Appendix 1 – Supplementary methods
Investing in the commons: transient welfare creates incentives despite open access

Stocking dynamics in a fisheries model

We used a common and well-studied fish population model to illustrate the effects of stocking on fish populations:

$$\frac{dX}{dt} = \dot{X} = rX(1 - \frac{X}{k}) - H + S, \text{ where } \quad H = qEX \qquad \text{Eq.A1.1}$$

where X = fish density, H = harvest, r = the intrinsic rate of increase, k = carrying capacity, q = catchability coefficient (proportion of the fish stock removed with one unit of effort), E = total fishing effort, and S = stocking rate. All state variables are in uppercase, and parameter values are in lowercase. This model assumes that hatchery-derived and wild fish have similar survival and value to anglers. These assumptions are supported by empirical evidence of high survival of older and larger stocked fingerlings (Santucci and Wahl 1993; Szendrey and Wahl 1996) and no significant effect of the relative abundance of wild versus hatchery derived fish on the utility anglers gain from fishing (Arlinghaus et al. 2014).

Open access angler effort from multiple user groups

We followed Horan et al. (2011) and assumed that angler utility was linear in benefits from fishing, so effort dynamics were similar to the Smith (1968) model and followed:

$$\dot{E_i} = \delta E_i(p_i qX - c_i) \qquad \text{Eq.A1.2}$$

Here p_i = the marginal willingness to pay for fish harvest by angler group i, and c_i = marginal cost of fishing effort for angler group i, which represents access costs. This effort equation follows Clark's (1990) formulation of sluggishness, with the sluggishness parameter δ controlling the rate at which effort from angler group i responds to changes in the average net benefits from harvest.

We explicitly incorporated angler heterogeneity in our model by including two typical angler groups in inland recreational fisheries: lakeshore residents and roving anglers. We allowed the marginal costs of effort and the marginal willingness to pay for harvest to vary between the resident and roving angler populations. We modeled resident angler effort (E_{res}) and roving angler effort (E_{rov}) using Equation A1.2. Setting $\dot{E_i} = 0$ provides two solutions at equilibrium where effort from user group i is either greater than or equal to zero,

$$0 = \delta E^*_{rov}[p_{rov}qX^* - c_{rov}] \text{ if } \begin{cases} p_{rov}qX^* = c_{rov}, & E^*_{rov} > 0 \\ E^*_{rov} = 0 \end{cases} \qquad \text{Eq.A1.3}$$

$$0 = \delta E^*_{res}[p_{res}qX^* - c_{res}] \text{ if } \begin{cases} p_{res}qX^* = c_{res}, & E^*_{res} > 0 \\ E^*_{res} = 0 \end{cases} \qquad \text{Eq.A1.4}$$

where asterisks represent equilibrium values of state variables.

We focused on the case where both resident and roving effort were present at equilibrium because our interest lies in potential investments by local resource users despite open access and because in our study region there is a long history of use by both groups. In this case, the following condition must be met,

$$\frac{c_{rov}}{p_{rov}q} = \frac{c_{res}}{p_{res}q} = X^* \rightarrow p_{rov} = \frac{c_{rov}p_{res}}{c_{res}} \quad \text{Eq.A1.5}$$

Thus, the higher marginal cost of effort for rovers than for residents that characterizes this system implies that the rovers' marginal willingness to pay for harvest must also be higher with $p_{rov} = \frac{c_{rov}p_{res}}{c_{res}}$, assuming catchability of the two groups to be approximately equivalent. Therefore, we assumed that the higher access costs that rovers face, compared to residents, are balanced by higher value of harvest. This assumption was supported by valuations of roving and resident angler willingness to pay per walleye in our study region; on average marginal willingness to pay per walleye, calculated using the travel cost method, was 54% higher for non-waterfront property owners than for waterfront property owners (Murdock 2001). We also assumed that there was high latent resident and roving fishing effort in the fishery such that the number of potential resident and roving anglers never limited realized fishing effort (Hunt et al. 2011; Wilson et al. 2016).

Formulating the model with increasing (rather than constant) marginal costs of effort changes the conditions under which both resident and rover effort are present at equilibrium. We consider this alternative model formulation, and its implications for our key results, in Appendix 5.

Optimal stocking decisions by local and centralized managers

Our model considers stocking by either a local collective action organization of lakeshore residents, or by a centralized government agency. We defined each manager's objective to be finding the stocking rates through time that maximize the present value of net benefits (PVNB) to anglers. The local manager's objective function considers only the lakeshore resident anglers, while the centralized manager considers both the resident and roving anglers. Specifically,

$$PVNB_{Local\ MGMT} = \int_{t=0}^{\infty} e^{-\rho t}(p_{res}qE_{res}X - c_{res}E_{res} - \gamma S^2)\,dt \quad \text{Eq.A1.6}$$

$$PVNB_{Central\ MGMT} = \int_{t=0}^{\infty} e^{-\rho t}(p_{res}qE_{res}X - c_{res}E_{res} + p_{rov}qE_{rov}X - c_{rov}E_{rov} - \gamma S^2)\,dt \quad \text{Eq.A1.7}$$

where, ρ = the discount rate, γ is proportional to the marginal cost of stocking, and the terms in parentheses represent the net benefits of harvest for anglers less the cost of stocking. The integral of net benefits of harvest adds up the net benefits over time, with future benefits weighted less through the discount term $e^{-\rho t}$. We modeled the cost of stocking as a non-linear function to represent the increased production costs associated with the need to increase the production capacity of hatcheries or buying hatchery fish from exogenous sources at high stocking rates (Askey et al. 2013).

We solved for the optimal stocking rate over time that maximized the local or centralized manager's objective function, using numerical solutions of the constrained nonlinear multivariable functions. We used the fmincon function in Matlab to compute the optimal stocking rates over a 100-year planning horizon. The default initial conditions were E_{res} = 1, E_{rov} = 1, and X = 24 (carrying capacity). However, to demonstrate investment incentives in the least conducive conditions we also initialized the model from the no-stocking open access equilibrium. The equilibrium conditions for fish biomass and total effort were given by:

$$X^* = dq \quad \text{Eq.A1.8}$$

$$E_{Total}{}^* = \frac{(-bd+qr)}{q^2} \quad \text{Eq.A1.9}$$

where $b = \frac{r}{k}$ and $d = \frac{c_i}{p_i}$

We used the mean of the optimal stocking rate after the first 50 years to represent optimal stocking in equilibrium because equilibrium was always reached after this time frame. Although we derived the necessary optimal conditions using calculus of variations and the maximum principle, we relied on numerical solutions because the Hessian matrix, which must be concave or quasi-concave to satisfy sufficiency conditions for an optimal solution (Arrow and Enthoven 1961), was indefinite (Appendix 2). However, both methods led to similar results (Ziegler 2018).

To compare social welfare under centralized and local management we used the combined present value of net benefits of each angler group less the cost of stocking (Equation A1.6 and A1.7). Because PVNB is an integral of the trajectory of the system over time it is dependent on initial conditions of the state variables; therefore, we present the results over a range of the proportion of resident anglers in the angling pool at equilibrium, which is determined by the initial abundance of resident versus roving anglers (Fig. A1.1).

Model parameterization

For numerical solutions, we parameterized the model to reflect the recreational fishery for walleye (*Sander vitreus*) in northern Wisconsin, USA. We sought to use the most recent or most comprehensive data available, and converted all dollar amounts to 2016 dollars. Parameter values and associated references are summarized in Table A1.1.

We used empirically derived estimates of walleye intrinsic growth rate and carrying capacity (Hunt et al. 2011). For default values we choose the lower end of intrinsic rate of increase and higher end of carrying capacity reported in Hunt et al. (2011) but examine their full gradient in Fig. A1.2. We followed the approach of Hunt et al. (2011) and calculated area specific catchability using the maximum mean yearly walleye catch rate (1.53 walleye per hour) reported for our study region, assuming that catchability does not vary with density (Hansen et al. 2005). We converted catch rate to mean yearly catch rate per trip (0.84 walleye per trip) using data on the average time an angler spent fishing, the number of walleye anglers, and the total number of trips walleye anglers took (McClanahan and Hansen 2000).

We set δ, the sluggishness of fishing effort to average net benefits of harvest, equal to 0.01. Setting δ to a low value like this speeds convergence to equilibrium, and sensitivity analyses varying δ over the range from 0 to 1 indicated that the correlation between observed and predicted stocking rates was insensitive to δ (Fuller et al. 2013, Ziegler 2019).

The γ parameter describes how the total cost of stocking, C, varies with the stocking density, S ($C = \gamma S^2$; Eq. A1.6 and A1.7). We calculated a value for γ using data on the average price per stocked fish $\bar{z}_a$, average stocking density $\bar{S}_a$, and rate of survival to adulthood m_a for fish stocked at small fingerling, large fingerling, and extended growth fingerling size classes a (Wisconsin Dept. of Natural Resources 1999, Kampa and Hatzenbeler 2009). First, we calculated the density of stocked fish that survive to adulthood, $\tilde{S}_a = m_a \bar{S}_a$ (fish ha^{-1} y^{-1}). The size of small and large fingerlings stocked in Wisconsin (median length of 41mm and 178mm, respectively) corresponded to $m_{small\ fingerling}$ = 0.01 and $m_{large\ fingerling}$ = 0.21 in Kampa and Hatzenbeler (2009). For extended growth fingerlings, which are stocked at a catchable size and immediately enter the fishery, we assumed $m_{extended\ growth}$=1. Next, we calculated the expenditures on stocking, $C_a = \bar{z}_a \bar{S}_a$ (\$ ha^{-1} y^{-1}). With these estimates we solved for a value of γ for each size class, $\gamma = C_a / \tilde{S}_a{}^2$, and then took the average across the size classes (=1.74 \$ ha y fish^{-2}) to use as the default value of γ in our simulations.

Comparison to empirical data

We examined whether model-predicted rates of local and centralized stocking, and model-predicted fish abundance, were similar to observed data from 46 lakes in Vilas and Oneida counties, northern Wisconsin. For each of lake we parameterized a version of the model that included lake-specific estimates of resident and roving angler effort, roving angler access costs and willingness to pay for harvest, and catchability.

We estimated resident and roving angler effort from a large creel survey study in the region (Table A1.1). Creel clerks surveyed angler groups on lakes and recorded if they used the boat landing to launch their boat (roving anglers) or if they came from a lakeshore residence (resident anglers). The number of angler groups interviewed per lake ranged from 79 to 5,548 with a median of 1,108. Total angler effort in our empirical data set ranged from 2 to 35 angler trips per hectare per year (Fig. A1.3), and residents accounted for 0.1% to 92% of that effort (Table A1.1).

We calculated per-trip costs of roving anglers using the round-trip distance of a lake to the nearest urban center, the average operational cost of a sport utility vehicle in the USA (\$0.11 USD per km, American Automobile Association 2016), and the average operating cost of a boat for a freshwater angler in the USA (U.S. Census Bureau 2016). We then estimated the value of fish harvest for roving anglers using Equation A1.5.

We calculated lake specific walleye catchability using walleye harvest by both angler groups, effort by both angler groups, and walleye populations estimates for each lake (Table A1.1). For the three lakes where we did not have walleye population estimates we used the median catchability across the other 43 lakes.

We obtained data on stocking rates and walleye densities from the Wisconsin Department of Natural Resources, including all records of government and local organization stocking of walleye fingerlings; angler effort; and walleye population estimates in public access lakes in our study region (DNR 2019, see Fig. A1.3 for distributions of these data among our lakes). Data on stocking rates and walleye densities were divided by lake area to match the areal density units of the model. Our study lakes ranged in area from 46 to 1626 ha (median 190 ha).

We tested if observed and model predicted optimal stocking rates and walleye densities were similar for both local and centralized management. We used paired t-tests to determine if the mean of differences in observed and predicted state variables were significantly different from zero for both local and centralized management.

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Table A1.1. Parameter values for bio-economic stocking model. Prices in 2016 U.S. dollars.

Parameter	Definition	Unit	Value		Reference/equation
			Model default	Empirical case (min - max)	
α	Percent resident angling effort	%	50	0.05 – 92	(DNR 2019), $\frac{E_{res}}{(E_{res}+E_{rov})}100$
c_{rov}	Roving angler access cost (round trip travel plus boat operation)	$ trip^{-1}	10.00	6.22 – 10.74	(American Automobile Association 2016; U.S. Census Bureau 2016), $round\ trip\ distance\ \times 0.11\ + 6.22$
q	Catchability, the proportion of the fish stock removed with one unit of effort	hectare trip^{-1}	0.04	0.001 – 1.47	Model default: (Hunt et al. 2011) Empirical case: (DNR 2019), $\frac{harvest}{(E_{res}+E_{rov})X}$
p_{rov}	Roving angler marginal willingness to pay for harvest	$ fish^{-1}	47.46	29.52 – 50.96	Equation 5
p_{res}	Resident angler marginal willingness to pay for harvest	$ fish^{-1}	29.52	29.52	(Johnson et al. 2006)
c_{res}	Resident angler access cost (boat operation)	$ trip^{-1}	6.22	6.22	(U.S. Census Bureau 2016)
γ	Proportional to the marginal cost of stocking a fish	$ hectare year fish^{-2}	1.74	1.74	(DNR 1999; Kampa and Hatzenbeler 2009). See *Model parameterization*.
r	Walleye intrinsic growth rate	year^{-1}	0.34	0.34	(Hunt et al. 2011)
k	Walleye carrying capacity	fish hectare^{-1}	24	24	(Hunt et al. 2011)
δ	Sluggishness of fishing effort to average net benefits of harvest	trips $$^{-1}$ year^{-1}	0.01	0.01	(Clark 1990)*
ρ	Discount rate of net benefits of harvest	% year^{-1}	10	10	(Fenichel et al. 2010)*

* Does not provide an empirical estimate of model parameter

Figure A1.1

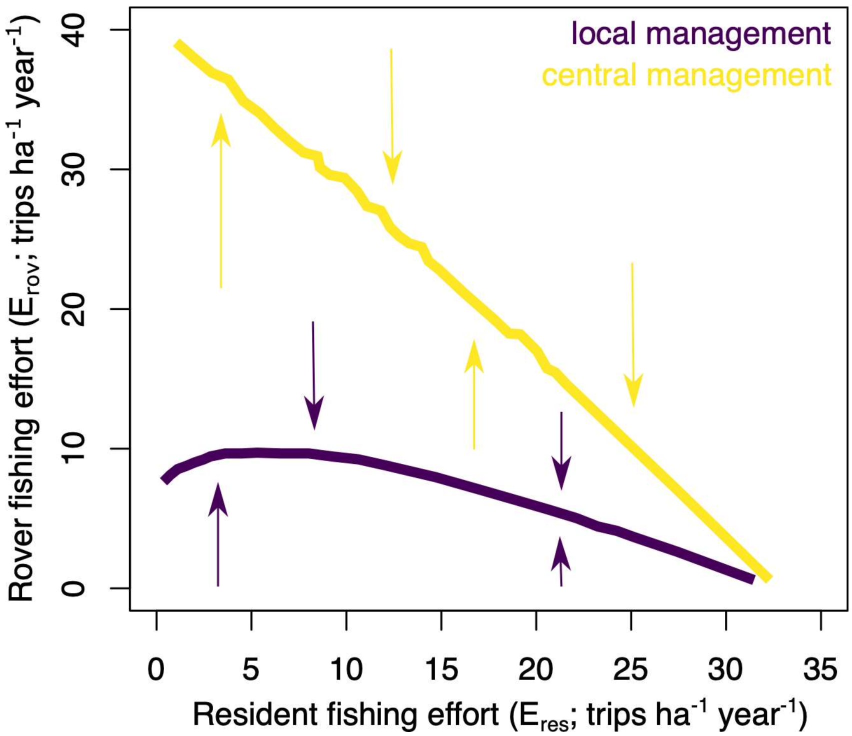

Figure A1.1. Phase plane of equilibrium fishing effort by resident and roving anglers, under local and centralized management. High initial fishing effort from either angler group confers an advantage for equilibrium fishing effort of that group because it reduces catch benefits for the alternative angler group, attracting less of their effort.

Figure A1.2

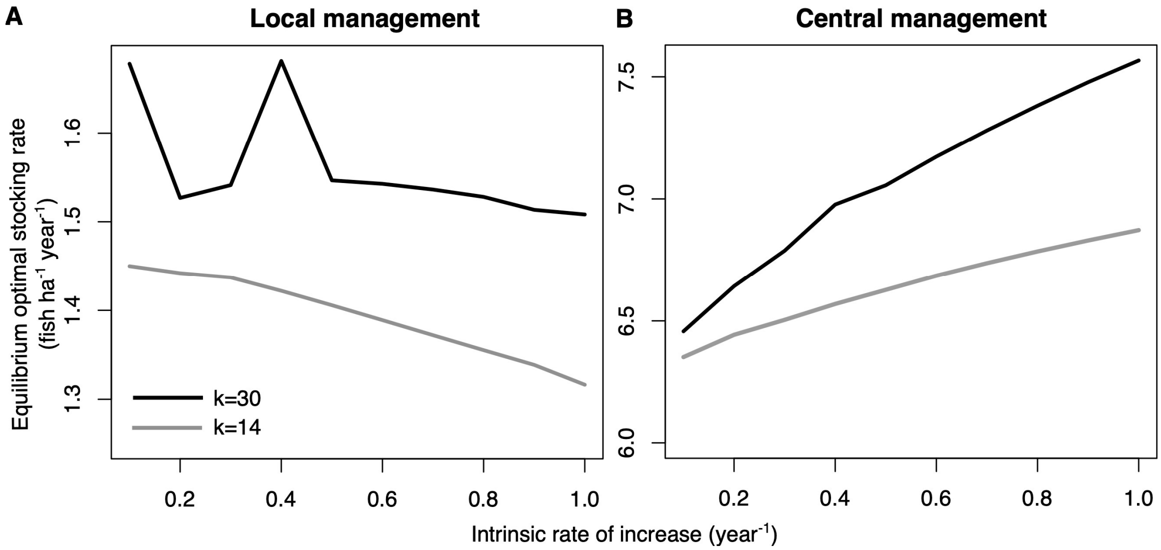

Figure A1.2. Optimal stocking rates for high (black) and low (gray) carrying capacity as a function of the intrinsic rate of increase of the fish population when stocking is conducted by (A) local and (B) centralized management.

Figure A1.3

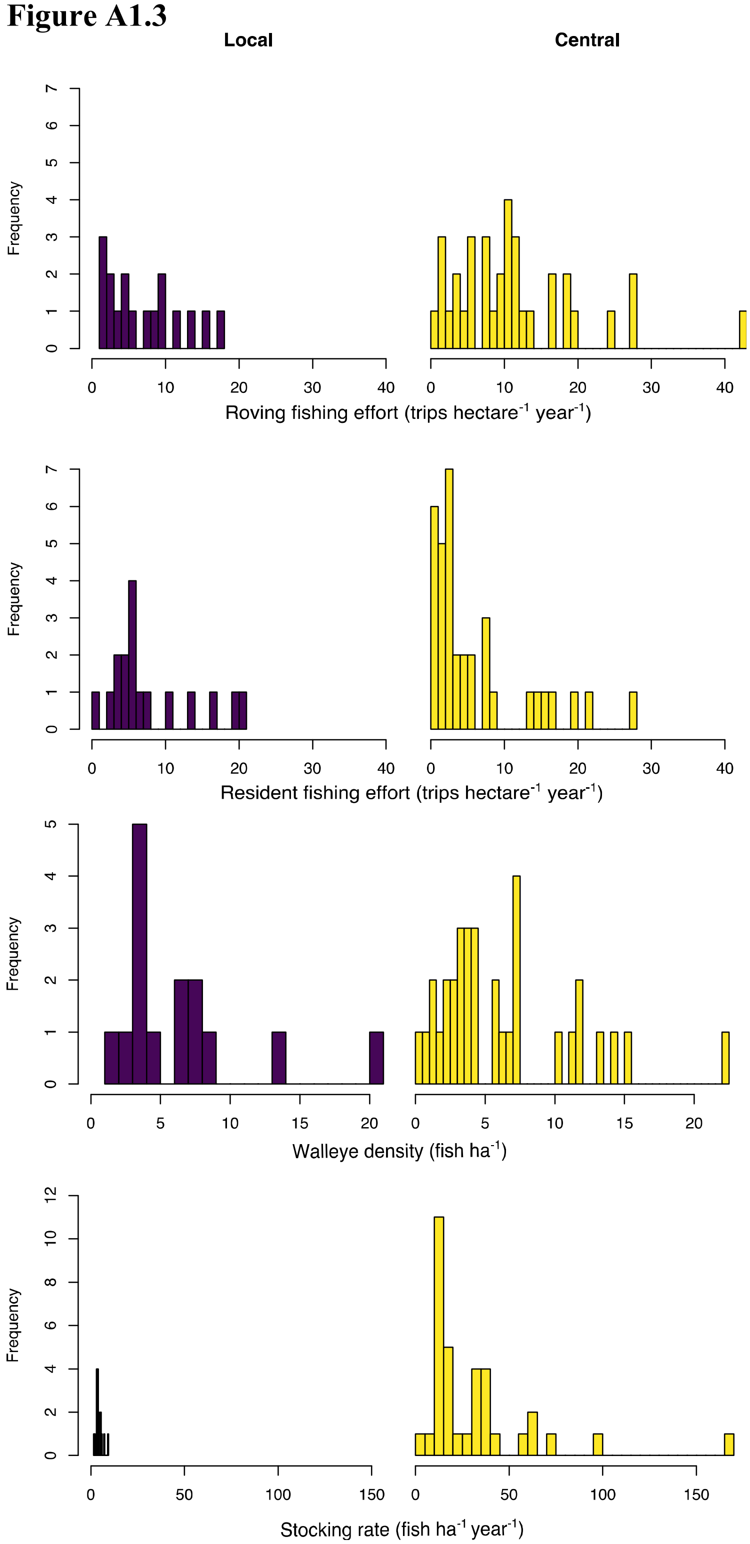

Figure A1.3. Frequency distributions of roving and resident angler effort, walleye population densities, and local and centralized stocking rates of walleye in 46 lakes in Vilas and Oneida counties, northern Wisconsin, USA. Data from Wisconsin Department of Natural Resources (DNR 2019).