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Social-ecological outcomes in recreational fisheries: the interaction of lakeshore development and stocking

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Abstract. Many ecosystems continue to experience rapid transformations due to processes like land use change and resource extraction. A systems approach to maintaining natural resources focuses on how interactions and feedbacks among components of complex social-ecological systems generate social and ecological outcomes. In recreational fisheries, residential shoreline development and fish stocking are two widespread human behaviors that influence fisheries, yet emergent social-ecological outcomes from these potentially interacting behaviors remain under explored. We applied a social-ecological systems framework using a simulation model and empirical data to determine whether lakeshore development is likely to promote stocking through its adverse effects on coarse woody habitat and thereby also on survival of juvenile and adult fish. We demonstrate that high lakeshore development is likely to generate dependency of the ecosystem on the social system, in the form of stocking. Further, lakeshore development can interact with social-ecological processes to create deficits for state-level governments, which threatens the ability to fund further ecosystem subsidies. Our results highlight the value of a social-ecological framework for maintaining ecosystem services like recreational fisheries.

Key words: *coarse woody habitat; lakeshore development; natural recruitment; recreational fisheries; refuge; social-ecological systems; stocking.*

Introduction

Many ecosystems continue to experience rapid transformations due to processes like land use change and resource extraction, often with significant gains in human well-being, which exemplifies the persistent problem of maintaining natural resources in continually human-dominated landscapes (Halpern et al. 2008, Jentoft and Chuenpagdee 2009, Raudsepp-Hearne et al. 2010). A systems approach to maintaining natural resources focuses on how interactions and feedbacks among variables of complex social-ecological systems generate social and ecological outcomes (Berkes and Folke 1998, Ostrom 2009). Generalized frameworks aid in the difficult task of dealing with the complexity of diverse social-ecological systems because they facilitate the development of models to explain processes and predict outcomes (McGinnis and Ostrom 2014).

For example, the McGinnis and Ostrom (2014) social-ecological system framework (SESF) is an interdisciplinary diagnostic tool to determine which variables interact in a given social-ecological system and how these interactions can affect the sustainability of that system (Hinkel et al. 2014, Bots et al. 2015). The SESF is a multi-tiered framework of variables that can be collapsed or expanded to describe a social-ecological system as needed. At the most general level (first-tier variables), the framework describes a social-ecological system as natural resources units embedded in resource systems that are affected by interactions of actors and governance systems to create outcomes that can feedback to determine future contextual variables (Ostrom 2009, McGinnis and Ostrom 2014). The SESF is particularly useful compared to other prominent social-ecological frameworks when considering reciprocal social and ecological interactions that occur on the micro (i.e., individual actions) to macro (i.e., group and societal actions) scale (Binder et al. 2013). The purpose of the SESF is to organize knowledge on diverse social-ecological systems to facilitate shared understanding of how to maintain natural resources (McGinnis and Ostrom 2014). However, shared understanding cannot be achieved without testing the framework through applying it to diverse social-ecological systems and action situations (McGinnis and Ostrom 2014, Bots et al. 2015). Despite the popularity of the SESF (combined number of ISI web of science citations for Ostrom [2009] and updated McGinnis and Ostrom [2014] is 995), it is seldom applied to case studies and tested in a quantitative manner (Leslie et al. 2015).

Inland recreational fisheries are salient examples of prominent social-ecological systems (Carpenter and

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Brock 2004, Liu et al. 2007, Lorenzen 2008, Hunt et al. 2013, Schlüter et al. 2014). In North America, lake resource systems are widely used for the recreational benefits they provide, resulting in preferential human development on or near lakes (Walsh et al. 2003). Lakefront property owners typically use lakes for swimming, boating, and aesthetic appeal, which often favors removal of littoral structure in the form of aquatic vegetation and coarse woody habitat (CWH). Removal of riparian trees for viewing corridors and landscaping can lead to decreased inputs of CWH into a lake (Sass et al. 2006*a*). Therefore, both aquatic vegetation and CWH are often present at very low densities with increased lakeshore development (defined as the number of buildings per kilometer shoreline; Jennings et al. 2003, Francis and Schindler 2006, Hicks and Frost 2011). Removal of littoral structure can affect fish, the focal resource unit in recreational fisheries, through a reduction in refuge for juveniles, which can determine recruitment success and stock rebuilding (Schindler et al. 2000, Walters and Kitchell 2001, Sass et al. 2006*a, b*). Walleye (*Sander vitreus*), a commonly sought after and stocked sport fish, experience reduced young of the year (YOY) survival with loss of CWH through predation, competition, and benthic siltation (Appendix S1: Table S1). Lakeshore development can also affect adult mortality as proximity of human development increases fishing pressure and harvest of adult fish, which can lead to a collapse of targeted fish populations (Appendix S5; Post et al. 2008).

When the ecosystem service of recreational fishing declines, resource users and managers tend to stock lakes with fish to maintain adult populations (van Poorten et al. 2011). The institutional arrangements that determine stocking decisions are diverse and can be structured into operational rules, collective choice rules, and external arrangements (see Lorenzen 2005, 2008 for a detailed description). However, a structured decision-making process that includes stakeholder input on stocking decisions is recommended and often employed (WDNR 2014, Arlinghaus et al. 2015). Stocking has become the most dominant management panacea for recreational fisheries worldwide (Eby et al. 2006, van Poorten et al. 2011), and it has implications for nearly every aspect of aquatic food webs including trophic interactions, nutrient cycling, cross-ecosystem linkages, and genetic and species diversity (Eby et al. 2006). Stocking also influences the economic state of a social-ecological system, as rearing and stocking costs can be high, especially for extended-growth fingerlings, which are larger and have higher survival rates than smaller fingerlings (Santucci and Wahl 1993, Szendrey and Wahl 1996).

As this background and SESF suggest, common interactions in inland recreational fisheries may lead to outcomes that then feed back to determine further social-ecological contexts (Ostrom 2009, Hunt et al. 2013, McGinnis and Ostrom 2014). We consider the SESF applied to recreational fisheries in a well-studied lake region to determine if lakeshore development interacts with stocking and what potential implications may be for maintaining recreational fisheries with increased lakeshore development. We used a social-ecological model and empirical data to explore these dynamics. Our model contained a stage-structured fish population of hatchery and wild individuals with stocking based upon structured decision making and recruitment based upon lakeshore development dependent habitat (Fig. 1). We compared our model output to empirical data on stocking rates and fishery-related economic costs and benefits in our study region. We hypothesized that lakeshore development would increase resource extraction and alter recruitment dynamics that would then feed back to reinforce stocking and create emergent ecological and socioeconomic outcomes.

METHODS

Social-ecological model formulation

Our social-ecological fisheries model follows McGinnis and Ostrom's (2014) framework of a generalized social-ecological system (see Appendix S2 for a detailed description of our study system and application of Hinkel et al. 2015 diagnostic procedure for applying the SESF). We based our model on van Poorten et al. (2011) and Roth et al. (2007) with a few important modifications (see Appendix S3). The ecological portion of the model defines dynamics of a stage-structured walleye population, from which people harvest adult walleye and to which they stock fingerlings to the YOY stage or extended-growth fingerlings to the juvenile stage (Fig. 1). The survival of YOY fish depends on availability of littoral structure, which is negatively related to the density of lakeshore housing development. The social portion of the model defines a structured decision-making process, whereby loss of natural recruitment and decreased adult densities lead to stocking of fingerlings or extended-growth fingerlings. High post stocking mortality due to predation leads to stocking extended-growth fingerlings, while a decline in adult densities between stock assessments and the responsiveness of management influences the amount of fingerlings or extended-growth fingerlings stocked. Similar to van Poorten et al. (2011) we used a Ricker stock recruitment model, which assumes density dependence through decreased per capita recruitment with increasing size of the spawning stock. We increased harvest rates of adult walleye as a function of increased lakeshore development. This assumption was supported by empirical analysis relating angling effort and lakeshore development (see Appendix S5).

Model simulation

We parameterized our social-ecological model to reflect walleye stocking and stage specific processes in Vilas County lakes in the Northern Highlands Lake

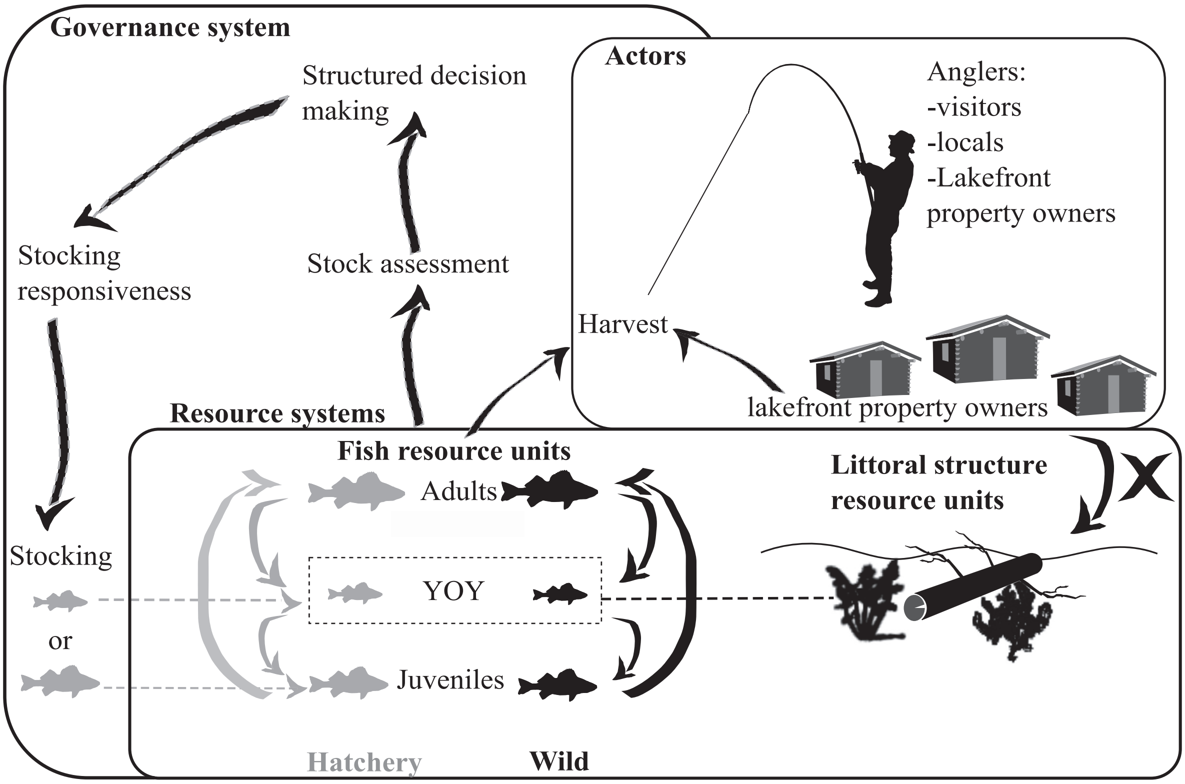

Fig. 1. Social-ecological fisheries model based on van Poorten et al. (2011) and Roth et al. (2007). The resource system in the model includes resource units that are described by the dynamics of a stage-structured walleye fish population. Actors in the form of anglers and lakefront property owners interact with the resource system via harvest of adult walleye and removal of littoral structure, which decreases survival of young-of-year (YOY) walleye. A government organization maintains the resource units of fish through stocking walleye fingerlings or extended-growth fingerlings to the YOY or juvenile stage, respectively. Stock assessments by the government organization inform structured decision making that determines if stocking occurs and the degree of stocking. See Appendices S2, S3, and S4 for more detail on our study system, model formation, equations, and parameters.

District of Wisconsin, USA. This area is a well-studied system where recreational fishing is very important socially, economically, and ecologically (Liu et al. 2007). We focused on walleye, as this is a commonly stocked and sought after fish species in this region. A structured decision making process is used in Wisconsin to determine whether a lake will be stocked with walleye by the Wisconsin Department of Natural Resources (WDNR) (WDNR 2014). Adequate natural recruitment to support a walleye population and fishery, adult densities, and the likelihood of recruitment success based on physio-chemical predictors are the three greatest concerns when prioritizing lakes for stocking in Wisconsin (see Appendix S3 for further details, WDNR 2014, Hansen et al. 2015).

To determine ecological outcomes of lakeshore development on our walleye population we simulated lakes along a lakeshore development gradient. Our dependent variables were adult and YOY wild and hatchery fish densities obtained once simulations reached dynamic equilibria after 150 years. We used mean output values from 50 time steps to capture inter annual variation and our lake gradient of lakeshore development was 0–50 by an increment of 1.

Empirical walleye data

We compared model output of walleye stage-specific densities and stocking outcomes to a data set from 158 Vilas County lakes spanning a gradient of lakeshore development. All lakes in our data set had walleye present, were >20 ha, and had publically available satellite images taken in 2013 or 2015, from which we determined lakeshore development (number of buildings/km shoreline). To test model-predicted walleye densities with empirical data we obtained walleye YOY and adult densities, determined using fall shoreline electrofishing and mark recapture in 29 and 58 of our lakes respectively, from the WDNR. YOY densities were estimated between 2011 and 2013 and adult densities were estimated between 1990 and 2014.

We modeled YOY counts (number of YOY walleye per kilometer of shoreline) using zero-inflated Poisson regression. Zero-inflated Poisson regression can account for two separate processes generating zeros in count data. In our application, zeros can be generated when YOY were present in a lake but failed to be detected by electrofishing or when YOY were actually absent from the lake.

Known predictors of YOY catch per kilometer of shoreline in Wisconsin are lake surface area and shoreline complexity (defined as shoreline development factor or the ratio of lake perimeter to the perimeter of a circle with an area equal to the lake; Hansen et al. 2015). Therefore, we included lake surface area and shoreline complexity in candidate models and compared them using Akaike Information Criterion corrected for small sample sizes (AIC_c). Because shoreline complexity and lake surface area were highly correlated we did not consider both predictors in the same model. Lake surface area and shoreline complexity were unrelated to lakeshore development in our 29-lake data set (R-squared = 0.02, $P = 0.43$, $n = 29$ and R-squared = 0.01, $P = 0.66$, $n = 29$, respectively). We related adult densities to lakeshore development using ordinary least squares regression.

To test stocking outcomes, we collected records of walleye stocking since 1972 for all lakes in our data set from the WDNR and by collecting records of approved permits for stocking by all lake associations and angling clubs in Vilas County. Lakes that have adequate natural recruitment to sustain a walleye fishery are not stocked in Wisconsin (WDNR 2014), therefore, we estimated the odds that a lake had substantial walleye natural recruitment by using a logistic regression relating presence or absence of walleye stocking to lakeshore development in all 158 of our lakes (Fig. 3a). We could not test if a switch to stocking extended-growth fingerlings occurred as a function of lakeshore development because we did not have lakeshore development data over time for our lakes. Instead, we relied on illustrating an increasing trend of stocking extended-growth fingerlings in recent years by determining the average length of walleye stocked in our lakes between 1972 and 2014. While the mechanisms in our social-ecological model that cause a shift from stocking fingerlings to extended-growth fingerlings closely mimic the decision process that the WDNR uses (Simonson et al. 2010; Appendix S3), an increased reliance on stocking extended-growth fingerlings over time does not provide definitive evidence that the mechanism underlying this trend is driven solely by lakeshore development. However, we feel it is a useful trend to illustrate as lakeshore development within Vilas County has increased substantially over the timeframe considered (Schnaiberg et al. 2002).

State and municipal government costs and revenues

To determine economic outcome metrics associated with lakeshore development we used economic estimates of state and municipal government costs and revenues based on our model output and parameter estimates relevant to Vilas County. We corrected all economic estimates for inflation to 2004 to allow comparison across estimates. We determined the average cost of rearing and stocking fingerlings and extended-growth fingerlings from the Wisconsin Legislative Audit Bureau summary of fish stocking activities in Wisconsin (WLAB 1997). We determined the property tax generated for an average lakefront building using assessments of lakefront property values, including renovation valuations, from lakefront properties sold between 1997 and 2004 in Vilas County (see Appendix S5 for details). We calculated the sales tax generated per fish harvested using estimates of total statewide expenditures by anglers, total fish harvested, and the sales tax rate in Wisconsin (U.S. Department of the Interior 2001, McClanahan and Hansen 2005). We scaled revenue from property and sales taxes and costs from stocking to U.S. dollars per lake per year using the average lake perimeter and area of the 158 lakes we considered in our empirical data set.

RESULTS

Social-ecological model

Results from our social-ecological model suggested that high lakeshore development eliminated natural recruitment and led to a reliance on stocking extended-growth fingerlings to sustain the walleye population and fishery. Natural recruitment failed because higher lakeshore development led to decreased survivorship for YOY walleye via the loss of CWH refuge. This loss of refuge affected wild YOY and stocked fingerling survival, such that wild YOY densities declined and remained low above 15 buildings per km of shoreline and low fingerling survival led to extended growth fingerling stocking (Fig. 2a). At high lakeshore development, wild adult stocks were extirpated and were replaced by hatchery individuals that were maintained by extended growth fingerling stocking (Fig. 2c).

Empirical walleye data

Empirical data on YOY and adult walleye densities supported our model predictions that lakeshore development can influence stocking through increased YOY mortality (Fig. 2b, d). A zero-inflated Poisson regression model that predicted the number of YOY per kilometer of shoreline as a function of lakeshore development and shoreline complexity had the greatest predictive power (ΔAIC of a model with lakeshore development alone = 13). Only lakeshore development had a significant effect on the odds that a lake had no YOY present (odds ratio = 1.17, $P = 0.01$). Specifically, an additional building per kilometer of shoreline increased the odds that a lake had no YOY present by 17% ± 13% (95% CI). Among lakes where YOY were present both lakeshore development and shoreline complexity had a significant negative effect on the number of YOY per kilometer of shoreline. An additional building per kilometer of shoreline decreased the expected number of YOY by 9% ± 2% (95% CI), while a unit increase in shoreline complexity decreased the expected number of YOY by 1%. These results are congruent with our model predictions of high predation pressure and lack of refuge at high lakeshore development leading to high YOY

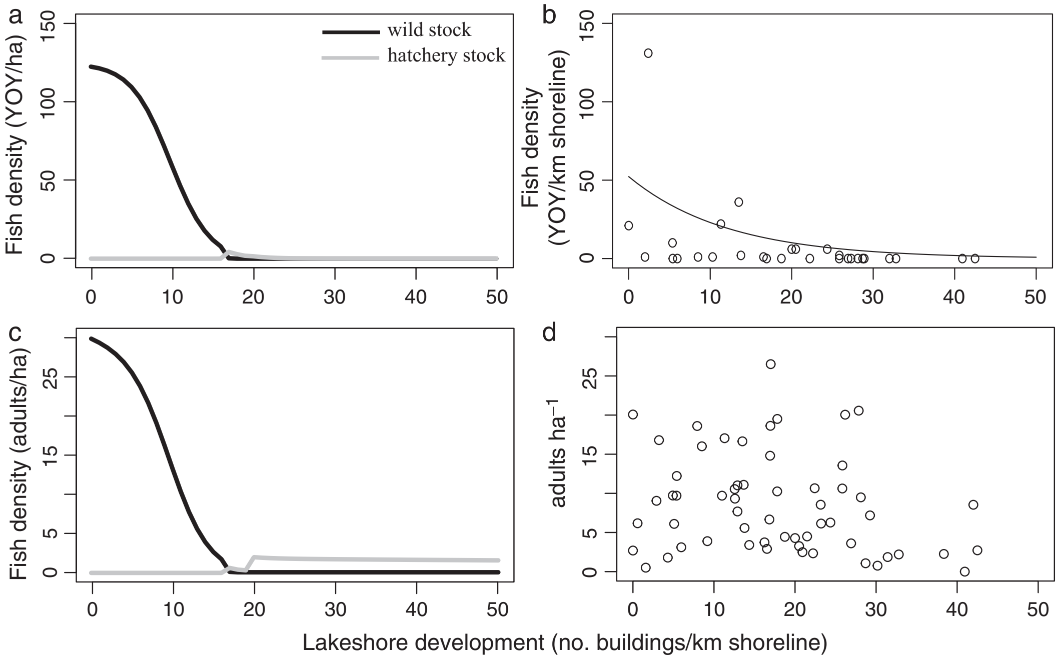

FIG. 2. (a and c) Social-ecological model output and (b and d) empirical data illustrating ecological outcomes of adult and young of the year (YOY) walleye densities with lakeshore development. (a) Wild YOYs declined to zero at approximately 20 buildings per kilometer of shoreline due to increased YOY mortality from loss of coarse woody habitat (CWH) related refuge. (b) Catch per kilometer of shoreline of walleye YOY significantly declined with lakeshore development in 29 Vilas County Wisconsin, USA, lakes (odds ratio = 1.17, $P = 0.01$). (c) Below 20 buildings per kilometer of shoreline, adult walleye densities were determined by wild stocks but, above 20 buildings per kilometer of shoreline, only extended-growth fingerlings determined densities. Adult densities were low but constant when the population was maintained only by stocking. (d) There was no significant effect of lakeshore development on adult walleye densities, determined by mark–recapture, in 58 Vilas County lakes despite higher fishing pressure with lakeshore development in this region (Appendix S5).

mortality and loss of natural recruitment (Fig. 2a). Decreased YOY densities could also be caused by reduced adult densities due to increased fishing pressure. However, despite increased fishing pressure with lakeshore development in our study region (see Appendix S5), there was no significant decline in adult walleye density with lakeshore development (Fig. 2d), likely because highly developed lakes were more reliant on stocking (Fig. 3a), which effectively decouples fishing pressure and adult walleye density (Post and Parkinson 2012).

Empirical data on stocking in 158 Wisconsin lakes further supported our model results of reduced natural recruitment in lakes with high lakeshore development and a need for stocking extended-growth fingerlings. Our logistic regression model determined that the odds that a walleye population and fishery were maintained by stocking increased significantly with lakeshore development (Fig. 3a, odds ratio = 1.1, $P < 0.001$). At 0 houses per kilometer of shoreline the odds of stocking were 50%, whereas, at 40 houses per kilometer of shoreline, the odds of stocking were 90% (Fig. 3a). The length of walleye stocked over time in the above mentioned lakes provided some support for our social-ecological model results that stocking practices tend to rely more on extended-growth fingerlings than fingerlings as development increases (Fig. 2a). Stocking records from 1972 to 2014 indicated an increase in the average size of walleye stocked in recent years (Fig. 3b). 1999 marked the onset of a trend of stocking larger walleye because regional biologists began requesting more extended-growth fingerlings, which are used when post-stocking mortality is high due to predation pressure (Simonson et al. 2010).

State and municipal government costs and revenues

Economic outcome metrics from our model results suggested that lakeshore development can have unintuitive effects on government revenue at the state level through its effects on stocking, harvest, and tax revenue. Below ~18 buildings per kilometer of shoreline, sales tax generated from recreational fisheries outweighed the cost of stocking (Fig. 4). However, by approximately 18 buildings per kilometer of shoreline the cost of stocking for a lake was one order of magnitude greater than the revenue generated by sales tax. Stocking costs were increased further once stocking switched to extended-growth fingerlings at approximately 20 buildings per kilometer of shoreline, despite the decrease in number of fish stocked (Fig. 4; Appendix S8: Fig. S2.1). Stocking costs at 50 buildings per kilometer of shoreline were two orders of magnitude greater than sales tax revenue. Municipal revenue from property tax when development

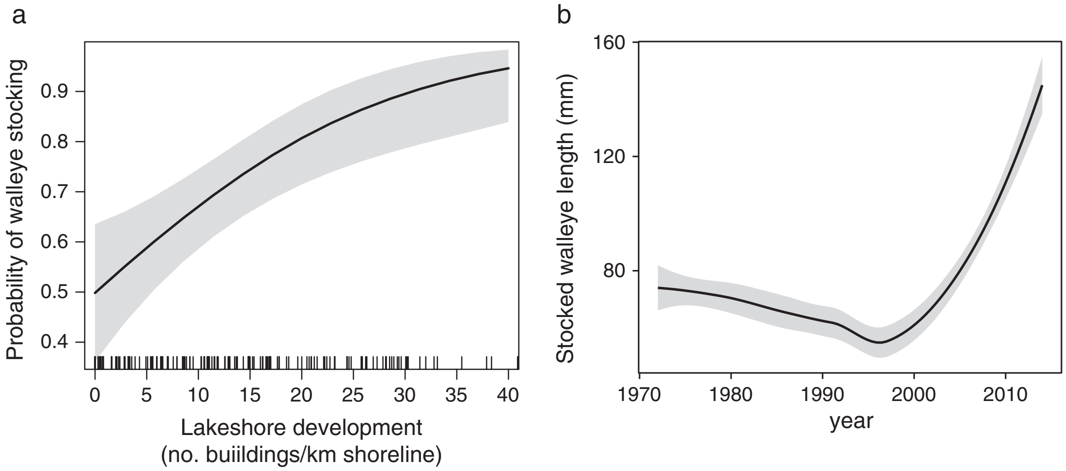

FIG. 3. Empirical walleye stocking data for Vilas County Wisconsin. (a) The probability that a walleye population and fishery were maintained by stocking increased significantly with lakeshore development in 158 Vilas County Wisconsin, USA lakes (odds ratio = 1.1, $P < 0.001$); 95% confidence intervals are plotted in gray. Vertical black marks on *x*-axis represent lakes observed at a given lakeshore development level. (b) Of the 158 lakes 109, were stocked. In these stocked lakes, the mean length of walleye stocked increased over time from stocking fingerlings (~50 mm) to extended-growth fingerlings (~150 mm). We fit a moving average smoother to the data and 95% confidences intervals are plotted in gray.

was present was high in comparison with state level stocking costs and sales tax revenue (Fig. 4). Even at one building per kilometer of shoreline, property tax revenue was one order of magnitude greater than sales tax and by 50 buildings per kilometer of shoreline property tax revenue was three orders of magnitude greater (Fig. 4).

DISCUSSION

Management that successfully maintains natural resources despite intensive land use change and resource extraction requires developing policy that is robust to possible future scenarios (Schindler and Hilborn 2015). Emergent outcomes from social-ecological interactions often lead to surprises in natural resource management (Holling et al. 2002). Therefore, developing a paradigm that incorporates emergent social-ecological outcomes is key to creating possible future scenarios that capture some of these surprises. For example, there has been an increasing call for incorporating human decisions and behaviors of anglers, managers, and stakeholders into recreational fisheries management (Arlinghaus et al. 2013, Hunt et al. 2013). Lakeshore housing development and stocking are two of the most prominent behaviors by users and managers of lake ecosystems (Schnaiberg et al. 2002, Eby et al. 2006). We illustrate how a SESF can be applied to recreational fisheries to determine emergent ecological and socioeconomic outcomes. Our results suggest that at low to moderate lakeshore development, a lake in our study region can produce positive state revenues, positive and quite substantial municipal revenues, and fishing opportunities, all while maintaining wild fish stocks. At higher development, the state makes modest investments in sustaining the fishery (and native stocks may be sacrificed) in order to maintain fishing, local economies, and local municipal revenue.

Loss of natural recruitment at high lakeshore development results in the need for funding structures to be in place to sustain constant stocking regimes or to fund initiatives to improve recruitment success if recreational fisheries are to be maintained. A government-financed

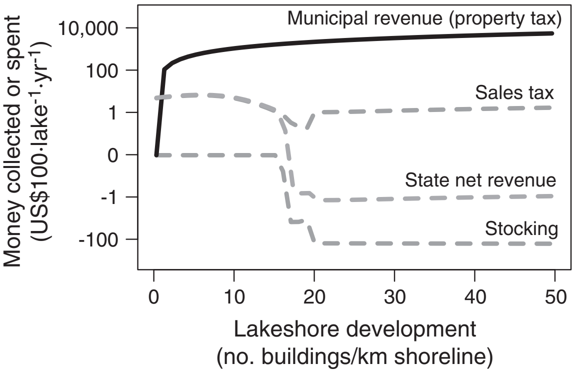

FIG. 4. Municipal and state revenues with lakeshore development. Local municipal government revenue from property tax is plotted in black, while state net revenue is plotted in gray. State net revenue was comprised of sales tax attributable to angler expenditures and costs of stocking, depicted in dashed lines. Parameters relevant to Vilas County Wisconsin, USA, and output from our social-ecological model results suggested that sales tax generated from recreational fisheries outweighed the cost of stocking below ~18 buildings per kilometer of shoreline but once a switch to stocking extended-growth fingerlings occurred at approximately 20 buildings per kilometer of shoreline, stocking costs were up to two orders of magnitude greater than sales tax revenue. Property tax revenue when development was present was one to three orders of magnitude greater than sales tax and stocking costs.

payment for ecosystem services is based on the beneficiary-pays principal and seeks to internalize the cost for maintaining an ecosystem service by charging users of the resource (Engel et al. 2008). This approach is employed in the United States, where revenue from taxes on gas and other expenditures by anglers fund recreational fisheries research, stocking, and maintenance costs (Buck 2009). However, our results suggest that revenue from sales tax generated by angler expenditures is two orders of magnitude lower than the cost of stocking on highly developed lakes. We note that our estimates of sales tax attributable to angler expenditure may be biased low because we used fish harvest instead of fishing effort to model these estimates, however, given the magnitude of stocking cost relative to sales tax revenue at high lakeshore development we feel our results are robust to this assumption. Therefore, a government financed payment for ecosystem services is only applicable at low lakeshore development where revenue from fisheries sales tax attributable to angler expenditure outweighs stocking costs. As lakeshore development increases an alternative funding structure is needed. One alternative funding structure is a third-party redistribution of costs, where government payment for stocking or habitat restoration comes from sources of revenue external to those generated by the resource users (Mauerhofer et al. 2013). In 2013, legislation was passed in our study area that used revenue from income tax and general sales tax, but not property tax, to fund stocking initiatives (Wisconsin Act 20 2013). Our results suggest that shoreline property tax revenue could be an alternative or additional source of funding for fisheries management in highly developed areas, as we demonstrate a relationship between lakeshore development and reliance on stocking. However, our simple cost benefit analysis is a first examination of potential socioeconomic outcomes and more in-depth economic valuations are required.

Managing development at the landscape level to promote heavily developed lakes while also conserving undeveloped lakes could represent a balance between state costs and local revenue in lake rich regions. Highly developing some lakes can provide substantial local revenue through property tax. However, stocking costs are reduced by natural recruitment and revenue from sales tax attributable to angler expenditure at low lakeshore development, therefore, conserving some lakes below the lakeshore development threshold where natural recruitment may be lost could minimize state costs of maintaining recreational fisheries. A similar approach to natural resource management is used in forestry. The triad approach for forest management divides forests into zones of intensive use, extensive management, and reserve zones (Seymour and Hunter 1992). Managers often use assessments for protecting forested land for conservation or reassigning it for other human uses like food production (Lin and Trianingsih 2016). The concept of Environmentally Sensitive Areas is also used in natural resource management to guide land use and zoning on landscapes where heavy pressure from tourism and development occur (Dai et al. 2011, Leman et al. 2016). For lakes, creating landscape level diversity in the form of policy can result in fisheries that are resilient to angler over-exploitation (Carpenter and Brock 2004). Our results provide a new cost–benefit perspective to this issue by suggesting that zoning some lakes for heavy development and others for no development may limit state costs while still benefiting municipal governments.

Our social-ecological model predicted no stocking at low lakeshore development but our empirical data showed a 50% chance of stocking even at no lakeshore development (Fig. 3a), which could be due to heavy use of some lakes by nonresidents, factors affecting natural recruitment other than lakeshore development, or stakeholder input in stocking decisions. Increased access to a lake through proximity to towns or roads, the reputation of a lake for fishing, and angler aversion to crowding could all result in higher than expected fishing pressure given the lakeshore development of a lake (Post et al. 2008, Hunt et al. 2011, Beardmore et al. 2014). Therefore, fishing effort on some low development lakes with high use could result in decreased adult densities and a need for supplementary stocking. Alternatively, some low development lakes may not have physio-chemical characteristics that allow for substantial natural recruitment. Hansen et al. (2015) found that lake surface area, water temperature degree-days, shoreline complexity, and conductivity were all predictors of walleye natural recruitment in Wisconsin lakes. Therefore, low development lakes that cannot support natural recruitment may be stocked especially if stakeholders have an interest in augmenting these fisheries. Stakeholder input from businesses owners, Native American tribes, and lake associations also influence stocking decisions in Wisconsin.

Although stakeholder input has substantially less weight for stocking decisions in our study area than natural recruitment and adult densities, there is an increasing call for co-management in natural resource management. Co-management in fisheries through stakeholder involvement in setting regulations is recommended to overcome “wicked” problems, which are defined as having many stakeholders with conflicting perspectives, unknowns, and no clear right/wrong solutions (Jentoft and Chuenpagdee 2009). Specifically, in regard to habitat and stocking regulations in recreational fisheries a stakeholder inclusive approach is recommended (Arlinghaus et al. 2015).

Although we did not consider interactions between lakeshore development and management techniques like catch-related regulations, our results suggest that increasing adult fish survival will not curb a reliance on stocking expensive extended-growth fingerlings at high lakeshore development. Management regulations like catch-and-release in highly developed lakes may increase the adult fish population if post-hook mortality rates are not too high (Muoneke and Childress 1994), however, lack of natural recruitment will inevitably lead to loss of the population without expensive inputs of extended-growth fingerlings (Arlinghaus et al. 2015). Therefore, if a management goal is to reduce reliance on stocking in highly developed lakes a focus should be placed on improving natural recruitment as opposed to altering catch regulations (Arlinghaus et al. 2015).

In our social-ecological model stocking of fish may have further exacerbated loss of natural recruitment with lakeshore development due to density dependent recruitment. Similar to van Poorten et al. (2011) we used a Ricker stock recruitment model, which assumes density dependence through reduction of per capita recruitment with increasing size of the spawning stock. Therefore, increasing the spawning stock through stocking extended-growth fingerlings may have exacerbated loss of natural recruitment if adult densities were high enough to cause declines in YOY. Given that stocking only occurred when YOY densities were low to begin with and that the amount of fingerlings and extended-growth fingerlings stocked were constrained to approximately 150 and 15 fish per hectare, respectively, it is unlikely that stocked adult densities had a noticeable effect on YOY densities through decreased per capita recruitment. However, our model did not take into account other community-level effects like emergent Allee effects, emergent facilitation, or predator exclusion, which can occur as a result of differential juvenile and adult mortality (Carpenter and Brock 2004, Persson and de Roos 2013, Schröder et al. 2014).

In a broader sense our results provide an example of how individual human behaviors can have large-scale outcomes that potentially threaten persistence of an ecosystem service without appropriate management of thresholds and social-ecological feedbacks. A review of prominent social-ecological frameworks by Binder et al. (2013) determined frameworks that predict macro-scale outcomes from micro-scale interactions and explicitly consider ecological, social, and reciprocal social-ecological dynamics are rare. Here we show behaviors of individual anglers and property owners (i.e., harvest and habitat removal) can have reciprocal large-scale ecological and socioeconomic outcomes. Specifically, our application of a general social-ecological systems framework (McGinnis and Ostrom 2014) to recreational fisheries determined that a well-known threshold of fish habitat loss with lakeshore development (Marburg et al. 2006, Liu et al. 2007) can lead to a reliance on stocking. Stocking can then feed back to determine economic states, which threaten persistence of recreational fisheries if lakeshore development is not adequately managed and funding structures put in place to maintain stocking and habitat restoration initiatives. These results are congruent with resilience planning approaches to maintaining ecosystem services, which highlight the need to manage thresholds and feedbacks (Bennett et al. 2005, Biggs et al. 2015).

While the SESF has been applied to recreational fisheries in Germany our application builds on this by considering a region with formal management oversight of stocking. Schlüter et al. (2014) and Hinkel et al. (2015) applied the SESF to recreational fisheries in Western Germany where informal institutions in the form of angling clubs and associations are in charge of managing the fishery. Our results suggest that harvest and habitat removal are more likely to have large-scale socioeconomic outcomes in a formal management context than an informal one. For example, in Western Germany clubs and associations collect fees to conduct stocking, which limit management costs to resource users and would be less likely to have large-scale socioeconomic outcomes observed in our study region through government payment for stocking programs using sources of revenue external to resource users (Schlüter et al. 2014). In a formal management context, the number of resource systems considered is much larger (i.e., all lakes within a region) making it difficult to monitor and create resource system specific regulations (Carpenter and Brock 2004). The number of resource systems is not considered in McGinnis and Ostrom (2014) as a second tier variable of resource systems but our application suggests that it is likely to interact with governance systems and affect both appropriation and provisioning action situations (Appendix S2). While the size of a resource system is included in the list of second tier variables this implies one resource system and ignores the heterogeneity of many discrete resource systems.

Ecosystems and the people that interact with them are diverse; therefore, ecological and economic outcomes are likely to differ among social-ecological systems. Simple models, like the one presented in this manuscript, do not fully characterize all social-ecological systems and implementation of management panaceas based on simplified models is sure to fail (Ostrom et al. 2007 and associated special issue). Our goal is to illustrate the utility of applying a social-ecological systems framework to help determine emergent social-ecological outcomes using recreational fisheries as a model system. We demonstrate that a social-ecological systems framework can provide useful insights of emergent social and ecological outcomes to inform policy that seeks to maintain ecosystem services.

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.1433/full

Data Availability

Data associated with this paper are available in the The Knowledge Network for Biocomplexity Data Repository: https://doi.org/10.5063/F17M05WJ; https://doi.org/10.5063/F1CC0XNB; https://doi.org/10.5063/F1H41PC2; https://doi.org/10.5063/F1MS3QPR; https://doi.org/10.5063/F1RJ4GC1