

EDUCATION

Participatory adaptive management leads to environmental learning outcomes extending beyond the sphere of science

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Resolving uncertainties in managed social-ecological systems requires adaptive experimentation at whole-ecosystem levels. However, whether participatory adaptive management fosters ecological understanding among stakeholders beyond the sphere of science is unknown. We experimentally involved members of German angling clubs ($n = 181$ in workshops, $n = 2483$ in total) engaged in self-governance of freshwater fisheries resources in a large-scale ecological experiment of active adaptive management of fish stocking, which constitutes a controversial management practice for biodiversity and ecosystem functioning when conducted inappropriately. The collaborative ecological experiments spanned several years and manipulated fish densities in 24 lakes with two species. In parallel, we experimentally compared changes in ecological knowledge and antecedents of proenvironmental behavior in stakeholders and managers who were members of a participatory adaptive management treatment group, with those receiving only a standard lecture, relative to placebo controls. Using a within-subjects pretest-posttest control design, changes in ecological knowledge, environmental beliefs, attitudes, norms, and behavioral intentions were evaluated. Participants in adaptive management retained more knowledge of ecological topics after a period of 8 months compared to those receiving a standard lecture, both relative to controls. Involvement in adaptive management was also the only treatment that altered personal norms and beliefs related to stocking. Critically, only the stakeholders who participated in adaptive management reduced their behavioral intentions to engage in fish stocking in the future. Adaptive management is essential for robust ecological knowledge, and we show that involving stakeholders in adaptive management experiments is a powerful tool to enhance ecological literacy and build environmental capacity to move toward sustainability.

INTRODUCTION

The most pressing global environmental issues cut across academic disciplines and reach beyond the boundaries of science (1–3). Issues such as climate change, invasive species, overharvesting, loss of biodiversity, and erosion of ecosystem function and services (4) hinge on human behavior (5, 6) and associated adaptive capacity, defined as the ability of the governing and managing institutions of a coupled social-ecological system to adapt to changing internal and external demands (7). In this context, it is widely stated in the sustainability science literature that collaborative partnerships between scientists, natural resource users, and managers are fundamentally important to steer humanity toward sustainable resource use (8–10). However, even under a perfect collaborative scenario, producing robust knowledge on which to base management decisions is not a trivial task, and forecasting and prediction have been found to be challenging or even impossible for fisheries and other complex natural resource systems (11–13).

Adaptive management has been proposed as a tool to assist management of social-ecological systems by targeting critical uncertainties about system dynamics, to learn the effects of management interventions at the system level (12–16). Adaptive management is

defined as rigorous experimentation with a set of competing management strategies at the level of managed ecosystems (14) and comes in two variants—passive and active (14, 17). Relative to the passive adaptation of policies as new monitoring information becomes available, active adaptive management is characterized by planned manipulation using rigorously designed and monitored field experiments to elevate the inference space, generate robust ecological learning, and sort out critical uncertainties (14, 17). The ultimate aim of active adaptive management is the identification of policies that safeguard sustainable trajectories under uncertainty (12). Thus, active adaptive management conducted in collaboration with stakeholders and managers is potentially the ideal synergy of rigorous scientific knowledge coproduction, stakeholder engagement, and science communication. However, it is unknown on quantitative grounds whether involving management-empowered stakeholders in the active adaptive management process produces effects on ecological understanding, attitudes, norms, and beliefs, and whether it ultimately alters behavioral intentions.

Although joint “learning by doing,” engagement, and knowledge exchange with stakeholders are assumed benefits of adaptive management (17) and participatory processes (18), no large-sample, controlled experimental data are available to support the assumption that ecological system knowledge from adaptive management, participatory governance, and knowledge coproduction extends beyond the sphere of scientists to managers and stakeholders (18–20). However, the way stakeholder-inclusive adaptive management is often conducted (by experimenting on managed ecosystems with resource users) theoretically supports joint knowledge formation through constructivist learning (21), where new information is internalized by managers and stakeholders through own experience (22). This is promising, because an environmentally conscious and

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scientifically literate public is key to fostering environmental sustainability in management and public policy (6, 23). However, in the absence of controlled quantitative evidence for participatory active adaptive management–induced learning by stakeholders (18, 19), calls for increased use of stakeholder-inclusive research (1), the assumed efficacy of knowledge coproduction to foster environmental literacy (18, 24–26), and the supposed existence of learning spillover effects of participatory adaptive management from science to stakeholders (17) currently appeal mainly to common sense. This cannot be satisfactory from a scientific perspective. The U.S. National Research Council’s review of participatory environmental assessment and decision-making (18) specifically highlighted the need for controlled field studies both in environmental decision-making and on varying levels of public participation, and our work is in response to this call.

We hypothesized that collaborative production of knowledge by scientists, managers, and stakeholders in a participatory active adaptive management process would lead to deeper learning and retention of relevant ecological concepts by managers and stakeholders than a standard scientific lecture alone. Furthermore, adaptive management as a collaborative process was expected to affect more than just ecological knowledge, extending to basal human cognitions, such as beliefs, norms, or attitudes. Changing basal human cognitions related to the environment is of fundamental importance because it has long been known that environmental knowledge alone does not consistently lead to proenvironmental behavior (25) and that human behavior is strongly affected by values, beliefs, attitudes, norms, and other cognitions (27–30). Environmental psychology has thus repeatedly been identified as a relevant discipline in conservation and transdisciplinary research because it focuses on understanding human behavior or the immediate antecedents of behavior (31, 32). However, few sustainability education interventions have looked at cognitive-psychological processes in addition to knowledge gain (32, 33). This is a shortcoming because the path from new information to behavioral change is complex (31, 34), and understanding that path is important because knowledge alone is a poor determinant of subsequent behavior (5, 30, 32, 34).

Here, we drew on a cognitive hierarchy model (27, 35) that structures human cognitions from broad transcendental values to more

domain-specific beliefs (defined as expectations arising from information and experience), specific attitudes (defined as favorable or unfavorable evaluations of specific objects), and personal norms (defined as a perception of what ought to be done in a given context), leading to behavioral intentions and, ultimately, to behavior (Fig. 1). In addition to knowledge, all of these cognitions directly or indirectly influence behavioral intentions, which are the most direct predictor of actual behavior according to the well-established theory of planned behavior (28, 36). We structured the evaluation of stakeholder outcomes around domain-specific (that is, natural aquatic ecosystems) socio-psychological constructs, assessed using standardized questionnaires before and after involvement in active adaptive management compared to controls (Fig. 2).

Description of context, stakeholders, and institutional structure

Randomly selected angling clubs from Lower Saxony (northeast Germany) were involved in a multiyear active adaptive ecosystem experiment (Fig. 2), which involved the release of marked fishes of two ecologically distinct species to study outcomes of the common, popular, but ecologically controversial (37, 38) fisheries management practice of fish stocking. Stocking is the primary management tool of freshwater recreational fisheries in industrialized countries (39) and can provide substantial benefits to fisheries (40). However, indiscriminate stocking carries immense risks for biodiversity and ecosystem functioning depending on the origin of the stocking material (41), the intensity of stocking relative to wild fish production (40), and the species released into ecosystems (38, 42). Given its popularity, fish stocking has been implicated in the loss of wild fishes and local gene pools on a global scale (37). Unwise stocking operations can also be economically wasteful in the absence of stock-enhancing additive effects (43). The additive effects of stocking to increase stock size beyond natural levels are controversial and cannot be easily guaranteed (44–46), justifying an active adaptive management approach to reducing uncertainty on the efficacy of stocking under various ecological conditions (44, 47). Fish stocking is a thorny and nuanced issue, and insights garnered from

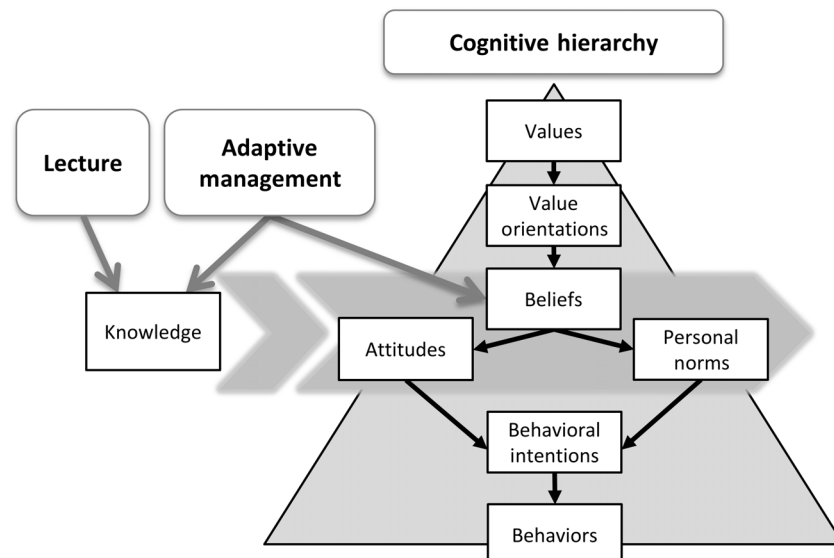


Fig. 1. Cognitive hierarchy including the theorized influence of newly acquired factual scientific knowledge on behavioral precursors.

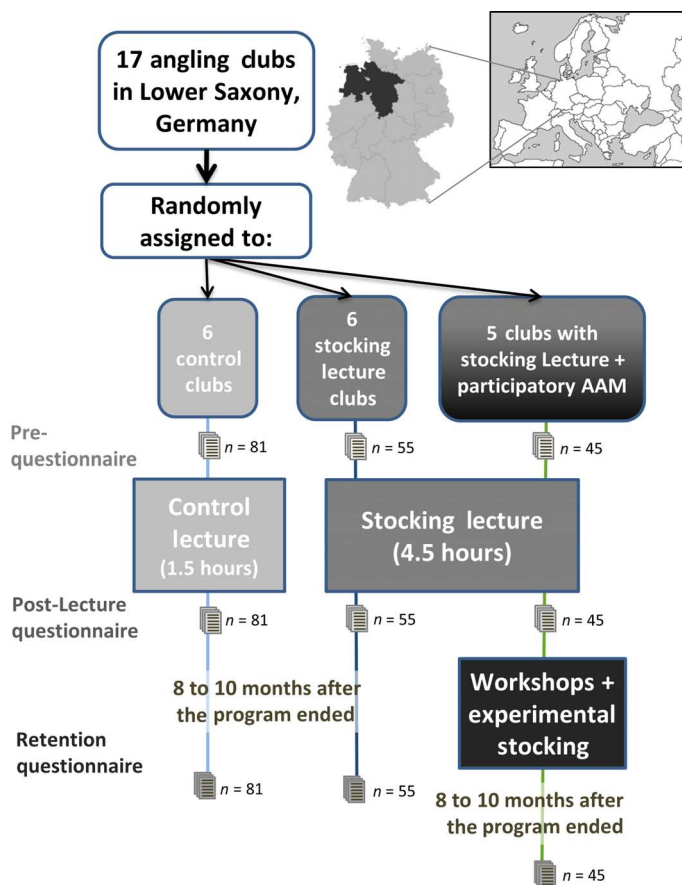


Fig. 2. Experimental design. AAM, active adaptive management.

collaborative learning on this topic are germane to the governance and management of many coupled social-ecological systems, where humans harvest wild-living animals or plants and are involved in release or replanting strategies, such as in hunting, fisheries, and forestry (37). Thus, the many ecological and evolutionary dimensions inherent in fish stocking (for example, local adaptation, density dependence, and size-dependent mortality) (40, 46) and the fact that German angling clubs self-govern decisions about whether and how many fishes of what origin to stock make the case relevant for a range of human-environment interactions.

In Germany, as in much of central Europe (for example, Netherlands, UK, and Austria), local fishery users (predominantly small angling clubs) are fishing rights holders and, in this position, are legally entitled users and managers of inland fisheries resources with effectively no input or control from fisheries agencies (43, 48). Management decisions about club waters (lakes and river sections) are taken by the club heads and club-level fisheries managers, who are elected from the general club membership. The general members of angling clubs exert substantial influence on management decision-making through social pressure and social norms to engage in certain practices, for example, stocking (37). Club leadership may consult with general club members to decide which stocking or other management actions to use to meet legal objectives of sustainability given the local club culture and goals (43). Although clubs may elect to strengthen state-level harvest regulations or conduct habitat enhancement, the standard management tool chosen is fish stocking with native fishes. As the role of agencies and public experts

is minimal in the current freshwater fisheries management system in Germany (43), for science or other forms of knowledge production to enter practice, it has to be internalized by local angling clubs and used to shape local management decisions. Managers of inland fisheries in angling clubs usually receive only basic training in fisheries management by authorities or angling associations and usually do not have university-level degrees in fisheries or environmental management. All management actions are self-financed through membership fees. The public benefits from the voluntary and self-financed actions of angling clubs because wild fish stocks are conserved or restored, and management actions, such as habitat restoration, increase the aesthetic value of inland ecosystems. Similar exclusive fishing rights systems where the right to catch fish is tied to the obligation to engage in sustainable management exist elsewhere in central Europe, rendering anglers and their organizations key environmental managers for inland water bodies (39).

Participatory active adaptive management experiments and treatment groups

We conducted a large quasi-experiment of environmental education with German angling clubs, with managers and interested anglers as sampling units, and evaluated learning outcomes using a pretest-posttest control design (49), also known in ecology as before-after-control-impact (BACI) design (50). Members of 17 angling clubs (the governing board and interested ordinary club members) were randomly assigned to either an extensive lecture (4.5 hours with three breaks) about principles of sustainable fish stocking ($n = 6$ clubs with 2832 organized anglers, 85 of whom attended the lecture), active adaptive management on sustainable fish stocking (which included the stocking lecture to provide a theoretical foundation to base their own experience in evaluating the outcomes of the stocking experiments; $n = 5$ clubs with 1768 organized anglers, 70 of whom attended the lecture), or a short control lecture (1.5 hours with one break; $n = 6$ clubs with 2616 organized anglers, 103 of whom attended the lecture). The control lecture taught general issues of piscivorous fish management without discussing stocking, serving as the control for comparison with the stocking lecture and adaptive management groups to account for social desirability bias and the Hawthorne effect (51) in respondents' answers. The stocking lecture provided modern evidence-based scientific principles of sustainable fish stocking (all lecture contents are in the Supplementary Materials).

The adaptive management group, in addition to being exposed to theory about sustainable stocking through the lecture, went on to practical testing of stocking outcomes using active adaptive management experimentation (14, 17). To this end, fisheries scientists collaborated with managers and stakeholders in the selected angling clubs in large-scale, replicated experiments stocking two popular angling species with contrasting ecologies: northern pike (*Esox lucius*) and common carp (*Cyprinus carpio*) [details can be found in Arlinghaus *et al.* (43)]. The adaptive experiment was designed to constructively learn principles of sustainable stocking and to appreciate ecological conditions that foster or prevent additive effects (that is, increases in stock size relative to the prestocking conditions) using whole-lake experiments, with replicated stocking density treatments using 18 lakes in the case of pike (including six unstocked controls) and 24 lakes in the case of carp (including five unstocked controls). In collaboration with scientists, workshop participants had three sessions where the experiments were planned, hypotheses were generated, decisions about the allocation of lakes to treatments were taken, and preliminary and final results were

discussed. Stocking experiments were conducted in multiple lakes per club, with stocking density treatments ranging from practically relevant to extreme. The purpose of this range of stocking densities was to challenge the ecosystems and arrive at a large inference space as would be typical for active adaptive management. All stocking experiments followed a BACI design with pretreatment and control data. Baseline environmental measurements were recorded from the lakes for 2 years before the experimental manipulations commenced, followed by 2 years after stocking. Data collection included 108 fishing campaigns, collaborative electrofishing for pike, and angling diaries for carp (2700 diaries per year for 2 years) to measure additive effects in catch. Because of the species choice, anglers were exposed to outcomes of stocking into self-reproducing stocks (in the case of pike) and stocking in nonrecruiting species (in the case of carp, which usually does not naturally recruit under German climatic conditions). The managers and anglers thus personally witnessed that securing fisheries enhancement success is much more uncertain with recruiting species because compensatory mortality of juveniles after stocking can often nullify any additive stocking effects (45). At the same time, the risks of stock enhancement to threaten biodiversity are large in the case of recruiting species, because of the possibility of losing locally adapted genotypes through hybridization with fishes that survive the stocking exercise (41). Although the success probability of stocking is generally higher in nonrecruiting species, which was supported in the present experiment for carp (43), overstocking particular species, such as carp, can also lead to water quality problems and food web disruption at high biomass densities (42)—an issue to which the anglers were also exposed as water quality was continuously monitored alongside the catch outcomes of carp stocking.

The ecological experiments were embedded in a social experiment to assess the learning outcomes of participatory active adaptive management. The research team presented the project at the club's general assembly and invited all club heads (including club-level fisheries managers) and any interested anglers to attend the workshops and lectures, up to a maximum workshop size of 25. Participation in the workshops and lectures was voluntary and without remuneration. The effectiveness of the treatments was assessed through three questionnaires sent to all club members, including the workshop participants (Fig. 2): before (sent and returned by mail), after (completed on-site immediately after lecture), and long-term (8 months) retention questionnaires (sent and returned by mail). Questionnaire items and contents were designed to measure the full range of environmental cognitions (beliefs about the functionality of stocking and of alternatives to stocking, attitudes toward stocking, and personal norms toward stocking) and various ecological knowledge domains surrounding fish stocking (for example, concepts of genetic biodiversity, stocking impacts, and density dependence) that were theorized to be key components of the underlying psychologically motivated cognitive hierarchy behavioral model to either support stocking (ordinary anglers) or engage in stocking (decision-makers of the clubs) (Fig. 1 and table S2). We also assessed the behavioral intention to alter stocking in the future as the most direct antecedent to actual behavior (28, 36). Response rates were high for the workshop participants and similar across treatments; 78.6% of the control lecture group, 65.7% of the stocking lecture group, and 64.3% of the participatory active adaptive management group completed all three questionnaires. We assessed changes in cognitions and ecological knowledge domains as well as behavioral intentions as a function of treatment using within-subjects mixed models, with individual-level random effects nested within

club-level random effects. All respondents who did not complete the three questionnaires were dropped from the analysis.

RESULTS

Participatory active adaptive management outperformed the standard lecture at conveying complex ecological and evolutionary knowledge and changing cognitions in the long term to managers and stakeholders, always relative to the control (Fig. 3). Analysis of the immediate post-lecture questionnaire showed that the lecture was initially an effective science communication tool, because all ecological knowledge domains as well as all cognitions except norms were affected in the expected directions relative to the control (Fig. 3). Eight months later, anglers and managers who attended only the stocking lecture still showed a decreased positive attitude toward and lowered functional belief in stocking. Stocking lecture-only anglers also retained increased knowledge on whether or not stocking generates additive effects on the stock size, and that there are fishery advantages to stocking with local genotypes who often show higher local survival (52). They also appreciated the genetic risks of stocking (for example, introgression of non-native genotypes and disruption of locally adapted populations).

These changes from pre to post relative to the control group in terms of knowledge, attitudes, and functional beliefs were also seen 8 months later in the participatory active adaptive management group. However, in contrast to the lecture-only group, personal norms toward stocking were significantly reduced, and support for alternative management to stocking remained elevated. Also, the participatory group retained knowledge about the potential negative impacts of stocking (for example, as a result of competition or predation effects in the food web), an effect that was not present in the lecture-only group 8 months after the program ended (Fig. 3). No significant long-term increases in knowledge relative to the control were seen in adaptive management knowledge and the related knowledge domain on methods for monitoring the success of stocking (Fig. 3). However, as discussed later, this may be due to provision of specific content in the control lecture that led to some degree of learning by the control group related to these two topics.

The ultimate goal of science communication is to have practitioners apply what has been learned to their future actions, and a good surrogate measure of future behavior is the intention to perform that behavior (36). With regard to behavioral intentions toward the future reliance on stocking, the differences between lecture-only and participatory active adaptive management treatments were particularly stark 8 months after the program ended (Fig. 4). Groups engaged in the active adaptive management and stocking lecture-only treatments showed strong and significant behavioral intentions to reduce stocking pike relative to the control lecture group (Fig. 4). The intention to reduce pike stocking was commensurate, with emphasis placed in the lectures, and was supported by the active adaptive field experiments that revealed the lack of additive effects from pike stocking in the angler-managed lakes (43). In addition, the participatory group showed a significantly reduced intention to stock species other than those that are currently stocked and intended to stock less overall—effects not seen in anglers and managers that were only exposed to the lecture about sustainable fish stocking (Fig. 4). The participatory group also indicated their intent to stock fewer carp and small-bodied juvenile fishes in the future (Fig. 4), although these results were not robust to model specification (Fig. 4 and fig. S1). Cumulatively, the

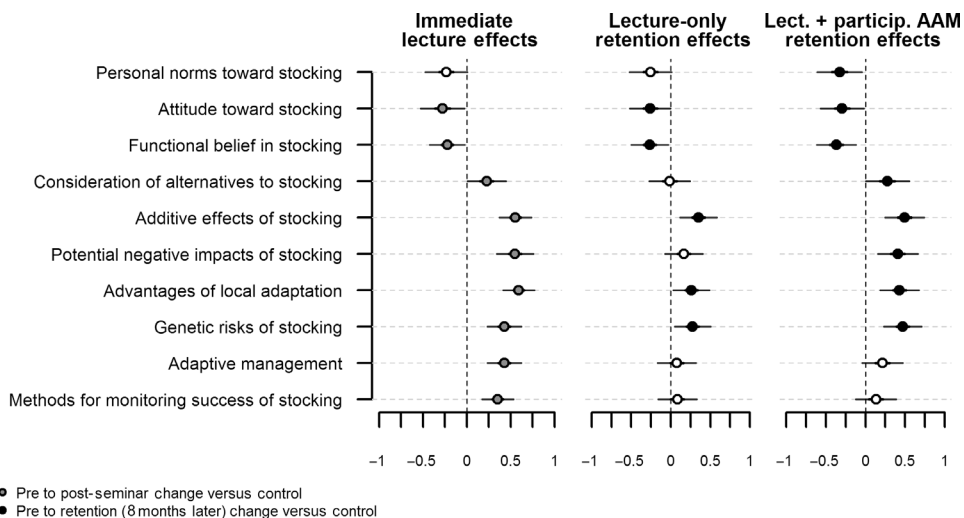


Fig. 3. Treatment effect coefficients relative to the placebo control lecture group. Treatment effect coefficients with 95% confidence intervals (y axis) showing immediate effects of the stocking lecture versus the control group (gray) and long-term retention effects (8 months after the end of the respective treatment; black) on knowledge and cognitions for the lecture-only and lecture plus participatory active adaptive management treatments versus the control lecture group. Confidence intervals that do not overlap zero indicate statistically significant changes in knowledge and cognitions relative to the control group; treatment effect coefficients not significantly different from zero at the $P < 0.05$ level are shown in white.

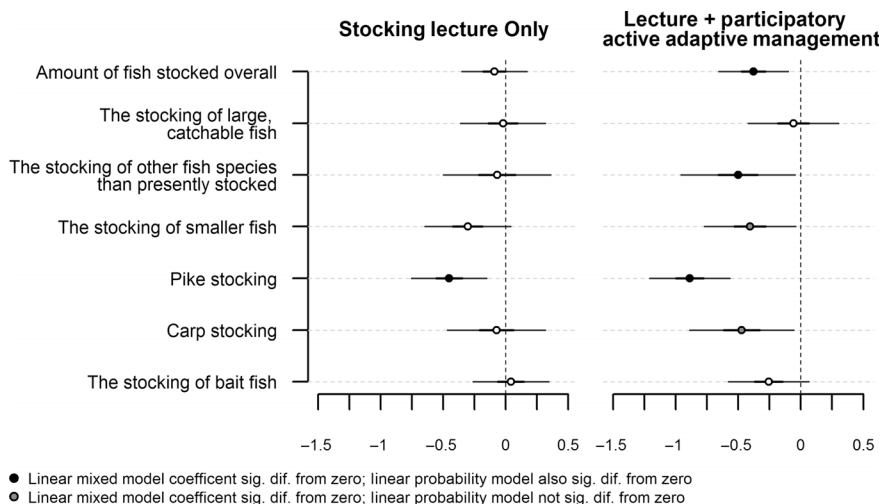


Fig. 4. Changes in behavioral intentions. Plots of coefficients and 95% confidence intervals (x axis) from a linear mixed model comparing changes in behavioral intentions of the stocking lecture and active adaptive management groups versus the control lecture group. Black circles are treatment effects significantly different from zero in linear mixed model analyses that are also significant in linear probability model robustness checks. Gray circles are coefficients significantly different from zero in the linear mixed model but not in the robustness check. Confidence intervals that do not overlap zero indicate statistically significant changes in behavioral intention relative to the control; treatment effect coefficients not significantly different from zero for any of the models at the $P < 0.05$ level are shown in white.

observed changes in behavioral intentions to stock in the future strongly suggested that anglers involved in participatory adaptive management developed a stronger inclination to rely less on stocking compared to lecture-only anglers and controls (Fig. 4). Note that for ethical reasons, we presented results from the collaborative experiments with carp and pike to all angling clubs after the project ended. Hence, it was not possible to determine actual changes in club-level stocking rates because of the interventions.

DISCUSSION

Lecture-based instruction about sustainable stocking performed well at conveying ecological knowledge in the long term, including diffi-

cult knowledge about contentious topics such as genetic biodiversity and local adaptation. This result differs slightly from our previous analyses (53), largely because the present study focused on respondents who completed all three assessments (pre, post, and retention). The present study shows that lectures can be effective when the goal is to elevate ecological and genetic knowledge of highly motivated stakeholders (for example, those who remained through the multiyear program). Maintaining genetic biodiversity in the context of stocking is a notoriously contentious subject even among the scientific community (54); thus, it is of importance that both lecture and participatory groups retained knowledge in the long term regarding genetic and more fundamental ecological issues surrounding fish stocking that relate to potentially irreversible threats. Our findings are of considerable

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relevance for biodiversity conservation in the context of stocking, as native genetic biodiversity is thought to be under greatest threat from contemporary stocking regimes (37, 41). In addition, the spread of non-native species through species introductions is a major environmental issue worldwide (55). It is very promising that anglers were able to strongly internalize nuanced and controversial evolutionary knowledge domains, even when “only” exposed to a long seminar. However, the participatory group in addition retained knowledge about ecological risks involved in stocking (for example, overstocking), which was not the case in the lecture-based group. As mentioned previously, our study involved highly motivated and management-empowered stakeholders. Therefore, the knowledge domains measured were of immediate relevance to the respondents. We would not expect these strong lecture effects in all contexts with less engaged and motivated stakeholders.

The gold standard of science communication in relation to sustainability involves the difficult task of affecting higher-order cognitions that are fundamentally related to proenvironmental behavior and support for environmental policies (6, 25). Here, the participatory group outperformed the lecture-only group as well. Behaviorally relevant cognitions were altered unequivocally only in the adaptive management group, as prostocking personal norms and attitudes and belief in the efficacy of stocking all declined relative to the control lecture (Fig. 3). By contrast, the lecture-only group only showed a sustained dip in prostocking attitudes and functional beliefs about stocking, but personal norms to engage in stocking were not affected. According to the norm activation model (29) and a recent meta-analysis (30), personal norms are key determinants of proenvironmental behavior. It is thus particularly important that the participatory group showed a sustained decline in the personal norm to engage in stocking in the future. Social norms are also very important to motivate or demotivate sustainable behavior (56), and fisheries managers are no different in that they often respond to social norms expressed by anglers to engage in stocking (37). An alteration of individual personal norms in aggregate affects social norms, and our data indicate that participation in active adaptive management leads to a cognitive reshuffling of the mental model and a lower personal conviction that stocking is a panacea. Correspondingly, the participatory group directly expressed a reduced intention to engage in stocking in the future and a greater acceptance of alternatives to stocking, such as habitat management or stricter harvest regulations, commensurate with the state of knowledge that many ongoing fish stocking programs fail to deliver additive effects while generating substantial risks for biodiversity and ecosystem functioning (40, 57). Thus, from a behavioral perspective, participation in active adaptive management had stronger effects than exposure to lecture-based instruction only.

As our adaptive management treatment included a lecture component on top of the collaborative research, we cannot separate the learning outcomes of “pure” collaborative experimental management associated with planning, execution, and evaluation of the stocking experiments from the effect of the theoretical foundation given through the initial lecture in combination with interactions of scientists and stakeholders over time. Our work suggests that the program as a whole has been effective without specifying a particular component of the process. Some background information is always required for effective constructivist learning (58), which seems to be a common misconception regarding constructivist learning—that information should never be told directly to learners and instead they must construct it entirely for themselves. In contrast, our results support the view that

understanding is built upon a foundation of knowledge (59). By logistical and ethical necessity, the experimental design varied both the type of involvement with scientists (general control lecture, stocking-focused lecture, and collaborative active adaptive management) and the length of “contact” with scientists. Thus, in relation to the adaptive management group, we cannot dismiss the possibility that merely the increasing gradient of time in contact with scientists (rather than the personal experience of the adaptive management outcomes) contributed to our findings. However, intensive involvement with scientists over a longer period of time (relative to other, more constrained scientist-stakeholder interactions, such as lectures) is naturally necessary for the participatory active adaptive management intervention, and our treatment replicates the best practices for how this management would be performed with stakeholders. Therefore, our experimental design and results are practically relevant, acknowledging that it is precisely the increased input of “contact time” that has been identified as a common “burden” of participatory processes (18). There have been calls in the literature for rigorous studies to contrast different levels of involvement in participation, to validate the increased time and investment in participatory processes (18, 20, 60, 61). Our research shows that increased involvement with scientists, a requirement of participatory active adaptive management, may contribute to ecological learning and proenvironmental behavioral intentions among stakeholders.

Despite the focus of the lectures and participatory active adaptive management, long-term gains in knowledge of the adaptive management process and the associated need for rigorous monitoring techniques proved to be elusive (Fig. 3). All three groups (control, stocking lecture, and adaptive management) showed a highly significant increase in adaptive management and monitoring knowledge compared to a baseline group, which consisted of anglers who completed pre and retention questionnaires but were not part of this experiment and had no contact with scientists (fig. S2). Thus, it appears that the increased knowledge in the control lecture group over time washed out statistical treatment effects when compared with the stocking lecture and adaptive management treatments. It was ethically and logistically impossible to have a content-free control lecture. The control lecture contained fundamental fisheries management planning principles (including the need to remain flexible and try out management tools, which is a component of active adaptive management) as well as an emphasis on how anglers could engage in monitoring stock developments using angling diaries based on catch per unit effort (43). The control lecture group differs from the untreated baseline group in both exposure to the content of the lecture and contact with scientists; thus, it is not possible to definitively say whether the increased scores in adaptive management knowledge in the control can be attributed to the content of the lecture. The control lecture itself was meant to serve as a placebo to help disentangle how interaction with scientists may affect respondents’ answers in comparison with other treatment groups. However, we can say that, collectively, our results suggest that lectures on fish management topics are sufficient for highly motivated stakeholders and managers to uptake flexible management concepts.

If we compare the control lecture group to the untreated baseline group, control lecture attendees (despite receiving only a cursory mention of stocking) actually increased their belief that stocking works in all circumstances (belief in the functionality of stocking; fig. S2). However, there was also an increase in consideration of alternatives to stocking in the control lecture group compared to the baseline anglers (fig. S2). The control lecture elaborated heavily on alternative means to manage fisheries, emphasizing stricter harvest

regulations, such as harvest slots designed to protect both immature and very large, fecund fishes (62). Therefore, these findings in the control group are consistent with the content of the control lecture. Increased support for stocking seen in the control group may have emerged because stocking might be perceived as an easy and quick fix to declining stocks relative to other management actions emphasized in the lecture (such as harvest regulations) that tend to be less preferred by anglers compared to stocking (63).

Although this study focused on outcomes for managers and stakeholders, we do not intend to imply a hierarchy for knowledge transfer (64). Managers and other angling stakeholders defined the stocking-related uncertainties within their social-ecological systems and shared local ecological knowledge (64, 65), and researchers and anglers learned from each other, built relationships, and continue to collaborate in applied science and resource management. Collaborative coproduction of knowledge and two-way knowledge transfer as conducted here are important elements of transdisciplinary science, integrating stakeholders in the knowledge-generating process, to increase the impact of environmental research and solve real-world sustainability problems (24, 66). There have been ample calls to increase transdisciplinarity in sustainability science (1–3). As with active adaptive management, because of the constructivist and social learning (64, 67) processes inherent in transdisciplinary science, superior science communication outcomes have been assumed to exist for transdisciplinary science compared to other forms of stakeholder science communication (24, 25, 68), but no experimental evidence exists (20, 60, 61). Our work adds empirical evidence that effective collaborative coproduction of knowledge occurs in transdisciplinary science. Also, although this work did not focus on social learning, active adaptive management as conducted here facilitated key elements of the process of social learning in natural resource management, such as joint problem identification, collaborative understanding of the managed system, and building working relationships and trust (67).

An important avenue for future research would explore how gender influences knowledge exchange and learning outcomes of participatory active adaptive management. Although women were present both in leadership roles and among the general angling club membership, the overall proportion of female anglers in our sample was low (2.7%), which is representative of the lower participation rate in general for females in recreational angling for a variety of reasons, some relating to gendered structural and societal influences (69, 70). Given the importance of diverse (including gendered) perspectives in ecological management (71), more work on the role played by gender in the process of knowledge coproduction in active adaptive resource management is needed.

To conclude, we have shown that lectures can be an effective tool to foster learning, proenvironmental cognitions, and behavioral intentions in motivated and empowered stakeholders. Stakeholder participation in active adaptive management serves a dual role of facilitating rigorous scientific learning about managed ecosystems (16) while leaving a legacy of enhanced ecological knowledge, altered cognitions, and revised behavioral intentions among managers and stakeholders that likely affect future management decisions. Furthermore, knowledge coproduction and collaboration between scientists and stakeholders build the adaptive management and governance capacity of stakeholders (26) to conduct and analyze experiments and manage resources adaptively on their own. From strictly scientific grounds, engaging in some form of adaptive management is considered funda-

mentally important for sustainable fisheries (72) and natural resource management in general (12, 14, 17). On the basis of our findings, these initiatives can also leave a strong legacy in the ecological mental models, personal norms, and behavioral intentions of those involved in the process. These results are of particular importance for the common situation in fisheries, hunting, forestry, and agriculture, where local stakeholders are not only users of renewable resources but also managers of the environment. The benefits of increased ecological literacy, proenvironmental cognitions, and behavioral intentions for sustainable resource use may well be higher than the transaction costs induced by working cooperatively, and the societal impact of environmental research is similarly increased. Based on our work, we suggest that there are few alternatives to collaborative adaptive management when the aim is to achieve sustainable practices in complex ecosystems, even if this means that researchers increasingly leave their comfort zone and interact proactively with stakeholders.

MATERIALS AND METHODS

Experimental design and sample selection

Our research was part of a 5-year inter- and transdisciplinary project called “Besatzfisch” (www.besatz-fisch.de). The program was a joint research project of fisheries biologists, local angling stakeholders, environmental sociologists, and psychologists. The main goal was to jointly research and communicate sustainable stocking practices. German regulations on research with human subjects were followed. All participation was voluntary, no participants were harmed, all data are reported anonymously, and all participants were debriefed after the study.

Seventeen randomly selected angling clubs from the German state of Lower Saxony participated in this project. All anglers from each club or 400 randomly selected anglers from a given club for clubs with >400 members, and all club members involved with the direct management decisions and actions for stocking were the sampling frame for this study. The clubs were randomly sorted into treatment groups (Fig. 2). Preliminary questionnaires to assess stocking-related knowledge, basal cognitions, and behavioral intentions were sent to anglers in the sampling frame. Participants in the workshops and lectures were self-recruited from the entire club membership after the project was presented by the project scientist (R.A.) at the annual general assembly. Generally, most of the club’s board (that is, direct resource managers) and avid and interested anglers attended the lectures (about 15 to 20 people from each club; participation in the workshops was capped at a maximum of 25 per club). The small size of the treatments relative to the size of the angling clubs was designed to foster interactions between the researchers and a small group of participants. Group sizes were also small to mimic a typical classroom context, which is familiar to German fisheries managers in angling clubs who have to take courses in fisheries management and to ordinary anglers who have to pass angling examinations to obtain a German fishing license (73). Lectures took place in the club’s residency or in local restaurants with an appropriate workshop facility. Immediately after lecture, a post-questionnaire was administered and completed on-site by lecture participants, but no post-lecture questionnaire was sent to nonlecture participants. All managers and anglers who completed a preliminary questionnaire were mailed (both lecture and workshop members and the wider sampling frame) a retention questionnaire 8 to 10 months after their respective treatment program concluded. In all, 2483 anglers completed at least one questionnaire.

Description of interventions

Lecture contents

All lectures were administered by the same individual (R.A.) to account for instructor effects. The stocking lectures and the PowerPoint presentations in German (original) and with English translations can be found in appendix S2. Video recordings of the lectures can be found online (in German; www.besatz-fisch.de).

Control lecture

The control lecture lasted 1.5 hours. It taught basics for freshwater piscivorous fish management, monitoring and planning (including methods for monitoring such as tracking catch per unit effort), and basic fish population ecology, and focused on population dynamics and harvest regulations. Stocking and habitat management were mentioned as alternative management options, but there was no detail given on stocking as a tool to manage fisheries; $n = 6$ clubs were exposed to this lecture.

Stocking lecture

The stocking lecture was provided to $n = 6$ clubs, lasted 4.5 hours, and had three units. The first unit also included basic freshwater fish ecology, as in the control lecture. The second lecture unit went into depth into determinants and examples of successful and unsuccessful stocking, potential risks of stocking, stocking genetics, the benefit of locally adapted stocks, and the risks of biodiversity loss due to stocking nonlocal genetic material. Emphasis in the third lecture unit was on planning, monitoring and evaluation, and flexible iterative thinking about management choices (adaptive management). Decision trees on how to manage fish stocks focused on stocking, and its alternatives were strongly emphasized.

Collaborative active adaptive management

$N = 5$ clubs were initially exposed to the stocking lecture as described above. Self-selected active adaptive management club members additionally participated in up to three additional workshops with fisheries researchers, each lasting approximately 3 hours. In the initial workshop, the researchers provided information on the size and composition of fish communities in each club's waters, lake morphology, and food web structure. Given this information, the anglers designed their own experiments to test the effects of stocking density with pike and carp (as explained in the main body of the text to serve as examples of self-reproducing and non-naturally recruiting stocks, respectively), given the unique characteristics of their managed waters and club-specific stocking goals, plans, and uncertainties. Together, the experiments designed individually by the five clubs were orchestrated to form a broad active adaptive experiment on evaluating stocking success for pike and carp, given that the different habitat qualities and characteristics of the 24 lakes in Lower Saxony all belong to the $n = 5$ clubs involved in the active adaptive management collaboration. There were two stocking levels for pike (35 or 70 fish/ha, with 70 fish/ha being extreme), whereas the carp experiments were carried out in a gradient of stocking densities from 0 to 180 kg/ha (sizes of pike were about 20 cm; sizes of carp were about 35 cm). The stakeholders were free to choose in which lakes they wanted to test the different levels. Overall, the research team made sure that each club experienced a gradient of carp and both stocking rates of pike (including the no-stocking controls) because of the importance for learning by comparison. In subsequent workshops, the researchers shared preliminary results of the collaborative stocking experiment, as well as other stocking experiments that demonstrated no additive effects of stocking. Club anglers also participated in gathering data through log-books of their catch and experimental fishing (all workshop members

were always invited to join the field work), to record how catch per unit effort (a standardized measurement of catch) changed because of the stocking experiments. The goal of jointly conducting stocking experiments in the active adaptive management group was to expose anglers and managers to the complexities and uncertainties of stocking and to jointly generate evidence of effective and ineffective stocking practices immediately relevant to anglers. Scientists and anglers evaluated the study outcomes, which demonstrated a lack of additive stocking effects with pike (self-reproducing stock) and successful additive stocking effects with carp [non-naturally reproducing species; for empirical details, see the study of Arlinghaus *et al.* (43)]. In a final meeting, anglers saw the results of their own club's experiment, as well as the results compiled from angler-designed experiments across all 24 lakes, and discussed management options for the future. A documentary provides an overview of the whole process (www.youtube.com/watch?v=sFMvsz4YufY). The stocking lecture and control lecture anglers were debriefed after the retention assessment about the entire results in a separate workshop 8 to 10 months after the program ended.

Untreated baseline group

The untreated baseline group consisted of 1462 anglers from the 17 angling clubs that did not directly interact with researchers but did receive and complete both the pre and retention questionnaires. In the untreated baseline group, there were 599 control lecture club anglers, 488 stocking lecture club anglers, and 375 active adaptive management club anglers who did not receive any treatments but did return their questionnaires.

Questionnaire design

Likert scales were constructed from multiple five-level response format items (see questionnaire in the Supplementary Materials) to operationalize the environmental domains shown in table S2. Questionnaires were developed in collaboration with experts in the field of fisheries management to verify that the knowledge content related to fish stocking reflected current state of the art. Moreover, the questionnaire was codeveloped by experts in education sciences and social psychology.

Questionnaire items were mostly constructed in an ad hoc fashion related to the topic of interest (stocking), because few published item lists were available. In addition to assessing personal norms and attitudes toward stocking, as well as functional beliefs about stocking, the assessment of ecological content focused on key areas that were emphasized in the stocking lecture and reflected current state-of-the-art biological knowledge on the topic. These included ecological knowledge that there may be no additive effects of stocking into self-reproducing populations (46), potential negative ecosystem impacts of stocking including intraspecific competition and risk of invasive species introductions (37, 38), advantages of locally adapted stocks versus hatchery fish of different genetic origin (52), and genetic risks of stocking including introgression and outbreeding depression (41). Two further knowledge domains addressed flexible thinking about management as an active process of adaptation (72). The "adaptive management" knowledge domain assessed understanding that stocking operations should be flexible under changing conditions, and "methods for monitoring success of stocking" evaluated knowledge of effective monitoring methodology to rigorously inform adaptive management of stocking programs.

Cognitive behavioral precursors assessed in the questionnaire were "personal norms regarding stocking" and "attitude toward stocking," along with "belief in the functionality of stocking" (that stocking usually

works to increase fisheries catch) and the related but opposing belief “consideration of alternate management options to stocking” (that alternative management options are equally effective as, if not more effective than, stocking). The latter concept was assumed to measure the “inverse” of the former belief because anglers who believe that stocking always leads to positive outcomes would be unlikely to consider other options such as habitat enhancement or harvest regulations to maintain stocks or to increase fisheries yield.

Statistical analysis

Constructs of each assessment domain (that is, knowledge and cognitions) were obtained from Likert scales constructed from batteries of Likert response format items and analyzed with parametric methods (74, 75). Data were analyzed in a pretest-posttest control framework (49). Clubs had been randomly assigned to the treatment and control groups, and to account for the panel nature of clubs as well as individuals; hierarchical random effects were used with individual-level random effects nested within club-level random effects, in a generalized linear mixed model approach to providing parameter estimates for fixed effects (76). Linear mixed models were fit by maximum likelihood in the statistical package R (<http://cran.r-project.org>) using the package nlme (77) and compared to null models using likelihood ratio tests (tables S11 to S13) to assess fit metrics, because restricted maximum likelihood (REML) cannot be used to compare models with different fixed effect structures (78). Plots of residuals versus fitted values were visually inspected for deviations from homoscedasticity, and residuals were tested against predictors for evidence of endogeneity; neither was found. Final models were fit using REML criteria with the package lmerTest (79). Residual versus fitted plots were checked to satisfy homoscedasticity, and normal probability plots were checked for normality assumptions. Satterthwaite approximations to degrees of freedom were used to conduct *t* tests on model fixed effects, with an α cutoff of $P < 0.05$ for rejection of the null hypothesis. For each model, the Likert scale construct was the dependent variable with dummy coefficients for fixed effects for the pretest versus the posttest (or pretest versus retention test), control versus stocking seminar treatments, and the interaction between the two (the treatment effect), with individual-level random effects nested within club-level random effects parsed from global variance.

Behavioral intentions were assessed with individual five-level response format items that ranged from “strongly increase” to “strongly decrease.” Applying the linear mixed model as we did to the Likert scale constructs applies an interval assumption to ordinal-scaled data. This is a common practice, for example, in psychology, and the interval assumption is conservative because it increases the likelihood of type II error (80). Because the quantity of interest in our analysis is the treatment effect coefficient, we could not use an ordered logit because interpretation of interactions in nonlinear models is nontrivial. Instead, for a model robustness check, we used a linear probability model with a binary dependent variable, collapsing the five-level response format into two categories: strongly increase/increase/stay the same (the status quo for management of these fisheries) versus decrease/strongly decrease. Diagnostics for model fit, normality, homoscedasticity, and endogeneity were performed as elaborated in the previous paragraph for the linear mixed model; fit, homoscedasticity, and endogeneity checks were performed as appropriate for the generalized linear mixed model (table S13).

For the analysis presented in this paper, missing values were replaced with the neutral response category (for example, “not sure” and “neither agree nor disagree”). For robustness, we also analyzed

cases where all individuals missing an item for a construct were dropped from analysis of that construct and a second case where all missing values were replaced with a respondent’s average response for a given scale. Results were similar in all analyses, and only the “neutral replacement” variant is presented here for brevity. The structure of the data further supported this decision, as missing values clustered on particular items instead of occurring uniformly, and more missing values were found in the pretest than in the posttest. This suggested that a missing value indicated a lack of understanding or confidence.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/3/6/e1602516/DC1>

- fig. S1. Changes in behavioral intentions (pre to retention) relative to the control lecture group.
fig. S2. Treatment effect coefficients (pre to retention) relative to a baseline group of anglers.
table S1. Brief overview of the two lecture interventions and the active adaptive management intervention.
table S2. Description of domains measured through Likert constructs in the evaluation questionnaires.
table S3. Immediate post-lecture effects.
table S4. Treatment effects versus the control lecture group.
table S5. Treatment effects versus the baseline untreated group.
table S6. Changes in behavioral intentions related to future stocking for the stocking lecture-only group compared to the control lecture group.
table S7. Changes in behavioral intentions related to future stocking for the active adaptive management group compared to the control lecture group.
table S8. Changes in behavioral intentions related to future stocking for the control lecture group compared to the baseline untreated group.
table S9. Changes in behavioral intentions related to future stocking for the stocking lecture group compared to the baseline untreated group.
table S10. Changes in behavioral intentions related to future stocking for the active adaptive management group compared to the baseline untreated group.
table S11. Akaike information criterion, log likelihood, and likelihood ratio test results versus the null model for BACI models with treatment effects compared to the control.
table S12. Akaike information criterion, log likelihood, and likelihood ratio test results versus the null model for BACI models with treatment effects compared to the untreated baseline group.
table S13. Akaike information criterion, log likelihood, and likelihood ratio test results versus the null model for behavioral intention models with treatment effects compared to the control lecture group.
table S14. Individual-level (by treatment) descriptive summary statistics.
table S15. Club-level (by treatment) descriptive summary statistics.
appendix S1. Questionnaire contents: complete list of questions in the original German with English translation for each item.
appendix S2. Lecture slides (in the original German with English translation).
appendix S3. Data.

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