

Social-ecological interactions, management panaceas, and the future of wild fish populations

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We explored the social and ecological outcomes associated with emergence of a management panacea designed to govern a stochastic renewable natural resource. To that end, we constructed a model of a coupled social-ecological system of recreational fisheries in which a manager supports naturally fluctuating stocks by stocking fish in response to harvest-driven satisfaction of resource users. The realistic assumption of users remembering past harvest experiences when exploiting a stochastically fluctuating fish population facilitates the emergence of a stocking-based management panacea over time. The social benefits of panacea formation involve dampening natural population fluctuations and generating stability of user satisfaction. It also maintains the resource but promotes the eventual replacement of wild fish by hatchery-descended fish. Our analyses show this outcome is particularly likely when hatchery-descended fish are reasonably fit (e.g., characterized by similar survival relative to wild fish) and/or when natural recruitment of the wild population is low (e.g., attributable to habitat deterioration), which leaves the wild population with little buffer against competition by stocked fish. The potential for release-based panacea formation is particularly likely under user-based management regimes and should be common in a range of social-ecological systems (e.g., fisheries, forestry), whenever user groups are entitled to engage in release or replanting strategies. The net result will be the preservation of a renewable resource through user-based incentives, but the once natural populations are likely to be altered and to host nonnative genotypes. This risks other ecosystem services and the future of wild populations.

stocking panacea | wild population collapse | angler satisfaction | social-ecological model | cultural ecosystem service

A panacea refers to a blueprint for a single type of governance (e.g., private property) or management action [e.g., release of cultured organisms to restore declining natural stocks (1)] that is applied across a variety of social-ecological (SE) contexts (2–4). Assuming they help deal with complex resource-management problems, many decision makers and stakeholders advocate for, and subsequently apply, a certain panacea across situations (2, 4). Broadly prescribed solutions to complex problems are usually problematic (2, 3, 5), but more work is needed to understand the causes and consequences of panaceas for coupled social-ecological systems (SESs), for theory development and to gauge solutions (2, 5). Integrated models constitute a tool to understand further the importance of feedbacks between humans and nature in driving emergent properties of SESs, including formation of management panaceas and associated outcomes, such as overuse, loss of natural resources, or erosion of system resilience (2, 3). Such understanding is ultimately needed for developing sustainable resource-management policies, which are to remain flexible and adaptive to change (2, 3, 6).

Against this background, our objectives are, first, to construct a conceptually realistic and empirically informed SE model of recreational fisheries to study conditions that promote the emergence of fish stocking as a management panacea in the face of natural stochasticity and, second, to explore the long-term con-

sequences of stocking panacea formation for both the managed wild population and the social system. Stocking, defined here as the repeated injection of juvenile fish from various sources (mainly hatchery-bred offspring from hatchery or wild spawners) to support wild fish populations (7, 8), is a common management practice in fisheries involving billions of individuals released annually across the world (7, 9). Stocking is perceived by many as the most obvious solution to declining populations (10, 11), but conservation biologists increasingly warn against unintended and often irreversible repercussions for aquatic biodiversity, ranging from genetic to community scales (e.g., 1, 12–14). Therefore, understanding the evolution of stocking as a panacea-like management tool in the coupled SES of recreational fisheries and studying its impacts on wild fish populations are globally relevant (15), particularly because in many industrialized countries, fishing for recreational rather than commercial or subsistence purposes constitutes the dominant use of wild freshwater fish populations (16).

Recreational fisheries are governed using a diversity of property-rights regimes, ranging from public property in North America to private property in much of Europe (17, 18). Irrespective of the property rights regime, normative pressure exerted by resource users (e.g., anglers) on managers to maintain stocks in the face of exploitation and other threats influences management decisions, such as stocking (10, 18, 19). Peer pressure may be particularly direct and intense under the private rights regime, where managers usually operate voluntarily in the interest of the angler constituency (e.g., in angling clubs and associations) as leaseholders of fisheries in central Europe (17). Indeed, semi-structured interviews with numerous recreational fisheries management boards in German angling clubs revealed that many water bodies managed by them were regularly stocked and that social norms exerted by anglers affected stocking decisions (*SI Text* and *Table S1*). These interviews also revealed that the degree of peer pressure for fish stocking on managers depended on angler satisfaction, which is strongly catch/harvest-dependent across most angler groups (20). Angler satisfaction may be affected by past catch/harvest experiences and the resulting expectations about future rewards (21). Natural fish stocks usually exhibit large between-year fluctuations in recruitment (22), which has an impact on angler catch/harvest levels and angler satisfaction. The dynamic interplay between naturally fluctuating resources, satisfaction, and angler norms for adjusting management intervention may constitute a mechanistic explanation driving the development of a fish stocking panacea in the recreational fishing SES. Although possibly maintaining or stabilizing angler satisfaction (compare with

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23), the stocking panacea may have negative consequences for wild fish populations, thus creating relevant tradeoffs between wild fish conservation objectives and angler welfare. We test this prediction using an integrated SE model. Although the SE interactions and feedbacks in our model have been informed by properties of recreational fisheries, we contend the mechanisms leading to panacea formation are more general and are present in other user- and incentive-based natural resource governance systems, such as community-based hunting and forestry management systems.

Model Overview

Our model incorporated the key interactions between anglers, a managed fish population, and a management response involving stocking, as formalized in a generic coupled SES of recreational fisheries (Fig. 1). The model was structured following a newly developed framework for the analysis of SESs (4) distinguishing stochastic natural resource units (fish) striving in a resource system (e.g., a lake) that is exploited by local resource users (anglers) and affected by management institutions and the governance system (fisheries manager responding to angler-formed norms for management interventions). The social submodel represented two salient social-psychological processes inherent in many SESs: (i) reward-seeking behavior by users (i.e., angler satisfaction) and (ii) a management response (i.e., stocking) to feedback signals about the resource state in terms of user (dis)satisfaction with current rewards (i.e., harvest). Satisfaction by anglers in our model was formed in light of past reward levels [as is typical in human reinforcement learning (24)] and was conceptualized as the difference between expected and realized harvest (20, 25). Actual harvest levels were affected by natural stochastic fish population fluctuations (26). Annual harvest expectation in-

tegrated remembered past fishing rewards based on a default memory model (MM), where past harvest levels were forgotten based on a standard forgetting rate (27, 28). Humans tend to recall particularly emotionally rewarding stimuli from the past [so-called positivity effect in attention and memory (29)] when judging current rewards (e.g., harvest levels); thus, a second plausible variant memory model (MM*) was also tested, where exceptional fishing successes in terms of harvest were weighed more heavily (*SI Text*). To represent fisheries managers reacting to social norms exerted by (dis)satisfied anglers, the number of fish stocked annually was determined by a hypothetical manager responding to an aggregate level of angler satisfaction. Accordingly, stocking decisions followed a default stocking decision model (SDM), where fish stocking numbers stayed constant when angler satisfaction was neutral, increased when it was negative, and decreased when it was positive. Again, a second plausible scenario, the variant stocking decision model (SDM*), with stocking numbers remaining constant at positive satisfaction levels, is presented in *SI Text*.

The ecological submodel consisted of a generic single species, stage-structured model of a stocking-enhanced and recreational angling-exploited fish population (Fig. 1). Similar to the study by Lorenzen (7), the model separately tracked the wild and stocking-descended subpopulations of the same hypothetical fish species under varying stocking rates (determined by angler satisfaction dynamics) with density-dependent ecological competition and interbreeding between wild and hatchery fish (Fig. 1). This allowed examination of stocking impacts both in terms of density dependence (7) and hybridization-induced fitness depression (30). The stocking-descended subpopulation (for simplicity, hereafter called hatchery fish) consisted of recently stocked young of the year (YOY), a life stage often stocked in recreational fisheries (7, 8), and naturally spawned hatchery fish. Progeny from both pure hatchery and hatchery-wild crosses were assigned to the hatchery subpopulation to account for the often-reported reduced fitness in hatchery fish or hybrids relative to wild fish (30, 31). Prestocking early YOY numbers of each subpopulation were determined by a Ricker stock-recruitment function (22), resulting in density-dependent survival regulated by ecological competition, as is typical in nature (7, 32). A recruitment deviate added stochasticity that propagated through later life stages, resulting in natural population fluctuation (26). Stocking was subsequently conducted at the early YOY stage, resulting in a second density-dependent regulation through competition between stocked and naturally spawned YOY directly after stocking (7). Surviving late juveniles and adults were regulated by density-independent factors, as is common in nature (7, 32). Only adults were subjected to harvesting, mimicking exploitation using minimum-sized limits larger than size at maturation (16). The biological submodel was parameterized for a generic fish species and informed by meta-analyses on stock-recruitment relationships across important recreationally exploited taxa ([Table S2](#)).

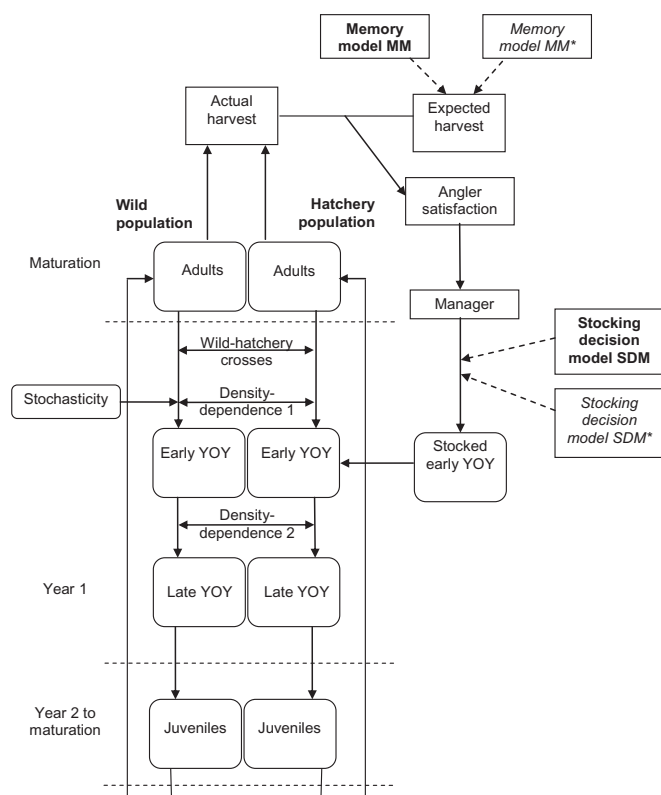


Fig. 1. Schematic representation of the life cycle of the wild and hatchery fish subpopulations and their interactions. The default decision models are in bold. YOY, young-of-the-year. Details are provided in *Methods*, and parameters are defined in [Table S2](#).

Results and Discussion

The interplay of social dynamics and resource stochasticity in our model affected the formation of a stocking-based management panacea, along with its effect on human well-being and potential repercussions for the wild fish population (Fig. 2). In particular, users (here, anglers) remembering past harvest experiences when exploiting a stochastically fluctuating renewable resource (here, fish) facilitated the emergence of a management panacea (here, stocking) over time. An example from our base scenario (MM/SDM; parameters are shown in [Table S2](#)) is visualized in Fig. 2 for a reasonably productive and stochastically varying wild fish population under conditions of stocking reasonably fit (i.e., relative survival of stocked to wild fish of 0.9) fish of the same species. At an unrealistically high ($\lambda = 0.9$) or medium ($\lambda = 0.5$) forgetting rate of past harvest levels by anglers (Fig. 2, *Left and Center*), fairly

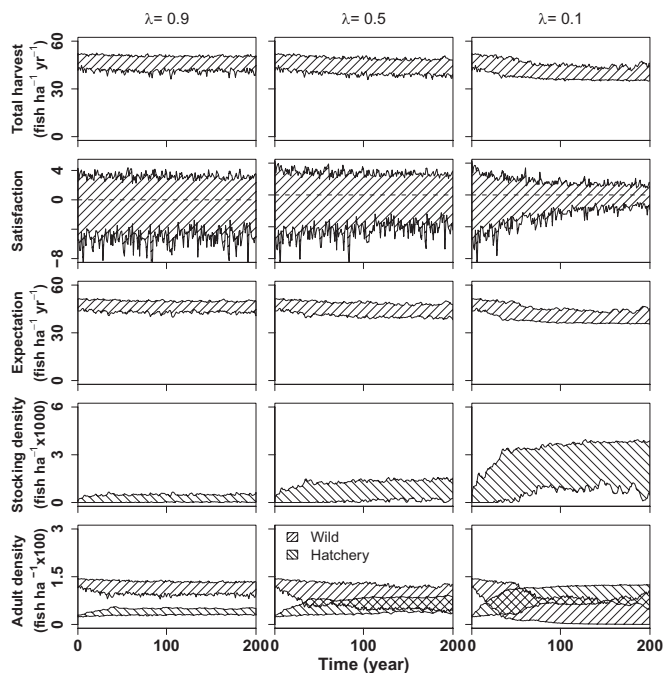


Fig. 2. Influence of the forgetting rate of past harvest (λ) for determining total harvest, angler satisfaction, expected harvest, stocking density, and adult density of wild and hatchery-descended subpopulations under the MM and the SDM. The range of 100 model runs over 200 y is shown for three levels of λ . A low λ means that all previous years are equally remembered; at a high λ , only the last few years are taken into account. Maximum memory length of anglers is fixed at 15 y, and the stocking response to angler satisfaction is set at 50 fish ha^{-1} .

low stocking rates emerged through SE interactions over time and the wild component was maintained over all 200 simulated years. Under the more realistic assumption of anglers remembering all past experiences up to 15 y with nearly equal clarity ($\lambda = 0.1$) and basing future harvest expectation on them (Fig. 2, Right), regular and high annual stocking rates were developed as a panacea. The main mechanism for panacea formation was the initially highly variable and often negative angler satisfaction attributable to stochastic natural recruitment (Fig. 2), which then stimulated the manager to increase stocking rates. Coincident with panacea development, angler expectation and satisfaction declined over time, but satisfaction variability was reduced because of the dampening effect of stocking on top of stochastic natural recruitment (Fig. 2), providing a substantial social benefit attributable to increased stability. Increased stocking over time maintained the exploitable resource but had ecological consequences by changing the composition of the fish population toward a greater proportion of hatchery fish, eventually even resulting in extirpation of the wild population in as few as 100 y (Fig. 2) under certain parameter settings (Fig. 3 and Figs. S1 and S2). Such replacement was not caused by development of unrealistically high stocking densities relative to wild recruitment in our model. For example, when the wild population started to collapse in the base simulation (Fig. 2), the median stocking rate was only about 60% of natural recruitment levels (Table S3), which is similar to ratios of stocked to natural densities reported in various recreationally important freshwater species (Table S4). Put differently, our model predicted the development of stocking ratios that aligned with empirical values reported in the literature, suggesting the model predictions reflect realistic situations.

To examine the conditions of a self-organized SES of recreational fisheries that affect the potentially most serious ecological outcome of stocking panacea formation, replacement of wild fish

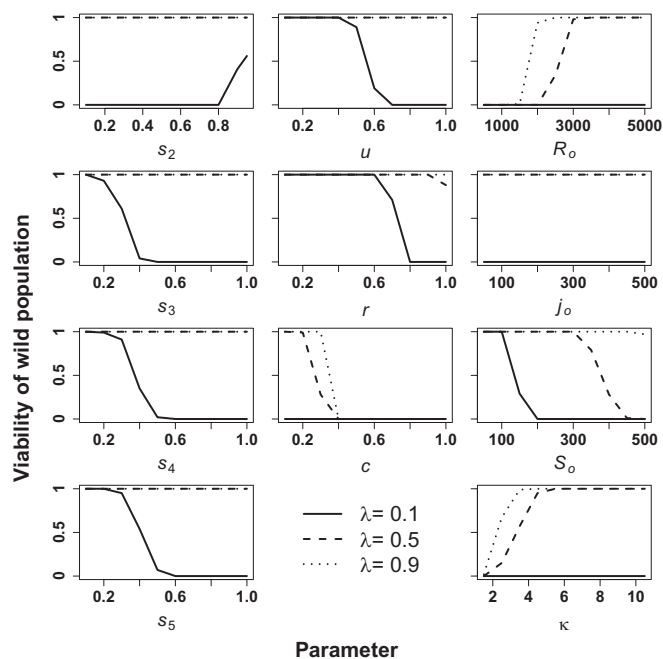


Fig. 3. Viability of the wild subpopulation across a range of values for each parameter and three forgetting rates of past harvest levels by anglers (λ) under the MM and the SDM. Maximum memory length is fixed at 15 y, and parameters are defined in Table S2.

by hatchery fish, fully, we explored population viability against key parameter and structural uncertainties. When forgetting rates of past harvest levels by anglers were unrealistically high or intermediate ($\lambda = 0.9$ or 0.5), the wild stock's viability (definitions provided in SI Text) was largely insensitive to variation in most parameters and no replacement of wild fish occurred as in the base simulation (Figs. 2 and 3 and Figs. S1 and S2). At a more realistic low forgetting rate, a systematic pattern of rapid shifts from viable to unviable wild populations emerged for most biological model parameters (Fig. 3 and Fig. S2). In the face of panacea formation, wild fish persisted only at low relative survival (i.e., fitness) of hatchery fish relative to wild fish (as represented by parameters s_3 , s_4 , and s_5) or at low immediate poststocking survival (u) and poor relative recruitment (r) of stocked fish (Fig. 3). Because the survival and reproductive success of stocked fish are often low in the wild (30), this may help to explain why wild genotypes are still found in many systems despite a long stocking history (examples are provided in Table S5). The viability of the wild population was also sensitive to the proportion of wild fish crossing with hatchery fish (c). There was also a strong impact of natural population productivity parameters, including the density of unfished early YOY (R_o), unfished spawners (S_o), and the compensation ratio (κ), in affecting wild population viabilities. Low S_o and high R_o and κ indicate a highly productive wild population, meaning adult abundance is relatively insensitive to harvest or competition stress attributable to relatively high reproductive and juvenile survival rates, and such conditions favored the viability of the wild population (Fig. 3). An interaction between population productivity parameters and relative fitness of stocked fish also existed, demonstrating that as fitness of stocked fish increased, the wild population must be increasingly productive to be maintained (SI Text and Fig. S2). These results suggest that conservation of the wild fish population is possible in nature but that shifts to hatchery fish-dominated states are equally plausible depending on a suite of factors (Fig. 3 and Figs. S1 and S2), which is in agreement with the vulnerability of other

SESs to slowly changing variables that drive system dynamics (6, 33). The possibility of wild fish replacement was found to be robust against the choice of the memory (i.e., MM/MM*) and stocking decision (i.e., SDM/SDM*) models (Figs. S3–S5).

Our model suggests that the SES of recreational fisheries is prone to stocking developing as a management panacea as a result of the reward-seeking behavior of anglers in a stochastic world and corresponding social dynamics between anglers and managers. This panacea will likely maintain an exploitable resource and stabilize angler satisfaction in the long term, which may be positively perceived from a fisheries perspective (23) and considered a success of incentive-driven resource conservation by fisher groups (34). However, the potential of stocked fish interbreeding with wild fish or otherwise impairing them through ecological competition is real and widespread (1), indicating tradeoffs between stability of user well-being and wild population conservation objectives. Such tradeoffs have been similarly reported from forestry systems (35) and likely take place in other resource-management contexts (e.g., hunting), where technical fixes, such as planting trees or releasing animals, can be used by local user groups to counter declining resources (1). From a management and governance perspective, the problem is particularly insidious under user-based management regimes, because the general willingness of local users to preserve, restore, and enhance the resource base through releases may indeed help conserve the stock; however, as our model has shown, it may also become a serious issue from a genetic conservation perspective if alien genotypes are used in supportive plantings (1). This is particularly problematic if users have a different awareness of the risk associated with introducing alien genotypes into a given ecosystem, as is often the case (15).

Our model suggests continuous stocking on top of naturally reproducing populations may eventually extirpate wild populations (Fig. 2), yet we acknowledge that the actual impacts of a stocking panacea on wild fish stocks will depend on various biological (Fig. 3 and Fig. S6) and social factors (Table S5), many of which were outside the scope of our model. The most crucial aspects, however, were explicitly or implicitly inherent in our model formulation, such as the importance of natural productivity providing a buffer against stocking impacts and stocking success being a function of the relative fitness of stocked fish (Fig. 3 and Fig. S2). The share of cultured fish in wild stocks after continued stocking has been empirically found to vary from near zero to almost complete displacement of wild populations (Table S5). Near-complete replacement of the wild stock seems to be especially likely in populations experiencing habitat impairments (36) (Table S5), which have an impact on population production. This finding was also present in our sensitivity analyses, because full replacement of the wild stock was most likely when natural productivity was low (which is equivalent to impaired natural recruitment attributable to habitat loss) (37) (Fig. 3 and Fig. S2). Many natural water bodies have been impaired by habitat changes (16) (Table S5), increasing the likelihood of wild population replacement after formation of stocking as a panacea. Almost ironically, habitat impairments often motivate stocking programs (8, 11), such that stocking practices may actually put an additional burden on already threatened or declining wild stocks. Generally, our prediction that long-term replacement of wild by planted organisms can occur in a self-organized SES, such as recreational fisheries, forestry, or hunting, should be considered a worst-case yet plausible scenario. Our findings also suggest that the cases of observed replacement might increase over time because they may take at least 100 y to materialize (Fig. 2), and intensive stocking has taken place for less than a century in much of the world. Thus, in many cases, replacement of wild fish by stocking-descendant fish may either not happen because of stocking with “unfit” fish (i.e., low relative survival in the wild) or because the natural population exhibits a high degree of resiliency (i.e., high pro-

ductivity). Alternatively, replacement may not have been recognized yet because of the lack of genetic tools or samples from the unstocked past (38). However, our findings should not be misinterpreted as a call against all forms of stocking, because under particular conditions (e.g., following irreversible habitat destruction or in artificial fisheries), stocking can be the only tool to maintain stocks and fisheries (37, 39).

Our prediction that the stocking panacea can lead to replacement of wild fish may be criticized because stocking decisions in our model directly and exclusively tracked angler satisfaction. Actual stocking decisions will often take into account a variety of factors, and will therefore be more cautious than in our base simulation, reducing the likelihood of impact on the wild fish stock (Fig. S7). Indeed, the German angling clubs we surveyed acknowledged a variety of factors influencing stocking decisions. In all clubs, however, angler desires were important determinants of stocking (Table S1), and angler pressure has similarly been found to influence decisions by North American management agencies to stock fish (19). Therefore, despite the simplification of actual stocking decision making in our model, emergence of stocking as a panacea in response to social norms reflecting reward expectations may still be a reasonably robust prediction and explain the widespread use of cultured fish in fisheries worldwide (1, 7, 8, 11). There is room for testing alternative specifications and processes and for expanding the model to represent more comprehensive decision-making scenarios, but that was not our purpose. We aimed to ask generally how memory of the past and reward-seeking behavior by humans act in a stochastic world to form management panaceas that may unwillingly prove deleterious for wild populations. Based on our model, we contend that one of the most important mechanisms explaining this feature is the interaction of social and ecological systems when fraught with natural stochasticity, and the human tendency of striving to control variability in the face of uncertainty. Our results should thus be viewed as a mechanistic approach to explain why the specific management panacea of releasing animals (or plants) is to be expected across many SESs, particularly those where local users are empowered to influence management decisions involving releasing organisms—a governance panacea often believed to result in sustainable trajectories (34, 35). Outcomes of such a panacea, however, include replacement of wild fish by stocking-descended fish, which often represent alien genotypes from different localities (1, 40), and homogenization of wild gene pools attributable to interbreeding (Table S5). Such outcomes are usually regarded as socially unacceptable from a biodiversity conservation perspective (15) and can penalize the stability of yields in the long term (41) (Fig. S8), despite providing obvious social benefits through dampening of natural variability and increased stability of user satisfaction.

The susceptibility of SESs to panaceas is a reaction to the difficulty of decision making under pervasive uncertainty (3). Panaceas are often easier to communicate to resource users than more complex approaches, and people tend to trust a simpler message over a more complex message (42). Often, as in the case of stocking (19), a panacea has been heavily relied on and advocated for by managers over extended periods of time, and it is then difficult to engage in novel solutions. Some have suggested that improved monitoring information on the population status and the fate of stocked fish might increase the adaptive capacity of fisheries governance systems to deal sustainably with ecological systems in the face of nonlinearity and stochasticity (43, 44). Monitoring, however, does not necessarily avoid the stocking panacea for two reasons. First, as shown in our model, stocking dampens natural stochasticity and stabilizes angler satisfaction, the main cultural ecosystem service sought by users. In the absence of fishery-independent monitoring information (e.g., information on true fish stock size and composition) and when the system variables monitored change slowly, panacea development

is difficult to be avoided even in the presence of monitoring and adaptive learning (2). Second, improved monitoring will only result in more cautious stocking if anglers or managers appreciate preservation of locally adapted populations as generating more aggregate utility than the benefits generated by stabilized harvest and angler satisfaction. In many recreational fisheries, this is probably not the case (45).

To conclude, although being specific to recreational fisheries, our analysis shows that the combination of generic psychological mechanisms and social processes, as well as the feedbacks between nature and humans in a stochastic world, helps in understanding the emergence of management panaceas that, in turn, drive the sustainability of a SES. The stocking panacea generates obvious benefits (i.e., preservation of the exploited stock, stabilized cultural ecosystem service), although potentially threatening conservation of the wild population in the long term. Stakeholders and policy makers interested in developing more adaptive and risk-averse stocking policies face the issue of confronting a complex policy system that involves multiple actors, institutions, conflicting goals, and competing notions of the problem (15). To achieve change and move to a more adaptive stocking policy, learning among coalitions of actors with different notions of the problem is important (15). This can best be achieved by redistributing authority among local level user organizations and higher governance levels (46). The resulting linkages may then help in dealing with multiple objectives by using multiple knowledge systems in the context of panacea management (46), with a view toward avoiding panacea development and facilitating development of adaptive management practices.

Methods

Ecological Submodel: Dynamics of a Stocking-Enhanced Fish Population. The density in the early YOY stage is based on the number of adults in each subpopulation, and survival is regulated by density-dependent competition as:

$$\begin{aligned} j_{1,1} &= (1-c)z_1 \alpha \cdot e^{-\beta(z_1+r \cdot z_2)+\omega} \\ j_{1,2} &= (c \cdot z_1 + r \cdot z_2) \alpha \cdot e^{-\beta(z_1+r \cdot z_2)+\omega}, \end{aligned} \tag{1}$$

where $j_{1,g}$ is density (fish-ha⁻¹) of early YOY produced for subpopulation g (wild = 1, hatchery = 2); c is the proportion of wild adults that interbreed with hatchery adults, producing offspring considered to be part of the hatchery subpopulation [attributable to reduced fitness of hybrids (7, 30, 37)]; $z_g(t)$ is the density of adults from subpopulation g in year t ; α is the recruits per spawner as spawner density approaches zero, β is the inverse of the density of spawners that produce the maximum density of recruits; and r is the relative recruitment success of hatchery fish (7, 37) (Table S2). This Ricker type stock-recruitment function (22) results in overcompensation at high density and is common in many recreationally important freshwater species (47, 48), accounting for competition among spawning adults for spawning sites, among early YOY for settling sites and intercohort cannibalism (22). The normally distributed recruitment deviate (ω) is set with an SD of 0.58 (Table S2).

Stocking is assumed to take place at the early YOY stage. Poststocking density-dependent survival to the late YOY stage is characterized using a Beverton–Holt type model (22):

$$x_g = \frac{r_o \cdot j_{1,g}}{1 + k(j_{1,1} + j_{1,2} + uS)}, \tag{2}$$

where r_o is the maximum survival rate and the carrying capacity of recruits is given by r_o/k . The addition of uS in this model represents the competitive impact of stocked hatchery YOY fish (5) that immediately survive following stocking, given a stocking survival rate u . Initial stocking mortality (represented by u) is characteristic of most stocking events and is often attributed to, for example, poor foraging efficiency, underdeveloped predator avoidance behavior, or transportation-induced poststocking mortality (49). The use of a Beverton–Holt type survival in Eq. 2 implies that late YOY experience less extreme density-dependent mortality at high density, which has been observed in several important recreationally fished species (32, 47, 48).

Combining Eqs. 1 and 2 provides the density (fish-ha⁻¹) of wild (x_1) and hatchery (x_2) late YOY at the end of the first year as:

$$\begin{aligned} x_{1,t+1} &= \frac{r_o [(1-c)z_{1,t}R]}{1 + k[R(z_{1,t} + r \cdot z_{2,t}) + uS]} \\ x_{2,t+1} &= \frac{r_o s_3 [(c \cdot z_{1,t} + r \cdot z_{2,t})R + uS]}{1 + k[R(z_{1,t} + r \cdot z_{2,t}) + uS]}, \end{aligned} \tag{3}$$

where R is the survival term from Eq. 1 and s_3 is the annual survival of hatchery fish relative to wild fish from the early to late YOY stage. Note that s_3 represents a fitness parameter that allows hatchery fish to perform worse than wild fish (7, 30).

Juvenile wild fish and hatchery fish (y_1 and y_2) that survive the first year of life experience constant survival and eventually mature at rate μ :

$$\begin{aligned} y_{1,t+1} &= s_1 [x_{1,t} + (1-\mu)y_{1,t}] \\ y_{2,t+1} &= s_4 s_1 [x_{2,t} + (1-\mu)y_{2,t}], \end{aligned} \tag{4}$$

where s_1 is the annual survival rate of juvenile fish and s_4 is the annual survival rate of hatchery juvenile fish relative to wild juvenile fish, again interpreted as a relative fitness parameter (7). Adult wild fish and hatchery fish (z_1 and z_2) are represented as:

$$\begin{aligned} z_{1,t+1} &= s_2 [\mu \cdot y_{1,t} + (1-h)z_{1,t}] \\ z_{2,t+1} &= s_5 s_2 [\mu \cdot y_{2,t} + (1-h)z_{2,t}], \end{aligned} \tag{5}$$

where s_2 is the annual adult survival rate, s_5 is the annual survival rate of hatchery adults relative to wild adults, and h is the annual harvest rate.

To parameterize the biological model, we defined the stock-recruitment function for a prototypical freshwater fish population targeted by anglers. We parameterized our stock-recruitment functions using unfished reference points and steepness, defined as the proportion of unfished recruitment when spawning stock is reduced to 20% of equilibrium unfished levels (50). Estimates of steepness from Salmonidae, Esocidae, and Percidae by Myers et al. (50) provided an average value of 0.63, which was converted to a compensation ratio (κ) to give $\kappa = 6.84$. From this, α and β in Eq. 1 can be estimated (22) as:

$$\alpha = \kappa \frac{R_o}{S_o}, \tag{6}$$

$$\beta = \ln\left(\frac{\alpha S_o}{R_o}\right) / S_o, \tag{7}$$

where R_o is the unfished density of recruits at an unfished spawner density, S_o . A similar procedure can be used to estimate r_o of Eq. 2, by replacing R_o and S_o in Eq. 6 with j_o and R_o , respectively, where j_o is the number of early YOY produced in an unfished population. The parameter k from Eq. 2 is estimated as (22):

$$k = \frac{(r_o \frac{R_o}{j_o} - 1)}{R_o}. \tag{8}$$

Given fixed population parameters and assuming equilibrium conditions when unfished (omitting stochastic recruitment), the first mortality parameter, s_1 , can be solved directly.

Parameters used to describe the biology of the modeled fish population are compiled in Table S2; a robustness analysis is presented in SI Text.

Social Submodel: Human Stocking Decision-Making Dynamics. Average angler satisfaction (U_t) was assumed as the difference between average actual angling success (represented by actual harvest, H_t^{act}) and the angling success expected by the angler population (i.e., harvest, H_t^{exp}) in year t (Fig. 1). Actual harvest from the biological model above is simply the harvest rate times the density of vulnerable (i.e., adult) fish from both wild and hatchery fish. Expected harvest in year t is related to past harvest using the MM, defined as:

$$H_t^{exp} = \frac{\sum_{i=1}^T [e^{-\lambda i} H_{t-i}^{act}]}{\sum_{i=1}^T e^{-\lambda i}}, \tag{9}$$

where λ is the relative importance of past harvest for determining current harvest expectations (i.e., forgetting rate) and i is a sequence of previous years up to a maximum memory about previous harvest of T years. In Eq. 9, λ can be any positive number: A value near 0 effectively weights all years

equally (i.e., all previous years are equally remembered), and a value greater than 2 effectively ignores all harvest before the past year.

When fishery managers decide on whether to stock and how much to stock based on satisfaction of the angler constituency and associated peer pressure (Fig. 1), the stocking density can be assumed to vary each year as $S_{t+1} = \max(0, S_t - dU_t)$, where d is the rate at which (dis)satisfaction leads to changes in stocking. This is referred to as the SDM.

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- Laikre L, Schwartz MK, Waples RS, Ryman N, Group TGW; GeM Working Group (2010) Compromising genetic diversity in the wild: Unmonitored large-scale release of plants and animals. *Trends Ecol Evol* 25:520–529.
- Brock WA, Carpenter SR (2007) Panaceas and diversification of environmental policy. *Proc Natl Acad Sci USA* 104:15206–15211.
- Anderies JM, Rodriguez AA, Janssen MA, Cifdaloz O (2007) Panaceas, uncertainty, and the robust control framework in sustainability science. *Proc Natl Acad Sci USA* 104:15194–15199.
- Ostrom E, Janssen MA, Anderies JM (2007) Going beyond panaceas. *Proc Natl Acad Sci USA* 104:15176–15178.
- Ostrom E (2007) A diagnostic approach for going beyond panaceas. *Proc Natl Acad Sci USA* 104:15181–15187.
- Carpenter SR, Brock WA (2004) Spatial complexity, resilience, and policy diversity: Fishing on lake-rich landscapes. *Ecology and Society* 9.
- Lorenzen K (2005) Population dynamics and potential of fisheries stock enhancement: Practical theory for assessment and policy analysis. *Philos Trans R Soc Lond B Biol Sci* 360:171–189.
- Cowx IG (1994) Stocking strategies. *Fish Manag Ecol* 1:15–30.
- Halverson MA (2008) Stocking trends: A quantitative review of governmental fish stocking in the United States, 1931 to 2004. *Fisheries (Bethesda, MD)* 33:69–75.
- Arlinghaus R, Mehner T (2005) Determinants of management preferences of recreational anglers in Germany: Habitat management versus fish stocking. *Limnologica* 35:1561–1562.
- Meffe GK (1992) Techno-arrogance and the halfway technologies: Salmon hatcheries on the Pacific coast of North America. *Conserv Biol* 6:350–354.
- Holmlund CM, Hammer M (2004) Effects of fish stocking on ecosystem services: An overview and case study using the Stockholm Archipelago. *Environ Manage* 33:799–820.
- Eby LA, Roach WJ, Crowder LB, Stanford JA (2006) Effects of stocking-up freshwater food webs. *Trends Ecol Evol* 21:576–584.
- Lewin W-C, Arlinghaus R, Mehner T (2006) Documented and potential biological impacts of recreational fishing: Insights for management and conservation. *Rev Fish Sci* 14:305–367.
- Sandstrom A (2010) Institutional and substantial uncertainty—Explaining the lack of adaptability in fish stocking policy. *Mar Policy* 34:1357–1365.
- Arlinghaus R, Mehner T, Cowx IG (2002) Reconciling traditional inland fisheries management and sustainability in industrialized countries, with emphasis on Europe. *Fish Fish* 3:261–316.
- Arlinghaus R (2006) Overcoming human obstacles to conservation of recreational fishery resources, with emphasis on central Europe. *Environ Conserv* 33:46–59.
- Daedlow K, Beard DTJ, Arlinghaus R (in press) *A Property Rights-Based View on Management of Inland Recreational Fisheries: Contrasting Common and Public Fishing Right Regimes in Germany and the U.S.A.* (American Fisheries Society Symposium, Bethesda, MD).
- Jackson JR, Buxrucker JC, Willis DW (2004) *Propagated Fish in Resource Management*, American Fisheries Society Symposium 44, eds Nickum MJ, Mazik PM, Nickum JG, MacKinlay DD (American Fisheries Society Symposium, Bethesda, MD), pp 121–138.
- Arlinghaus R (2006) On the apparently striking disconnect between motivation and satisfaction in recreational fishing: The case of catch orientation of German anglers. *N Am J Fish Manage* 26:592–605.
- Gale RP (1987) Resource miracles and rising expectations: A challenge to fishery managers. *Fisheries (Bethesda, MD)* 12:8–13.
- Walters CJ, Martell SJD (2004) *Fisheries Ecology and Management* (Princeton Univ Press, Princeton).
- Essington TE (2010) Ecological indicators display reduced variation in North American catch share fisheries. *Proc Natl Acad Sci USA* 107:754–759.
- Sutton RS, Barto AG (1998) *Reinforcement Learning: An Introduction* (MIT Press, Cambridge, MA).
- Arlinghaus R (2004) Recreational fisheries in Germany—A social and economic analysis. *Berichte des IGB* 18:1–160.
- Jager W, Janssen MA, Vlek CAJ (2002) How uncertainty stimulates overharvesting in a resource dilemma: Three process explanations. *J Environ Psychol* 22:247–263.
- Evrev I, Roth AE (1998) Predicting how people play games: Reinforcement learning in experimental games with unique mixed strategy equilibria. *Am Econ Rev* 88:848–881.
- Ebbinghaus H (1885) *Memory: A Contribution to Experimental Psychology* (Translated from German) (Teachers College, Columbia University, New York).
- Mather M, Carstensen LL (2005) Aging and motivated cognition: The positivity effect in attention and memory. *Trends Cogn Sci* 9:496–502.
- Araki H, Berekian BA, Ford MJ, Blouin MS (2008) Fitness of hatchery-reared salmonids in the wild. *Evolutionary Applications* 1:342–355.
- Chilcote MW, Goodson KW, Falcu MR (2011) Reduced recruitment performance in natural populations of anadromous salmonids associated with hatchery-reared fish. *Can J Fish Aquat Sci* 68:511–522.
- Post JR, Parkinson EA, Johnston NT (1999) Density-dependent processes in structured fish populations: Interaction strengths in whole-lake experiments. *Ecol Monogr* 69:155–175.
- Biggs R, Carpenter SR, Brock WA (2009) Turning back from the brink: Detecting an impending regime shift in time to avert it. *Proc Natl Acad Sci USA* 106:826–831.
- Gutiérrez NL, Hilborn R, Defeo O (2011) Leadership, social capital and incentives promote successful fisheries. *Nature* 470:386–389.
- Persha L, Agrawal A, Chhatre A (2011) Social and ecological synergy: Local rulemaking, forest livelihoods, and biodiversity conservation. *Science* 331:1606–1608.
- Englbrecht CC, Schlieven U, Tautz D (2002) The impact of stocking on the genetic integrity of Arctic charr (*Salvelinus*) populations from the Alpine region. *Mol Ecol* 11:1017–1027.
- Rogers MW, et al. (2010) A simulation model to explore the relative value of stock enhancement versus harvest regulations for fishery sustainability. *Ecol Modell* 221:919–926.
- Hansen MM (2002) Estimating the long-term effects of stocking domesticated trout into wild brown trout (*Salmo trutta*) populations: An approach using microsatellite DNA analysis of historical and contemporary samples. *Mol Ecol* 11:1003–1015.
- Hickley P, Chare S (2004) Fisheries for non-native species in England and Wales: Angling or the environment? *Fish Manag Ecol* 11:203–212.
- Ayllon F, Martinez JL, Garcia-Vazquez E (2006) Loss of regional population structure in Atlantic salmon *Salmo salar* L., following stocking. *ICES J Mar Sci* 63:1269–1273.
- Schindler DE, et al. (2010) Population diversity and the portfolio effect in an exploited species. *Nature* 465:609–612.
- Degnbol P, et al. (2006) Painting the floor with a hammer: Technical fixes in fisheries management. *Mar Policy* 30:534–543.
- Chapin FSJ, 3rd, et al. (2010) Ecosystem stewardship: Sustainability strategies for a rapidly changing planet. *Trends Ecol Evol* 25:241–249.
- Nagendra H (2007) Drivers of reforestation in human-dominated forests. *Proc Natl Acad Sci USA* 104:15218–15223.
- Johnson BM, Arlinghaus R, Martinez PJ (2009) Are we doing all we can to stem the tide of illegal fish stocking? *Fisheries (Bethesda, MD)* 34:389–394.
- Berkes F (2007) Community-based conservation in a globalized world. *Proc Natl Acad Sci USA* 104:15188–15193.
- Johnston FD, et al. (2007) The demography of recovery of an overexploited bull trout, *Salvelinus confluentus*, population. *Can J Fish Aquat Sci* 64:113–126.
- Elliott JM (1985) Population dynamics of migratory trout, *Salmo trutta*, in a Lake District stream, 1966–83, and their implications for fisheries management. *J Fish Biol* 27(Suppl A):35–43.
- Berg S, Jorgensen J (1991) Stocking experiments with 0+ and 1+ trout par, *Salmo trutta* L., of wild and hatchery origin: 1. Post-stocking mortality and smolt yield. *J Fish Biol* 39:151–169.
- Myers RA, Bowen KG, Barrowman NJ (1999) Maximum reproductive rate of fish at low population sizes. *Can J Fish Aquat Sci* 56:2404–2419.

Supporting Information

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SI Text

Angling Club Survey Methods. Angling clubs in four purposely selected counties in northern and southern Germany were surveyed between March 2008 and May 2009 to understand the importance of stocking decisions being driven by angler desires. In both regions, we matched governance traditions of fisheries in our sampling by surveying angling clubs in West and East Germany along state borders within the same geographical areas (to control for the impact of ecological states of managed water bodies). We distinguished West and East (former German Democratic Republic) Germany because of historical differences in stocking decision-making levels within private fishing rights (1). In West Germany, angling clubs, which are the fishing rights holders, decide about stocking in club waters independent of other stakeholders or agencies. In East Germany, stocking decisions are mainly made on regional levels by angler associations, which are the legal holders of fishing rights and serve as umbrella organizations of local angling clubs. Local clubs usually express stocking needs to the respective umbrella association, and thus have an indirect influence on stocking decisions for local water bodies. With our sampling design, all available situations under private fishing rights regimes in Germany were represented. We randomly selected 10 angling clubs from the total number of clubs in each of the four selected counties. In two counties, only 9 angling clubs were willing to participate in the survey. In total, 38 angling clubs participated. All interviewees were informed about the purpose and scope of the study, and all agreed in written format to record the interviews and process the data in an anonymous form.

The survey was conducted as in-depth semistructured interviews focusing on several important contemporary management issues, such as fish stocking, access and use regulations, state of the resource, comanagement with authorities and other user groups, and general organizational matters in club culture. Interviews were combined with visits to both standing and running water bodies to obtain personal observations about managed water bodies. Moreover, the site visits served to aid recall and improve the atmosphere during the interviews. Interviews were recorded, transcribed, and content-analyzed using a predefined coding scheme containing three dimensions: (i) the characteristics of the water body (standing or flowing and natural, man-made, or artificial); (ii) the level of stocking decision making (local, angling club; regional, angler association), and (iii) the degree of angler satisfaction and angler desires influencing fish stocking decisions on the particular water body (categories: high, medium, and low). High influence of angler desires for stocking decisions encompassed quotes by the interviewee that emphasized stocking being conducted to meet angler needs and wishes directly. The medium category was coded for quotes emphasizing that stocking is conducted to meet angler desires but stocking density is related to harvest reports from diaries. Low influence by anglers for stocking decisions was coded when angler satisfaction was perceived by interviewees only as one among several variables influencing stocking decisions. The coding scheme was applied to the information provided in the interviews for each water body visited ($n = 81$). Codes were given per water body, categorized as follows for standing waters: natural, lakes of different sizes (natural origin after the last glaciation); man-made, reservoirs (artificially created); and artificial, ponds (artificially created, usually small sized up to about 2.5 ha, and drainable). The corresponding categories for flowing water bodies were as follows: natural, natural rivers and creeks; and man-made, canals (artificially created, often with locks). The results were summarized according to the two di-

mensions of water body type and level of stocking decision (Table S1). Coding of interviews was completed by two independent coders. Both coders also conducted the survey and visited the water bodies. Subsequently, both coders compared their coded statements and discussed disagreements on codes that were previously assigned. Consensus decisions were finally taken, and no water body or interview was excluded from the analysis because of coder disagreement.

Angling Club Survey Results. The interviews revealed that all water bodies managed by the surveyed management boards were regularly stocked. In each case, angler demands, expressed by angler (dis)satisfaction with catches and harvest, were relevant to some degree for determining stocking measures (Table S1). They were particularly decisive for determining stocking measures in man-made water bodies and at least partially determined stocking decisions in more natural water bodies (Table S1). Our interviews suggested there are no fisheries in the surveyed regions in Germany in which angler desires were irrelevant for basing stocking decisions.

Performance of the Ecological Submodel. The stochastic population model with no harvest and no stocking produced plausible and relatively stable results (Fig. S8, *Left*). In 100 simulations of 200 y each, density of early YOY was quite variable, as is consistent with observations of recruitment in wild populations (2). The density of each subsequent life stage had a well-defined upper limit dictated by the density-dependent survival rates experienced by the two YOY life stages. Introducing a modest annual harvest rate on the adult population of 0.3 reduced the density of adults attributable to harvest losses but had little effect on other life stages because of compensatory improvements in spawner success and YOY survival (Fig. S8, *Center-Left*). Stocking at a constant rate of 1,500 YOY fish·ha⁻¹ with no interbreeding of the two subpopulations resulted in slight reductions in early YOY density and significant reductions in the maximum number of wild fish in all other life stages because of increased density-dependent competition in the YOY life stage (Fig. S8, *Center-Right*). Stocking at a constant rate of 1,500 YOY fish·ha⁻¹ with subsequent interbreeding of wild adults at a conservative proportion of $c = 0.1$ resulted in slight reductions in the density of all life stages attributable to the direct loss from the wild subpopulation through interbreeding and to density-dependent competition with additional interbred offspring (Fig. S8, *Right*). Constant stocking (i.e., no feedback of stocking numbers to population development and harvest) at a modest rate can thus have a negative impact on a naturally reproducing wild population (3). The wild stock is preserved but at a reduced density.

Robustness of Basic Fish Population Model. We tested the robustness of the biological model by evaluating the elasticity of mean wild adult density between years 150 and 200 to changes in the population model parameters $s_2, s_3, s_4, s_5, u, c, r, R_o, j_o, S_o,$ and κ . Elasticity represents the proportional response of the model to a proportional change in a parameter value and is useful when parameters are measured on different scales (4). We estimated elasticity as the mean proportional change in wild adult density divided by a 10% increase or decrease in each parameter. Therefore, a change in response in the same direction as the parameter was varied can be interpreted as the adult population density responding positively to a positive change in the parameter of interest, or vice versa. Varying each parameter in both

directions is informative, because the elasticity surface is not necessarily linear. Elasticity was evaluated using the SDM and the MM with a maximum memory of 15 y and a forgetting rate (λ) of 0.5. Overall, elasticity of the model was moderate. Moreover, predicted changes of the wild population to alternations of input parameters occurred in the expected direction. For example, lowering the relative fitness parameters of hatchery fish (s_3, s_4, s_5) increased the wild fish population, and thus preserved it to a greater extent in the face of stocking. Varying the adult survival rate (s_2) resulted in small changes in wild adult density in the same direction as the parameter was varied (Fig. S6). The immediate survival of hatchery fish (u) and the proportion of wild adults that interbred with hatchery fish had a negative effect on wild adult densities, with adult density varying in the opposite direction of the parameter change. The relative spawning success (r) of the hatchery subpopulation turned out to be the most elastic, and hence sensitive, parameter in our model, where increases or decreases in hatchery spawning success resulted in opposite effects on wild adult density. Changes in the number of early YOY in an unfishery population (R_o) and compensation ratio (κ) resulted in a change in the density of wild adults in the same direction. The wild adult subpopulation was found to be inelastic to changes in the number of unfishery late YOY (j_o). Changes in the number of unfishery spawner density (S_o) led to small changes in wild adult density (Fig. S6).

Alternative Stocking Decision-Making Models: MM* and SDM*. Alternative scenarios for both the MM and SDM were incorporated in our SE model, because empirical evidence on the various decision criteria was unavailable, necessitating an exploration of a series of plausible scenarios and to represent structural uncertainty.

In the alternative scenario, MM*, exceptional fishing successes in terms of harvest are weighed more heavily when determining future harvest expectations. It may indeed be that although anglers forget at a rate λ , years with exceptional harvest still stand out, determining future expected harvest. Accordingly, anglers weigh harvest in each previous year (i) as $\phi_i = \frac{H_i^{act}}{\bar{H}^{act}}$, where \bar{H}^{act}

is the mean harvest over the previous T years. This weighting is then incorporated into Eq. 9 as:

$$H_t^{exp} = \frac{\sum_{i=1}^T [e^{-\lambda i} H_{t-i}^{act} \phi_i]}{\sum_{i=1}^T e^{-\lambda i} \phi_i} \quad [S1]$$

In the alternative stocking decision scenario, SDM*, stocking numbers remain at current levels if satisfaction is positive rather than being reduced as in the SDM scenario:

$$S_t = \begin{cases} S_t & \text{if } U_t \geq 0 \\ S_t - dU_t & \text{if } U_t < 0 \end{cases} \quad [S2]$$

where S_t is stocking rate, d is the rate at which angler (dis)satisfaction leads to changes in stocking and U_t is angler (dis)satisfaction, defined as the difference between expected and realized harvest. The SDM* is a valid scenario when stocked hatchery fish are unmarked; therefore, anglers will presumably attribute positive satisfaction to past stocking efforts, in turn, attempting to keep the apparently successful action.

Model Results Under the MM* and SDM*. The results of the MM* (i.e., accounting for particularly memorable harvest years) under the SDM are presented in Fig. S3. They were comparable to the MM under the SDM (i.e., remembering the past resulted in

a boost of stocking rates, development of stocking as a panacea, and replacement of wild by hatchery fish). For both the MM and MM*, predictions were even more pronounced under the SDM*, where the stocking rate of the previous year was maintained when angler satisfaction was either positive or neutral (Figs. S4 and S5). This almost inevitably led to a collapse of the wild fish subpopulation and replacement by hatchery fish.

Robustness of Main Study Conclusions in Terms of Viability of Wild Fish Population. To test for the robustness of main study conclusions, we performed viability analyses of the wild subpopulation. Population viability was defined as the proportion of simulations over 500 y that resulted in a wild adult density remaining above 10 fish·ha⁻¹. We arbitrarily assumed an ecosystem size of 10 ha. The viability threshold represented 4% of the unfishery adult density or about 50 spawner pairs, an often-cited minimal viable fish population size (5).

When the forgetting rate, λ , and the maximum memory length, T , of past harvest experiences by anglers (Fig. S1) were systematically varied under the MM and SDM, nonlinear relationships in wild population viability in the face of a developing stocking panacea resulted (Fig. S1). There was a contrived region of the parameter space for low forgetting rate (Fig. S1, Upper) and brief length of memory (Fig. S1, Lower), where the probability of replacement of the wild fish changed abruptly. Under an unrealistically high forgetting rate ($\lambda = 0.5$ or 0.9) or unrealistically brief maximum memory period ($T = 5$ y), the wild subpopulation was preserved in the face of the potential for stocking evolving as a panacea (Fig. S1). This means wild fish populations were preserved only if anglers took the very recent years into account. This is unrealistic (28). The viability analysis of the MM* with the SDM (Fig. S1, Left-Center) demonstrated that, as for the MM, only short maximum memory length or high forgetting rates preserved the wild subpopulation. Again, a nonlinear interaction between memory time and forgetting rate (Fig. S1) occurred, affecting the viability prospects of the wild fish population in the face of stocking. With the SDM*, the viability of the wild fish population was always zero regardless of the memory model used (Fig. S1, Right and Right-Center).

The two main parameter classes in our biological model that were found to affect the viability of the wild stock (Fig. 3) are the productivity of the wild population and the relative fitness or survival of stocked fish. Therefore, we examined the viability of the wild population across interactions between these two parameter classes (Fig. S2). Not surprisingly, we find as fitness of stocked fish increases, the wild population must be increasingly productive (higher R_o , κ ; lower S_o) to sustain the wild population. By contrast, the intermediate unfishery density of juveniles (j_o) was found to be relatively insensitive to changes in stocked fish survival. These findings were qualitatively equivalent regardless of which measure of stocked survival was examined (s_3, s_4 , or s_5).

The likelihood of replacement of the wild subpopulation with stock fish was also found to be at least partially under the influence of the social manager. As satisfaction in harvest increases or decreases, the social manager in our model directly responded by changing the stocking density at a rate of d per level of (dis)satisfaction. We tested for the impact of d on viability of the wild population. Moderate changes in the stocking rate for changes in angler satisfaction ($d < 65$ fish ha⁻¹) still led to long-term sustainability of the wild subpopulation (Fig. S7). However, when the stocking rate changes strongly with (dis)satisfaction ($d > 75$ fish ha⁻¹), population viability of the wild population declined, leading to increased replacement by stocked fish and greater stability of the salient cultural ecological service provided by the fish stock (i.e., angler satisfaction).

Simulated and Empirical Ratios of Stocked to Naturally Spawned YOY Densities and Share of Stocked Fish Observed in Empirical Population Studies. The simulated time series following the introduction of stocking was broken up into 50-y time intervals to examine how the ratio of stocked early YOY to spawned wild and stocking-descended early YOY ($j_1 + j_2$) developed with the stocking panacea. Under the MM/SDM and at high or intermediate forgetting rates, the ratio of stocked to spawned early YOY was relatively low, with median values never exceeding 15% (Table S3). At a low forgetting rate ($\lambda = 0.1$), the median ratio reached 68% by 250 y after the initiation of stocking under a social manager. Under the MM/SDM*, much higher ratios of stocked to spawned early YOY were found; the median ratio exceeded 1.0 when assuming a low forgetting rate (Table S3).

Ratios of stocked to spawned YOY were also compiled from field studies reported in the literature (Table S4). Few ratios of stocked to spawned YOY were reported in the primary literature; thus, spawned YOY densities were compiled mainly from the Myers stock recruitment database (<http://www.mscc.dal.ca/>

[~myers/welcome.html](http://myers/welcome.html)), whereas stocked densities were compiled from primary and gray literature sources. The result is that ratios reported here are conservative compared with likely ratios derived from within the same system. A comparison with ratios obtained from our model (Table S3) revealed that the model did generate ratios in the range calculated for different fish species managed by stocking in recreational fisheries, and that it can therefore be ruled out that unrealistically high stocking levels were driving the potential for replacement of wild by hatchery fish under certain conditions predicted by our model (compare with *Results and Discussion* and Figs. 2 and 3).

Depending on the respective conditions (e.g., productivity of the wild stock, survival of hatchery relative to wild fish), our model predicted a range of outcomes in terms of the proportion of hatchery fish in the population, with replacement of wild by hatchery fish as a possible outcome (e.g., Figs. 2 and 3 and Fig. S2). This is in accordance with proportions found and factors and environmental conditions discussed in empirical studies (Table S5).

- Daedlow K, Beard DTJ, Arlinghaus R (in press) *A Property Rights-Based View on Management of Inland Recreational Fisheries: Contrasting Common and Public Fishing Right Regimes in Germany and the U.S.A.* (American Fisheries Society Symposium, Bethesda, MD).
- Walters CJ, Martell SJD (2004) *Fisheries Ecology and Management* (Princeton Univ Press, Princeton).
- Chilcote MW, Goodson KW, Falcy MR (2011) Reduced recruitment performance in natural populations of anadromous salmonids associated with hatchery-reared fish. *Can J Fish Aquat Sci* 68:511–522.
- Allen MS, Brown P, Douglas J, Fulton W, Catalano M (2009) An assessment of recreational fishery harvest policies for Murray cod in southeast Australia. *Fish Res* 95:260–267.
- Post JR, Mushens C, Paul A, Sullivan M (2003) Assessment of alternate regulations for sustaining recreational fisheries: Model development and application to bull trout. *N Am J Fish Manage* 23:22–34.
- Myers RA, Bowen KG, Barrowman NJ (1999) Maximum reproductive rate of fish at low population sizes. *Can J Fish Aquat Sci* 56:2404–2419.
- Elliott JM (1994) *Quantitative Ecology and the Brown Trout* (Oxford Univ Press, Oxford).
- Saura A, Mikkola J, Ikonen E (1990) Re-introduction of salmon (*Salmo salar*) and sea trout (*Salmo trutta*) to the Vantaanjoki River, Finland. *Management of Freshwater Fisheries, Proceedings of a Symposium by European Inland Fisheries Advisory Commission*, eds van Densen LT, Steinmetz B, Hughes RH (Gothenburg, Sweden), pp 127–136.
- Aass P (1984) *Brown Trout Stocking in Norway* (European Inland Fisheries Advisory Commission Paper 42) (European Inland Fisheries Advisory Commission, Rome), pp 123–128.
- Rasmussen G, Geertz-Hansen P (1998) *Stocking and Introduction of Fish*, ed Cowx IG (Fishing News Books, Blackwell Science, Cronwall, UK).
- Jokikokko E (1999) Density of brown trout, *Salmo trutta* L., and Atlantic salmon, *Salmo salar* L., parr after point and scatter stocking of fry. *Fish Manag Ecol* 6:475–486.
- Baer J., et al. (2007) *Gute fachliche Praxis fischerlicher Besatzmassnahmen (Good Practice of Fish Stocking Measures)* (Schriftenreihe des Verbandes Deutscher Fischereiverwaltungsbeamter und Fischereiwissenschaftler e.V., Friedberg, Germany). German.
- Borsuk ME, Reichert P, Peter A, Schager E, Brukhardt-Holm P (2005) Assessing the decline of brown trout (*Salmo trutta*) in Swiss rivers using a Bayesian probability network. *Ecol Modell* 192:224–244.
- Champiguelle A, Melhaoui M, Gillet C, Caudron A (2003) Stocking fed fry and demography of the brown trout (*Salmo trutta* L.) population of the River Redon, a Lake Leman's affluent interrupted by a weir. *Bulletin Français de la Pêche et de la Pisciculture* 369:17–39.
- Québec Ministère du Loisir, de la Chasse et de la Pêche (1988) Stocking guidelines for fish species other than anadromous Atlantic salmon (Ministère du Loisir, de la Chasse, et de la Pêche Québec City, QC, Canada), p 27. Cited in Lasenby TA, Kerr SJ (2001) Brown Trout Stocking: An Annotated Bibliography and Literature Review. (Fish and Wildlife Branch, Ontario Ministry of Natural Resources, Peterborough, ON, Canada), p 187.
- Hansen MJ, Bozek MA, Newby JR, Newman SP, Staggs MD (1998) Factors affecting recruitment of Walleyes in Escanaba Lake, Wisconsin, 1958–1996. *N Am J Fish Manage* 18:764–774.
- Kampa JM, Hatzenbeler GR (2009) Survival and growth of walleye fingerlings stocked at two sizes in 24 Wisconsin lakes. *N Am J Fish Manage* 29:996–1000.
- Jennings MJ, Kampa JM, Hatzenbeler GR, Emmons EE (2005) Evaluation of supplemental walleye stocking in Northern Wisconsin lakes. *N Am J Fish Manage* 25:1171–1178.
- Mitzner L (2002) Effectiveness of walleye fry and fingerling stocking in Rathbun Lake, Iowa, 1990–1999. *N Am J Fish Manage* 22:1007–1013.
- Fayram AH, Hansen MJ, Nate NA (2005) Determining optimum stocking rates using a stock-recruitment model: An example using walleye in Northern Wisconsin. *N Am J Fish Manage* 25:1215–1225.
- Michaletz PH, Allman JL, Banek TJ (2008) *Balancing Fisheries Management and Water Uses for Impounded River Systems*, *American Fisheries Society Symposium*, eds Allen MS, Sammons S, Maceina MJ (American Fisheries Society Symposium, Bethesda, MD).
- Keith WE (1975) *Black Bass Biology and Management*, eds Stroud RH, Clepper H (Sport Fishing Institute, Washington, DC), pp 489–496.
- Heidinger RC (1999) *Inland Fisheries Management in North America*, eds Kohler CC, Hubert WA (American Fisheries Society, Bethesda, MD).
- Wright GL (1991) *Warmwater Fisheries Symposium 1*, eds Cooper JL, Hamre RH (US Forest Service, Washington, DC).
- Duval MC (1991) *Warmwater Fisheries Symposium 1*, eds Cooper JL, Hamre RH (US Forest Service, Washington, DC), pp 291–295.
- Buckmeier DL, Schlechte JW, Betsill RK (2003) Stocking fingerling largemouth bass to alter genetic composition: Efficacy and efficiency of three stocking rates. *N Am J Fish Manage* 23:523–529.
- Mesing CL, Cateaux RL, Strickland PA, Long EA, Rogers MW (2008) Stocking of advanced-fingerling largemouth bass to supplement year-classes in Lake Talquin, Florida. *N Am J Fish Manage* 28:1762–1774.
- Kawamura K, Kobota M, Furukawa M, Harada Y (2007) The genetic structure of endangered indigenous populations of the amago salmon, *Oncorhynchus masou ishikawae*, in Japan. *Conserv Genet* 8:1163–1176.
- Englbrecht CC, Schliewen U, Tautz D (2002) The impact of stocking on the genetic integrity of Arctic charr (*Salvelinus*) populations from the Alpine region. *Mol Ecol* 11:1017–1027.
- Martinez JL, Dumas J, Beall E, Garcia-Vazquez E (2001) Assessing introgression of foreign strains in wild Atlantic salmon populations: Variation in microsatellites assessed in historic scale collections. *Freshw Biol* 46:835–844.
- Finnegan AK, Stevens JR (2008) Assessing the long-term genetic impact of historical stocking events on contemporary populations of Atlantic salmon, *Salmo salar*. *Fish Manag Ecol* 15:315–326.
- Marie AD, Bernatchez L, Garant D (2010) Loss of genetic integrity correlates with stocking intensity in brook charr (*Salvelinus fontinalis*). *Mol Ecol* 19:2025–2037.
- García-Marin JL, Jorde PE, Ryman N, Utter F, Pla C (1991) Management implications of genetic differentiation between native and hatchery populations of brown trout (*Salmo trutta*) in Spain. *Aquaculture* 95:235–249.
- Largiader CR, Scholl A (1995) Effects of stocking on the genetic diversity of brown trout populations of the Adriatic and Danubian drainages in Switzerland. *J Fish Biol* 47 Suppl A209–225.
- García-Marin JL, Sanz N, Pla C (1999) Erosion of the native genetic resources of brown trout in Spain. *Ecol Freshw Fish* 8:151–158.
- Machordom A, García-Marin JL, Sanz N, Almodovar A, Pla C (1999) Allozyme diversity in brown trout (*Salmo trutta*) from Central Spain: Genetic consequences of restocking. *Freshw Biol* 41:707–717.
- Antunes A, Faria R, Weiss S, Alexandrino P (2001) Complex evolutionary history in the brown trout: Insights on the recognition of conservation units. *Conserv Genet* 2:337–347.
- Hansen MM (2002) Estimating the long-term effects of stocking domesticated trout into wild brown trout (*Salmo trutta*) populations: An approach using microsatellite DNA analysis of historical and contemporary samples. *Mol Ecol* 11:1003–1015.
- Heggnes J, Roed KH, Hoyheim B, Roser L (2002) Microsatellite diversity assessment of brown trout (*Salmo trutta*) population structure indicate limited genetic impact of stocking in a Norwegian alpine lake. *Ecol Freshw Fish* 11:93–100.
- Almodovar A, Nicola GG, Elvira B, García-Marin JL (2006) Introgression variability among Iberian brown trout Evolutionary Significant Units: the influence of local management and environmental features. *Freshw Biol* 51:1175–1187.
- Berrebi P, Poteaux C, Fissier M, Cattaneo-Berrebi G (2000) Stocking impact and allozyme diversity in brown trout from Mediterranean southern France. *J Fish Biol* 56:949–960.
- Hansen MM, Fraser DJ, Meier K, Mensberg KLD (2009) Sixty years of anthropogenic pressure: A spatio-temporal genetic analysis of brown trout populations subject to stocking and population declines. *Mol Ecol* 18:2549–2562.

- 43. Susnik S, Berrebi P, Dovc P, Hansen MM, Snoj A (2004) Genetic introgression between wild and stocked salmonids and the prospects for using molecular markers in population rehabilitation: The case of the Adriatic grayling (*Thymallus thymallus* L. 1785). *Heredity* 93:273–282.
- 44. Miller LM, Mero SW, Younk JA (2009) The genetic legacy of stocking muskellunge in a Northern Minnesota lake. *Trans Am Fish Soc* 138:602–615.
- 45. Larsen PF, Hansen MM, Nielsen EE, Jensen LF, Loeschcke V (2005) Stocking impact and temporal stability of genetic composition in a brackish northern pike population (*Esox lucius* L.), assessed using microsatellite DNA analysis of historical and contemporary samples. *Heredity* 95:136–143.
- 46. Launey S, Morin J, Minery S, Laroche J (2006) Microsatellite genetic variation reveals extensive introgression between wild and introduced stocks, and a new evolutionary unit in French pike *Esox lucius* L. *J Fish Biol* 68(Suppl B):193–216.
- 47. Wirgin I, Currie D, Roy N, Maceda L, Waldman JR (2005) Introgression of nuclear DNA (nDNA) alleles of stocked Atlantic coast striped bass with the last remaining native Gulf of Mexico population. *N Am J Fish Manage* 25:464–474.

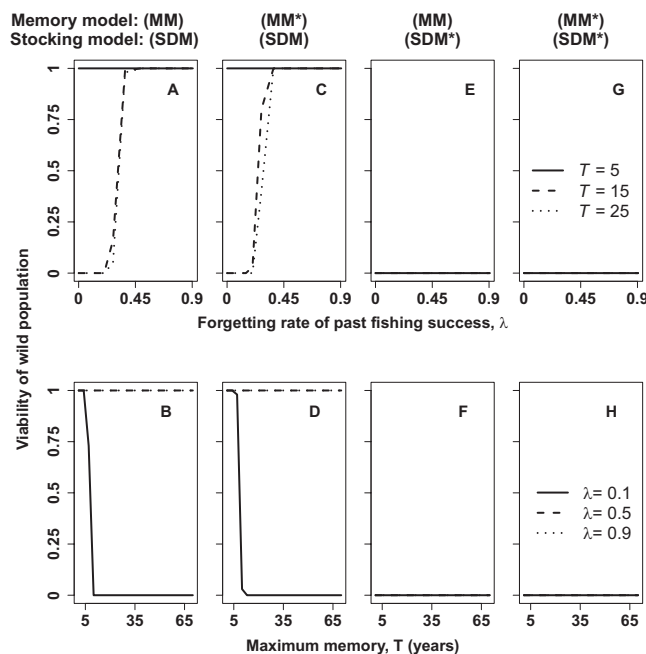


Fig. S1. Viability of the wild subpopulation across a range of forgetting rates, λ , (Upper) and the maximum number of years of memory, T , (Lower) of anglers of past harvest for different combinations of the two memory models (MM/MM*) and stocking decision models (SDM/SDM*). When λ is varied, T is held at 5, 15, or 25 y; when T is varied, λ is held at 0.1, 0.5, or 0.9.

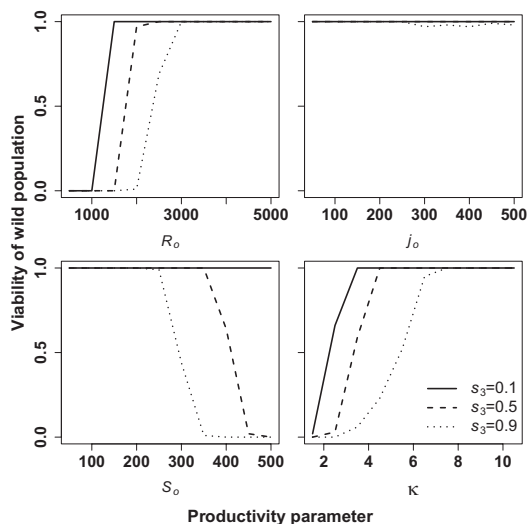


Fig. S2. Interaction between wild population productivity, represented by unfished wild recruitment (R_o), unfished wild late YOY density (j_o), unfished wild spawner density (S_o), and compensation ratio (κ), and hatchery fish fitness represented by relative survival of hatchery YOY (S_3) and their effects on wild population viability.

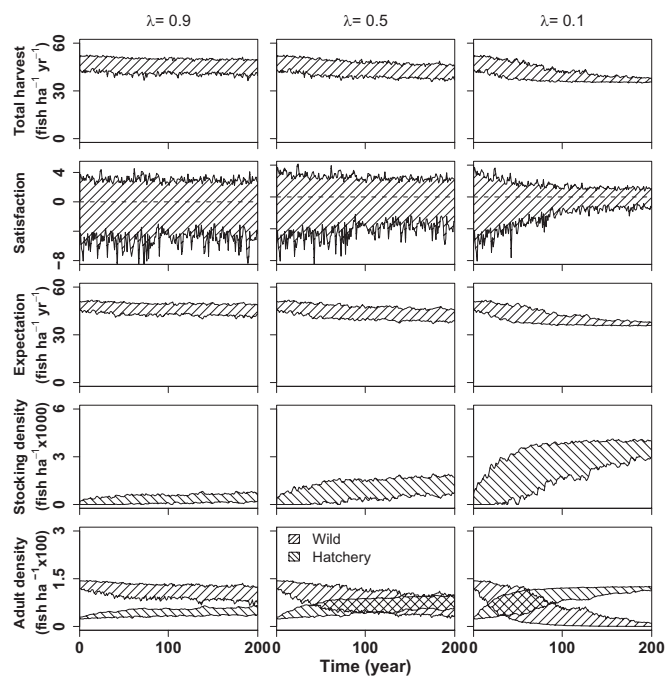


Fig. S3. Influence of the forgetting rate of past harvest (λ) for determining total harvest, angler satisfaction, expected harvest, stocking density, and adult density of wild and hatchery-descended subpopulations under the MM* and the SDM. The range of 100 model runs over 200 y is shown for three levels of λ . Maximum memory length of anglers is fixed at 15 y, and the stocking response to angler (dis)satisfaction is set at 50 fish ha⁻¹.

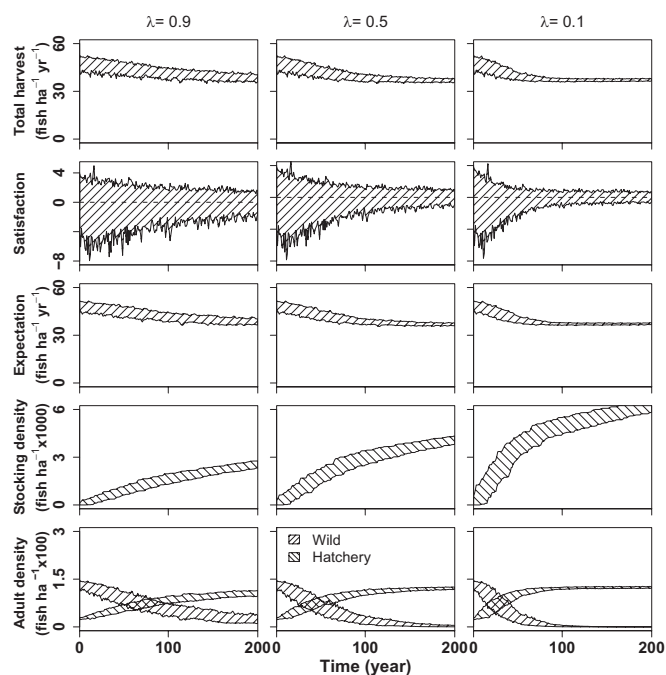


Fig. S4. Influence of the forgetting rate of past harvest (λ) for determining total harvest, angler satisfaction, expected harvest, stocking density, and adult density of wild and hatchery-descended subpopulations under the MM and the SDM*. The range of 100 model runs over 200 y is shown for three levels of λ . Maximum memory length of anglers is fixed at 15 y, and the stocking response to angler (dis)satisfaction is set at 50 fish ha⁻¹.

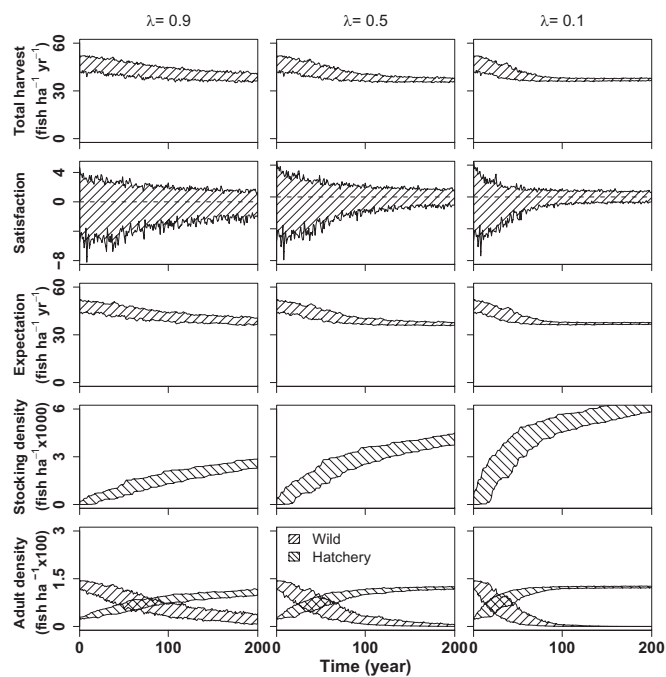


Fig. S5. Influence of the forgetting rate of past harvest (λ) for determining total harvest, angler satisfaction, expected harvest, stocking density, and adult density of wild and hatchery-descended subpopulations under the MM* and the SDM*. The range of 100 model runs over 200 y is shown for three levels of λ . Maximum memory length of anglers is fixed at 15 y, and the stocking response to angler (dis)satisfaction is set at 50 fish ha⁻¹.

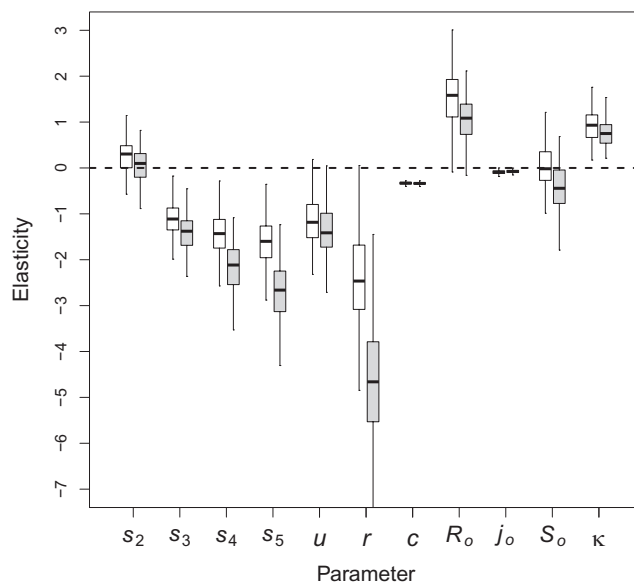


Fig. S6. Elasticity (i.e., proportional response to a proportional change in parameter value) in mean wild adult fish density when parameter values were varied by 10% relative to baseline values. Parameters are defined in Table S2. White and gray bars are elasticities over 100 simulations when the indicated parameter is decreased (white) or increased (gray) by 10%. Elasticity >0 means that wild adult density varies in the same direction as the parameter that is varied. Elasticity <0 means that wild adult density varies in the opposite direction as the parameter that is varied. Boxes represent the interquartile range, and vertical bars represent the 95th percentiles.

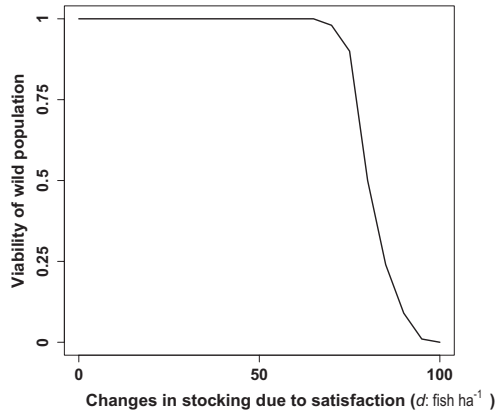


Fig. S7. Viability of the wild population across a range of values for d , the change in stocking rate attributable to angler satisfaction in units of fish ha^{-1} . Values were generated under the MM and SDM assuming a maximum memory (T) of 15 y and a forgetting rate (λ) of 0.5.

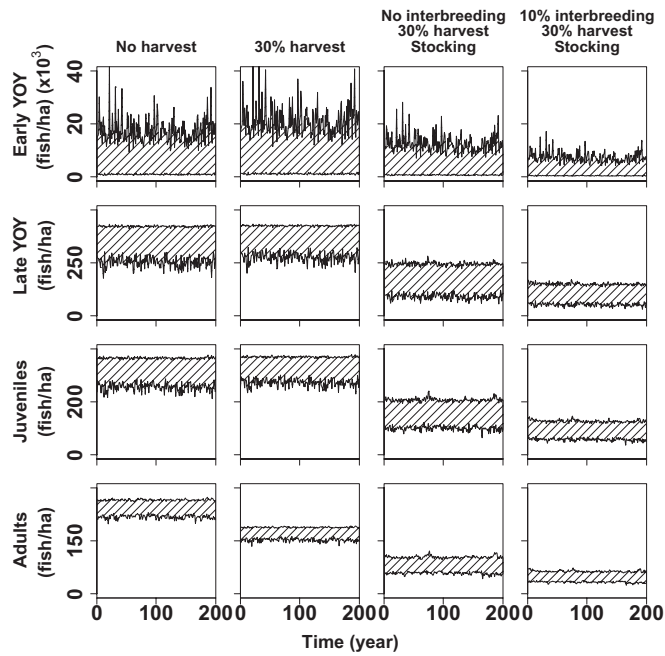


Fig. S8. Range of densities of four life stages of fish based on 100 simulations over 200 y of the wild subpopulation in the absence of harvest and stocking (*Left*); in the absence of stocking but allowing 30% annual harvest (*Center-Left*); allowing 30% annual harvest, constant annual stocking of 1,500 YOY $\text{fish}\cdot\text{ha}^{-1}$, and no interbreeding of wild and hatchery adults (*Center-Right*); and allowing 30% annual harvest, constant annual stocking of 1,500 YOY $\text{fish}\cdot\text{ha}^{-1}$, and interbreeding of wild and hatchery adults at the proportion $c = 0.1$ (*Right*).

Table S1. Importance of angler satisfaction for determining fish stocking decisions in angling clubs in Germany based on interviews with management boards in $n = 38$ angling clubs

	Local level decision* ($n = 24$ clubs)				Regional level decision* ($n = 20$ clubs)			
	High	Medium	Low	n	High	Medium	Low	n
Water body types								
Standing								
Natural	25	—	75	4	—	67	33	3
Man-made	57	43	—	7	—	100	—	7
Artificial	82	14	4	28	37.5	62.5	—	8
Flowing								
Natural	—	50	50	12	—	50	50	6
Man-made	—	100	—	3	—	33	67	3

$n = 6$ clubs with regional-level stocking decision making also stocked a small set of water bodies on the local level independent of the regional angler association. Therefore, sample size for local level stocking decision making is $n = 24$ (18 + 6 clubs). Data are percentages of managed water bodies with high, medium, or low influence of angler desires and their satisfaction driving stocking decisions (details are provided in *S1 Text*). The absence category did not occur. —, specific water body type not present.

*Local level decision means that angling clubs decide about fish stocking for a contrived number of fisheries. In these situations, local anglers know decision makers personally and meet each other often and decision makers are directly elected by anglers. Regional level decision means that angling associations (constituted by a union of a large number of local angling clubs) decide about fish stocking for a wide range of fisheries across a region. In these situations, anglers are less closely connected to a stocking decision maker but local angling clubs still exert influence on the stocking decision by expressing demands for stocked fish to higher level organizational bodies within the angler associations.

Table S2. Parameters used in the stocking model

Parameter	Explanation	Value	Unit
st (1)	Steepness	0.63	Recruits/spawner
κ	Compensation ratio	6.84	
S_o	Unfished equilibrium spawner abundance	250	fish-ha ⁻¹
R_o	Unfished equilibrium recruit abundance	3,750	fish-ha ⁻¹
μ	Maturation rate	0.5	y ⁻¹
r	Relative recruitment success for hatchery fish	0.9	
c	Proportion of wild fish that cross with hatchery-descended fish	0.1	
ω^*	Recruitment variance	0.58	
Juvenile survival			
u	Immediate survival for stocked hatchery fish	0.9	
j_o	Unfished equilibrium YOY abundance at the end of the first year	375	Fish
$s1$	Constant survival of wild juveniles	0.62	y ⁻¹
$s3$	Relative density-dependent survival of early to late YOY hatchery fish	0.9	
$s4$	Relative survival of hatchery juveniles	0.9	
Adult survival			
$s2$	Constant survival of wild adults	0.6	y ⁻¹
$s5$	Relative survival of hatchery adults	0.9	
Harvest			
h	Proportional annual adult harvest	0.3	y ⁻¹
Stocking decision			
λ	Forgetting rate	0.1, 0.5, 0.9	
T	Maximum memory length	5, 15, 25	y
d	Change in stocking rate as a multiple of satisfaction	25, 50, 100	Fish-ha ⁻¹

Parameters for which multiple values are provided represent parameters for which all values were evaluated in simulations. Hatchery fish, hatchery-descended fish; YOY, young of the year fish.

*Mean of recreationally important species found in the Meyers stock recruitment database (<http://www.mscs.dal.ca/~myers/welcome.html>).

1. Myers RA, Bowen KG, Barrowman NJ (1999) Maximum reproductive rate of fish at low population sizes. *Can J Fish Aquat Sci* 56:2404–2419.

Table S3. Simulated stocking densities and combined natural recruitment rates of wild and stocking-descended YOY generated from our coupled SE model and resulting ratios of stocking densities to natural recruitment densities

MM/SDM	Forgetting rate (λ)	Time range, y	Natural recruit density, fish-ha ⁻¹ ($j_{1,1} + j_{1,2}$), median (range)	Stocking density, fish-ha ⁻¹ (S), median (range)	Stocking: Natural recruit density median (range)
MM/SDM	0.1	1-50	4,833 (684-38,291)	844 (0-3,175)	0.16 (0.00-3.27)
		51-100	4,901 (598-39,059)	2,435 (103-3,770)	0.46 (0.02-4.80)
		101-150	4,884 (734-39,870)	3,022 (656-3,937)	0.60 (0.04-4.88)
		151-200	4,780 (601-45,284)	3,250 (1,324-4,024)	0.66 (0.07-5.48)
		201-250	4,839 (738-41,218)	3,328 (1,660-3,946)	0.68 (0.08-4.62)
	0.5	1-50	4,930 (510-49,284)	310 (0-1,190)	0.06 (0-0.86)
		51-100	4,806 (631-41,071)	621 (0-1,387)	0.12 (0-1.07)
		101-150	4,929 (575-33,315)	717 (0-1,586)	0.14 (0-1.86)
		151-200	4,918 (671-36,614)	744 (0-1,547)	0.14 (0-1.57)
		201-250	4,908 (662-48,633)	768 (0-1,489)	0.15 (0-1.45)
	0.9	1-50	4,829 (652-36,321)	230 (0-923)	0.04 (0-0.75)
		51-100	4,898 (804-36,099)	350 (0-933)	0.07 (0-0.74)
		101-150	4,808 (563-35,413)	390 (0-927)	0.08 (0-1.01)
		151-200	4,761 (524-38,551)	414 (0-1,016)	0.08 (0-1.01)
		201-250	4,813 (619-35,734)	421 (0-955)	0.08 (0-0.91)
MM/SDM*	0.1	1-50	4,872 (519-46,764)	1,204 (0-3,786)	0.22 (0.00-5.76)
		51-100	4,809 (457-32,400)	3,807 (1,822-4,811)	0.77 (0.10-8.55)
		101-150	4,835 (593-50,057)	4,583 (3,733-5,311)	0.94 (0.10-7.67)
		151-200	4,790 (444-31,857)	5,004 (4,478-5,683)	1.04 (0.16-11.27)
		201-250	4,807 (528-32,758)	5,348 (4,860-5,927)	1.11 (0.16-10.21)
	0.5	1-50	4,879 (337-33,132)	961 (0-2,337)	0.17 (0.00-3.51)
		51-100	4,914 (924-33,114)	2,470 (1,231-3,350)	0.49 (0.06-2.87)
		101-150	4,899 (612-48,547)	3,320 (2,354-3,883)	0.67 (0.07-6.00)
		151-200	4,867 (577-35,554)	3,873 (3,164-4,318)	0.79 (0.11-6.87)
		201-250	4,883 (729-95,281)	4,301 (3,646-4,727)	0.88 (0.04-5.95)
	0.9	1-50	4,851 (502-34,513)	900 (0-2,174)	0.16 (0.00-1.94)
		51-100	4,964 (510-35,942)	2,237 (1,296-3,023)	0.44 (0.04-4.21)
		101-150	4,899 (603-40,043)	3,061 (2,208-3,704)	0.62 (0.09-4.90)
		151-200	4,930 (608-43,220)	3,647 (3,020-4,216)	0.74 (0.09-6.04)
		201-250	4,867 (690-38,090)	4,100 (3,543-4,504)	0.84 (0.11-5.68)

MM refers to our default memory model where past harvest is forgotten with a standard forgetting rate. SDM refers to our default stocking decision model where stocking rate increases if anglers are dissatisfied with harvest and decreases if anglers are satisfied. SDM* refers to our alternate stocking decision model where stocking levels remain constant even if satisfaction is positive.

Table S4. Examples of ratios of stocking densities to natural recruitment densities for different species calculated from literature

Stage	NR, fish·ha ⁻¹ , median (range)	S, fish·ha ⁻¹	S/NR based on median NR (range)	Ref. (NR; S)
Brown trout (<i>Salmo trutta</i>)				
Alevin	562,500 (66,667–1,333,333)	30,000–70,000	0.05–0.12 (0.02–1.05)	7; 8
Alevin	40,833 (26,667–60,000)	30,000–70,000	0.73–1.71 (0.50–2.63)	7; 8
Alevin	562,500 (66,667–1,333,333)	20,000	0.04 (0.02–0.30)	7; 9, 10
Alevin	40,833 (26,667–60,000)	20,000	0.49 (0.33–0.75)	7; 9, 10
Alevin	562,500 (66,667–1,333,333)	6,300–26,300	0.01–0.05 (0.00–0.39)	7; 11
Alevin	40,833 (26,667–60,000)	6,300–26,300	0.15–0.64 (0.11–0.99)	7; 11
Alevin	562,500 (66,667–1,333,333)	3,500–20,000	0.01–0.04 (0.00–0.30)	7; 12
Alevin	40,833 (26,667–60,000)	3,500–20,000	0.09–0.49 (0.06–0.75)	7; 12
YOY, spring	57,083 (21,667–76,667)	3,31–8,114	0.01–0.14 (0.00–0.37)	7; 13
YOY, spring	10,000 (6,333–13,333)	3,31–8,114	0.03–0.81 (0.02–1.28)	7; 13
YOY, spring	57,083 (21,667–76,667)	4,000–6,000	0.07–0.11 (0.05–0.28)	7; 14
YOY, spring	10,000 (6,333–13,333)	4,000–6,000	0.40–0.60 (0.30–0.95)	7; 14
YOY, spring	57,083 (21,667–76,667)	1,500	0.03 (0.02–0.07)	7; 15
YOY, spring	10,000 (6,333–13,333)	1,500	0.15 (0.11–0.24)	7; 15
YOY, spring	57,083 (21,667–76,667)	400–5,000	0.01–0.09 (0.01–0.23)	7; 12
YOY, spring	10,000 (6,333–13,333)	400–5,000	0.04–0.50 (0.03–0.79)	7; 12
YOY, fall	15,333 (1,667–20,833)	136–1,954	0.01–0.13 (0.01–1.17)	7; 13
YOY, fall	1,667 (833–2,333)	136–1,954	0.08–1.17 (0.06–2.34)	7; 13
YOY, fall	15,333 (1,667–20,833)	up to 5,000	0.33 (0.24–3.00)	7; 9, 10
YOY, fall	1,667 (833–2,333)	up to 5,000	3.00 (2.14–6.00)	7; 9, 10
YOY, fall	15,333 (1,667–20,833)	200–300	0.01–0.02 (0.01–0.18)	7; 15
YOY, fall	1,667 (833–2,333)	200–300	0.12–0.18 (0.09–0.36)	7; 15
YOY, fall	15,333 (1,667–20,833)	400–5,000	0.03–0.33 (0.02–3.00)	7; 12
YOY, fall	1,667 (833–2,333)	400–5,000	0.24–3.00 (0.17–6.00)	7; 12
Walleye (<i>Sander vitreum</i>)				
YOY	87 (5–299)	25–124	0.29–1.43 (0.08–23.5)	16; 17, 18
YOY	87 (5–299)	12–25	0.14–0.29 (0.04–4.74)	16; 19
YOY	87 (5–299)	57–248	0.66–2.85 (0.19–46.99)	16; 20
YOY	87 (5–299)	70–80	0.80–0.92 (0.23–15.15)	16; 21
Largemouth bass (<i>Micropterus salmoides</i>)				
YOY, 0.5 a	371 (74–3,583)	12–494	0.03–1.33 (0.00–6.66)	22; 23
YOY, 0.5 a	108 (18–634)	12–494	0.11–4.57 (0.02–27.54)	24; 23
YOY, 0.5 a	382 (191–382)	12–494	0.03–1.29 (0.02–2.59)	25; 23
YOY, 0.5 a	371 (74–3,583)	10–41	0.03–0.11 (0.00–0.55)	22; 26
YOY, 0.5 a	108 (18–634)	10–41	0.09–0.38 (0.02–2.29)	24; 26
YOY, 0.5 a	382 (191–382)	10–41	0.03–0.11 (0.01–0.21)	25; 26
YOY, 0.5 a	371 (74–3,583)	15–60	0.04–0.16 (0.00–0.81)	22; 27
YOY, 0.5 a	108 (18–634)	15–60	0.14–0.56 (0.02–3.34)	24; 27
YOY, 0.5 a	382 (191–382)	15–60	0.04–0.16 (0.02–0.31)	25; 27

Natural recruitment densities were derived from studies listed in the Myers stock recruitment database (<http://www.mscs.dal.ca/~myers/welcome.html>). Stocking densities represent field studies or recommendations in practical fisheries management guidelines, assuming such guidelines are followed in practice. Simultaneous assessment of both parameters in field studies is very limited, which is why we choose to combined sources. a, years of age; NR, natural recruit density; S, stocking density.

Table S5. Examples of documented admixture or introgression in stocked fish populations with information on stocking history, origin of stocked fish, number of sites sampled, extent of replacement and potential factors leading to introgression or admixture *

Species	Method	History of stocking	Origin of stocked fish	No. sites sampled	Extent of admixture or introgression* (range across sampling sites)	Framework conditions; discussed or documented factors having an impact on admixture or introgression	Ref.
Amago salmon (<i>Oncorhynchus masou ishikawae</i>)	Microsatellite and mitochondrial DNA	30 y	Hatchery strain irregularly supplemented with wild fish	9	High admixture at 4 sites	Population decline attributable to habitat degradation	28
Arctic charr (<i>Salvelinus umbla</i>)	Microsatellite and mitochondrial DNA	110+ y	Stocking material transferred between neighboring and distant lakes but also produced from same lakes stocked	10	Low to complete replacement	Little stocking effect in habitats with stable environmental conditions	29
Atlantic salmon (<i>Salmo salar</i>)	Microsatellite	For 8 y 20 y ago	Foreign	1 repeatedly sampled over 30 y	<10%	Population declines attributable to habitat degradation and overfishing	30
Atlantic salmon (<i>S. salar</i>)	Microsatellite	For 15 y 40–50 y ago	Different drainages	8	1–18%	Potential reversion after stocking ceased	31
Brook charr (<i>Salvelinus fontinalis</i>)	Microsatellite	35+ y	Domestic and domestic-wild hybrids	24	1–77% admixture	Higher admixture at higher number of stocking events	32
Brown trout (<i>Salmo trutta</i>)	Isozyme	Many years	Exogenous	4	Impending or actual replacement	Population decline attributable to habitat degradation and overfishing	33
Brown trout (<i>S. trutta</i>)	Allozyme	100 y	Different drainage	17	80–100% introgression	Decreased natural reproduction attributable to habitat deterioration	34
Brown trout (<i>S. trutta</i>)	Allozyme	100+ y	Different drainage	147	0–100% introgression	Less introgression at stocked locations that are fished compared with unfished	35
Brown trout (<i>S. trutta</i>)	Allozyme	100 y	Foreign	8	2–30%	Population declines attributable to habitat degradation and overfishing	36
Brown trout (<i>S. trutta</i>)	Allozyme and mitochondrial DNA	Not specified	Nonnative origin	16	Lack of introgression despite presence of nonnative strains in the wild	Not specified	37
Brown trout (<i>S. trutta</i>)	Microsatellite	20+ y	Domestic strain, recent supportive breeding	2 repeatedly sampled over 50 y	6–88% admixture	Population decline attributable to overfishing and habitat degradation; propagation of domestic genes in supportive breeding program likely contributed to higher admixture at one site	38
Brown trout (<i>S. trutta</i>)	Microsatellite	40 y	Exogenous	4	<3%	Low introgression attributable to poor recruitment of stocked fish	39
Brown trout (<i>S. trutta</i>)	Allozyme	100+ y	Different drainage	307	1–100% introgression	Higher introgression with higher stocking effort and at environmental conditions favoring hatchery fish performance (fertile waters, even discharge); lower in migratory compared with anadromous populations	40

Table S5. Cont.

Species	Method	History of stocking	Origin of stocked fish	No. sites sampled	Extent of admixture or introgression* (range across sampling sites)	Framework conditions; discussed or documented factors having an impact on admixture or introgression	Ref.
Brown trout (<i>S. trutta</i>)	Allozyme	Not specified	Domestic mixed with local	13	0–77% introgression	High introgression in most altered catchment and at sites with longest stocking history, variable success of introduced fish as main factor for different introgression	41
Brown trout (<i>S. trutta</i>)	Microsatellite	30–40+ y	Domestic strain, recent supportive breeding	6 sampled twice within 50–80 y	14–64% admixture	Population declines attributable to habitat degradation and overfishing	42
European grayling (<i>Thymallus thymallus</i>)	Microsatellite	40+ y	Different drainage	7	40–50% admixture	Population decline attributable to habitat degradation, overharvesting and avian predation, stocking nonindigenous strains	43
Muskellunge (<i>Esox masquinongy</i>)	Microsatellite	For 20 y 20 y ago	Subsequently from two different drainages	1 repeatedly sampled over about 25 y	76% not pure ancestry	Reason for stocking undocumented	44
Northern pike (<i>Esox lucius</i>)	Microsatellite	10 y	Nonindigenous	1 sampled twice within about 45 y	<1% introgression	Population decline attributable to habitat degradation; low survival as freshwater origin fish stocked in brackish water	45
Northern pike (<i>E. lucius</i>)	Microsatellite	Several decades	Local and foreign hatcheries	6	20–65% admixture	Not specified	46
Striped bass (<i>Morone saxatilis</i>)	Microsatellite	10–40 y	Different lineage	Several repeatedly sampled over 40 y	50%	Population declines attributable to habitat degradation	47

*Terminology as used by the respective authors.