natural Resource Operations, and Rural Development (BC FLNRORD). Waterbodies were natural freshwater lakes stocked with hatchery-raised wild-strain rainbow trout *Oncorhynchus mykiss*. We assessed annual patterns in fish stocking biomass and angler effort from 1980 through 2018 for a total of 5206 different lake-years. Fish stocking occurred on an annual basis that varied in frequency (e.g., stocked every 1–3 years) and life stages including: fry (1.5 g), yearling (15 g), or catchable adults (>250 g). Annual angler effort (hrs) was estimated from observed effort based on several complementary methods including: aerial transects, highway cameras, trail cameras, and on-site angler interviews (see details in Carruthers et al., 2018 and van Poorten and Brydle, 2018).

Czech Republic – We evaluated 235 public lentic waterbodies in the Czech Republic (central Europe) that are managed by the Czech Fishing Union (Český Rybářský Svaz, z.s.). These waterbodies are diverse, ranging from dammed rivers to ponds and artificially created lakes. We assessed patterns in fish stocking and evaluated angler effort from 2005 through 2018. Fish stocking occurred on an annual basis and varied in frequency depending on the waterbody. Waterbodies were annually stocked with 25 important and popular fish species. Common carp *Cyprinus carpio* was the most stocked and harvested species (~80% of fish stocking and harvest by biomass). Other important fish species were bream *Abramis brama*, rainbow trout, European catfish *Silurus glanis*, northern pike *Esox lucius*, and pikeperch *Sander lucioperca*. Fish were stocked at various sizes either as fry and fingerlings (approximately 0–15 cm TL, total length) or as adults (approximately 15–100 cm TL). Biomass of stocked fish was assessed from mandatory plans for fish stocking. Angling effort was assessed from mandatory angling logbooks that are collected annually from all recreational anglers in the Czech Republic. Both datasets were provided by the Czech Fishing Unions. See Lyach (2020) for more details regarding the recreational fisheries in the Czech Republic.

Germany – We evaluated 327 public lentic waterbodies in the German State of Saxony that are managed by the Angler Association of Leipzig. We assessed patterns in fish stocking and angler effort from 2014 through 2017. Fish stocking occurred on an annual basis and the stocking density varied depending on the waterbody. Waterbodies were annually stocked with a variety of popular species (e.g., rainbow trout, eel *Anguilla anguilla*, pikeperch, pike, carp) at various sizes (e.g., fry, fingerlings, adults). Stocking records were accurate as we used the statistics by the umbrella angler association who is the decision maker of the stocking activities. Angler effort (angler days) was assessed in a decentralized fashion by angling clubs who are members of the association. Anglers fill mandatory logbooks including data on effort spent and this information was fed through the angling clubs into a lake-specific effort database held by the association. The lake-specific angling effort data were collected through the angler licenses where there was a requirement on each angler to document catches as well as effort in angling days. Due to the additional layer of aggregation, from individual reports over clubs that then aggregate the individual data, uncertainty was higher for the effort data than for the stocking data.

United States of America – We evaluated 618 public lentic waterbodies in the U.S. State of Nebraska that are managed by Nebraska Game and Parks Commission. These waterbodies are diverse, ranging from natural Sandhill lakes, borrow and sand-gravel mining pits, small ponds, to larger flood control and irrigation reservoirs (Porath and Hurley, 2005). We assessed patterns in fish stocking across all waterbodies and evaluated angler effort on a subset of waterbodies from 2000 through 2018. Fish stocking occurred on an annual basis and varied in frequency depending on the waterbody. Waterbodies were stocked with a variety of popular sportfish species (e.g., channel catfish *Ictalurus punctatus*, rainbow trout, walleye *Sander vitreus*) at various sizes (e.g., fry, fingerlings, adults). Angler effort was assessed and estimated during April-October on a subset of waterbodies, representing each waterbody-size group, according to methods described in Kaemingk et al. (2018).

2.3. Waterbody-size groups, surface area, fish-biomass stocked, and angler effort

We chose to explore relationships among ecosystem size, resource investment, and ecosystem services using waterbody-size groups; groups are evident from discontinuities or gaps in existing waterbody sizes on the landscape. This approach is rooted in discontinuity theory, which has been applied in both ecological and social contexts to understand and account for processes occurring at distinct spatial and temporal scales (Angeler et al., 2016; Nash et al., 2014). Our previous work has shown that waterbody-size groups correspond to unique angler behavior (e.g., trip distance, time fished, and fish released and harvested) in recreational fisheries, a putative result of different spatial and temporal processes influencing these systems (Kaemingk et al., 2019). Therefore, we anticipated that by identifying waterbody-size groups across the four regions it would allow us to further understand social relationships within recreational fisheries.

We assessed discontinuities in waterbody size for each of the four regions using the discontinuity detector (Barichievy et al., 2018). We used Gap Rarity Index values to identify significant ($\alpha = 0.05$) breaks or gaps in the distribution of waterbody sizes. This method offered an objective and meaningful way to group waterbodies into different waterbody-size groups; waterbody size-groups were loosely defined as extra small, small, medium, and large according to Kaemingk et al. (2019). We then calculated resource availability by summing surface areas for each waterbody-size group for each of the four regions. Fish-biomass stocked and angler effort estimates were measured and reported at the waterbody and annual level. We calculated mean fish-biomass stocked for each waterbody and waterbody-size group across the years sampled (datasets spanned 4 – 39 years) and standardized these estimates according to surface area (i.e., kg stocked per ha) to serve as a comparable measure of resource investment. Similarly, we calculated mean angler effort for each waterbody sampled and waterbody-size group throughout the study period for each region (datasets spanned 4 – 39 years) and standardized these estimates according to surface area (e.g., hr per ha). Our estimates essentially provide resource investment and ecosystem service indices for a typical (i.e., average) year for a waterbody within each waterbody-size group.

2.4. Analysis

We evaluated whether an overarching social match existed among the four regions using beta regression (Douma and Weedon, 2019). We specifically analyzed the relationship between the proportion of mean biomass stocked and angler effort (response variables) to mean waterbody size (explanatory variable) at the waterbody-size group level ($N = 11$). Proportions were calculated by region among the waterbody size groups for both biomass stocked and angler effort. Mean waterbody size (by waterbody-size group; reported in Table 1) was $\log_{10}$-transformed to meet statistical assumptions and the betareg package was used for analysis (Zeileis et al., 2016). We report pseudo R^2 values as a global measure of the variation explained and significant negative relationships would indicate support for our hypothesis that small ecosystems receive increased investment resources and provide greater ecosystem services (Fig. 1).

3. Results

We identified a pronounced social match between managers and anglers according to fish-biomass stocked as a measure of resource investment and angler effort as a measure of ecosystem service (Fig. 2). There were significant negative relationships between biomass stocked (per unit area) and waterbody size (pseudo $R^2 = 0.48$, $z = 2.56$, $P = 0.01$) and angler effort (per unit area) and waterbody size (pseudo $R^2 = 0.47$, $z = 2.52$, $P = 0.01$). We also found regional variation in the number of waterbody-size groups (range: 2–4) and resource availability (Table 1). Most of the available surface area was contained in the largest waterbodies for the assessed regions of Germany and the United States of America, whereas surface area was more evenly distributed among the waterbody-size groups for Canada and the Czech Republic. Despite lower or equal absolute availability in terms of area, small waterbodies represent an important resource within recreational fisheries due to the disproportionate amount of investment resources directed at these systems per unit area through fish stockings and the magnitude of ecosystem services generated and received by anglers within these smaller ecosystems, again per unit area (Fig. 2).

4. Discussion

As predicted, we found a pronounced social match, using ecosystem size, between the allocation of resource investments and contribution of ecosystem services within recreational fisheries in lake landscapes of four countries when examined on a per unit area. Our findings extend previously identified ecosystem size-related stocking patterns (Fujitani et al., 2020; Welcomme, 2001) to now include ecosystem size-related

Table 1

Waterbody-size groups for Canada, Czech Republic, Germany, and United States of America that were identified by the discontinuity analysis and general waterbody characteristics (ha).

Waterbody size	Mean	N	Median	Min	Max
Canada					
Small (S)	59.1	532	21.7	0.5	807.5
Large (L)	1788.3	13	1650.0	1154.4	2881.6
Czech Republic					
Small (S)	9.1	215	4.0	< 0.1	52.0
Medium (M)	99.9	20	95.7	61.0	160.0
Germany					
Extra small (XS)	1.2	238	1.0	< 0.1	3.7
Small (S)	7.8	62	6.3	4.0	18.2
Medium (M)	148.8	27	66.4	25.0	719.5
United States of America					
Extra small (XS)	13.9	559	3.2	< 0.1	104.4
Small (S)	140.2	20	139.6	114.9	182.1
Medium (M)	323.6	22	303.5	222.6	465.4
Large (L)	2612.3	17	1151.3	647.5	12140.6

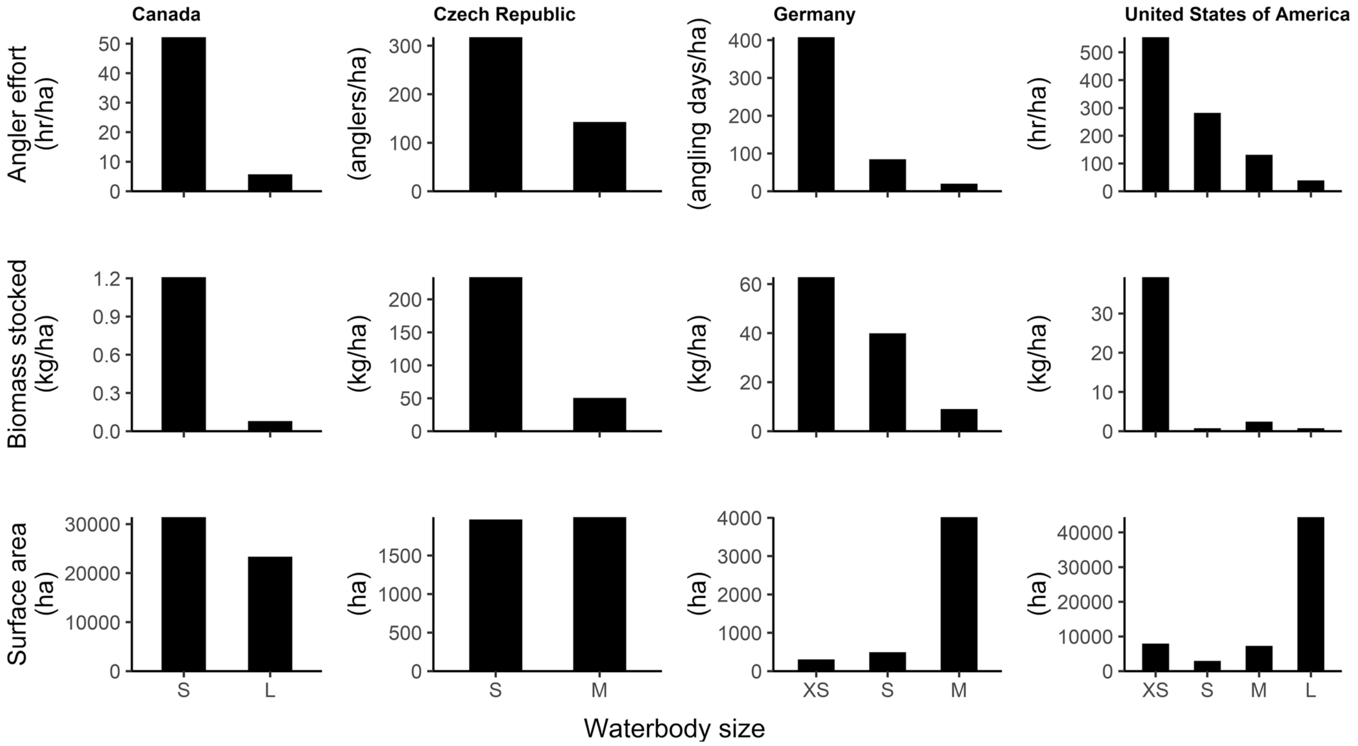

Fig. 2. Total surface area (ha) and mean fish-biomass stocked (kg/ha) and angler effort (hrs/ha, number of anglers/ha, or angling days/ha) for each waterbody-size group for regions of Canada, Czech Republic, Germany, and United States of America (see methods for details). Waterbody size-groups were loosely defined as extra small, small, medium, and large according to Kaemingk et al. (2019).

angler effort patterns, connecting an important relationship between natural resource managers and natural resource users. Our work also provides confirmation that ecosystem size can be used to predict complex social-ecological interactions at a (dynamic) equilibrium (Kaemingk et al., 2019), in this case the social importance of small waterbodies and their contribution and role in recreational fisheries. Exploring relationships among ecosystem size, investment resources, and ecosystem services reveal the potential co-evolution of social (e.g., angler access) and governance (e.g., stocking decisions) characteristics of coupled social-ecological systems.

Our findings suggest that social characteristics of recreational fisheries are important in terms of how ecosystem size scales with resource investments and angler use. Small waterbodies could be prioritized for stocking because it is more feasible and cost-effective to stock and monitor small systems (Fujitani et al., 2020; Welcomme, 2001). Angler access and behavior also varies across ecosystem size (Kane et al., 2020), with large systems often requiring a boat and greater financial investment. As a result, small systems were prioritized by both managers and anglers, likely because of their social characteristics and local accessibility (i.e., effects of strong spatial structuring, Kaemingk et al., 2020). Independent of the exact mechanism, our work shows a social match between managers and anglers within recreational fisheries. Inland landscapes contain a diversity of waterbodies that range in size, frequency, access and productivity. In this context, our work and other studies show that per unit area small waterbodies serve as extremely valuable fishery resources by disproportionately supporting a majority of angler effort (Flickinger et al., 1999; Meyerhoff et al., 2019) and attracting many resource investment decisions related to stocking (Fujitani et al., 2020). Further exploring how ecosystem size influences management decisions and subsequent efforts will aid in revealing overlooked relationships and afford options for managing complex social-ecological systems and sustaining ecosystem services. Arguably, all ecosystem sizes are valuable, but each size could be serving varied roles depending on the ecological, governance, and social priorities and context.

We identified overarching patterns among the four regions in resource investment and ecosystem services. Spatial patterns of investment-use relationships in inland recreational fisheries may therefore be robust to variation in geological, social, and ecological conditions that shape resource investment decisions and use within these social-ecological systems. The geology of lake formation and anthropogenic actions of creating reservoirs, pit lakes or ponds created variation in the size and frequency of waterbodies on the landscape leaving some regions (Czech Republic and Saxony, Germany - ponds, artificial lakes; Canada - alpine lakes) unable to support very large natural waterbodies. Although this could have led to variation in management and angler behavior among regions, on a per ha basis small waterbodies were consistently prioritized both in terms of investments as well as the ecosystem services provided to anglers.

It is worth noting that, though the resource investment patterns were similar across regions, there was variation in the magnitude of resource investment among regions (highest - Czech Republic, lowest – Canada). The number of management units may be responsible for the discrepancies in stocking rates; Czech Republic had the fewest number of small waterbodies (N = 215) and Canada had the greatest number of small waterbodies (N = 532), likely requiring investment resources to be spread more sparingly among management units for Canada.

Differences in the prioritization of ecosystem sizes may inform the development and implementation of management efforts to support and sustain key ecosystem services. Decision makers are likely adjusting and allocating resources to align with the magnitude of use and ecosystem services being generated by each ecosystem or their perceived importance within these complex systems (Mooney et al., 2020). Other reasons for management decision making broadly relates to “feasibility” of actions (Riepe et al., 2017). In our study, also differences in angler harvest could prompt management agencies to increase stocking efforts in small systems that may be more vulnerable to overexploitation (Mosindy et al., 1987). Strong feedbacks are likely to exist between anglers and managers (Fujitani et al., 2020; Matsumura et al., 2019; Mee et al., 2016; Riepe et al., 2017; van Poorten et al., 2011; Ward et al., 2016), potentially creating and reinforcing a match between investment resources and ecosystem services provided to anglers. It is also plausible that stocking efforts can lead to greater angler effort within small waterbodies (Dabrowksa et al., 2017), artificially elevating ecosystem services within these systems (Hühn et al., 2014; Johnston et al., 2018). Fish stocking might in some cases simply be a demonstrative action that agencies are interested in maintaining fish stocks (Arlinghaus et al., 2022), whereas the actual effectiveness of stocking in terms of generating fish catch is likely variable across systems and depends on whether the species is naturally recruiting or culture-based (Johnston et al., 2018; Lorenzen et al., 2012). When relying on release of catchable fish, fish stocking has been shown to increase angler effort immediately after stocking events (Harmon et al., 2018), creating pulsed patterns in angler effort and positive feedbacks (Askey et al., 2013; Mee et al., 2016). Anglers respond to changes in stocking over time through the ecological changes to fishing quality (Matsumura et al., 2019; Mee et al., 2016; Wilson et al., 2020). Anglers also affect fish stocks through catch and harvest that can deplete fish populations (Wilson et al., 2016) and move catches to a regional average (Matsumura et al., 2019; Wilson et al., 2020), meriting a subsequent management action in fish stocking. Importantly, it may be less feasible to stock larger waterbodies at the same per ha rate as small waterbodies (Welcomme, 2001), explaining our findings.

5. Conclusions

We demonstrate that considering ecosystem size extends beyond just ecology and benefits the multidisciplinary social-ecological framework to better understand complex systems (Ostrom, 2009). For example, discontinuities in ecosystem size can provide opportunities to reveal important social relationships (Kaemingk et al., 2019), shedding light on how ecosystems are being prioritized from a governance and social use standpoint. Future studies could expose critical social relationships for multi-user systems (agricultural landscapes, marine protected areas, managed forests) that are governed by different entities. Drawing from existing ecological-ecosystem size knowledge (e.g., Post et al., 2000), we can then add social knowledge to predict which ecosystems may be more vulnerable to a loss of key ecosystem services. Management efforts may then redirect limited resources to other overlooked, yet critical, ecosystem sizes and associated ecosystem services. Our work suggest that small lakes should receive attention by management, assessment, and science.

CRediT authorship contribution statement

Mark A. Kaemingk: Project administration, Supervision, Conceptualization, Visualization, Formal analysis, Writing – original draft. **Robert Arlinghaus:** Funding acquisition, Conceptualization, Data curation, Writing – review & editing. **Max H. Birdsong:** Data curation, Writing – review & editing. **Christopher J. Chizinski:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Roman Lyach:** Data curation, Writing – review & editing. **Kyle L. Wilson:** Data curation, Writing – review & editing. **Kevin L. Pope:** Funding acquisition, Project administration, Supervision, Methodology, Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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