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Diversity and complexity of angler behaviour drive socially optimal input and output regulations in a bioeconomic recreational-fisheries model

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Abstract

In many areas of the world, recreational fisheries are not managed sustainably. This might be related to the omission or oversimplification of angler behaviour and angler heterogeneity in fisheries-management models. We present an integrated bioeconomic modelling approach to examine how differing assumptions about angler behaviour, angler preferences, and composition of the angler population alter predictions about optimal recreational-fisheries management, where optimal regulations were determined by maximizing aggregated angler utility. We report four main results. First, accounting for dynamic angler behaviour changed predictions about optimal angling regulations. Second, optimal input and output regulations varied substantially among different angler types. Third, the composition of the angler population in terms of angler types was important for determining optimal regulations. Fourth, the welfare measure used to quantify aggregated utility altered the predicted optimal regulations, highlighting the importance of choosing welfare measures that closely reflect management objectives. A further key finding was that socially optimal angling regulations resulted in biologically sustainability fish populations. Managers can use the novel integrated modelling framework introduced here to account, quantitatively and transparently, for the diversity and complexity of angler behavior when determining regulations that maximize social welfare and ensure biological sustainability.

Keywords: angler specialization; age-structured model; harvest regulations; effort dynamics; utility

Introduction

Recreational anglers are the dominant users of most freshwater and some coastal fish stocks in industrialized countries (Arlinghaus and Cooke 2009). Accordingly, managers are faced with the challenge of balancing the interests of angling groups utilizing fisheries resources with concerns about the biological sustainability of exploited fish populations (Radomski et al. 2001; Peterson and Evans 2003; Arlinghaus 2006b). The lack of sustainable recreational-fisheries management in some areas of the world (Post et al. 2002; Lewin et al. 2006) suggests that current management strategies have not always been successful in achieving this balance. This may be because effectively managing a fishery requires understanding not only how fish respond to exploitation, but also how anglers alter their fishing behaviour in response to social and ecological changes in the fishery; consequently such behavioural dynamics must be incorporated into integrated fisheries-management models (Johnson and Carpenter 1994; Radomski et al. 2001; Post et al. 2008). In the past, however, recreational-fisheries researchers and managers have focused on the biological dimension of recreational fisheries, largely overlooking the "human dimension" (Aas and Ditton 1998; Cox and Walters 2002a; Arlinghaus et al. 2008a). To move forward, it is critical to quantify and integrate angler preferences and resulting behavioural decisions into recreational-fisheries models designed to determine optimal management policies (Radomski and Goeman 1996; Arlinghaus et al. 2008a).

Optimum social yield (OSY) is one management objective that can incorporate social and economic aspects into fisheries-management models and policies (Roedel 1975). In comparison with the traditional approach of managing for maximum sustainable yield (MSY) in both commercial and recreational fisheries

(Larkin 1977; Malvestuto and Hudgins 1996; Hilborn 2007), OSY is better suited to recreational fisheries because it incorporates socio-cultural benefits a fishery provides that are not measured by yield alone, such as an angler's satisfaction resulting from catching a large fish (Roedel 1975; Malvestuto and Hudgins 1996; Radomski et al. 2001). OSY integrates such social and economic factors with biological considerations, to develop a fisheries-management objective that maximizes the total utility (alternatively termed benefits or social welfare; Dorow et al. 2010) that a recreational fishery provides to society (Roedel 1975; Malvestuto and Hudgins 1996). Hence, similar to MSY, management for OSY may provide an unambiguous management objective against which to judge management developments and successes (Bennett et al. 1978; Barber and Taylor 1990; Radomski et al. 2001).

Despite the general advantages of a socioeconomic objective such as OSY over MSY for managing recreational fisheries, few recreational-fishing models based on utility theory have been developed to predict the optimal social welfare generated by different management schemes (e.g., Die et al. 1988; Jacobson 1996; Massey et al. 2006). Furthermore, angler-effort dynamics, if considered at all, are generally assumed to be predominantly or exclusively driven by catch rates, or by some other measure of fish abundance (Johnson and Carpenter 1994; Beard et al. 2003; Post et al. 2003). However, angler behaviour is likely much more complex (Carpenter and Brock 2004; Arlinghaus et al. 2008a). It is known from social-science research on recreational fisheries that, in addition to catch rates, a diverse set of social and biological attributes of a fishery – such as availability of preferred species, fish size, congestion, facilities, regulations and the perceived aesthetic value of the fishery – affect the participation decisions of anglers (reviewed in Hunt 2005). Therefore, angler-effort dynamics driven by catch rates alone can be unrealistic (Paulrud and

Laitila 2004). Hence, recreational-fisheries models designed to maximize angler utility should account for complexity in angler behaviour by incorporating multi-attribute utility functions that describe the fishing-participation decisions of anglers.

Another important, yet often overlooked, aspect of recreational fisheries is angler diversity (i.e., heterogeneity in angler behaviour; Anderson 1993; Jacobson 1996; Post et al. 2008). Various types of anglers will differ not only in their fishing preferences, and therefore in the utility they derive from fishing (Fisher 1997; Connelly et al. 2001; Arlinghaus et al. 2008b), but also with respect to their fishing practices (Bryan 1977; McConnell and Sutinen 1979; Hahn 1991). Hence, the potential impacts of fishing on fish populations likely vary with angler type (Dorow et al. 2010). For example, in many fisheries a minority of anglers catches the majority of fish (Baccante 1995), and this minority typically encompasses the most avid and specialized angler types (Dorow et al. 2010). Human-dimension researchers have repeatedly highlighted that accounting for angler diversity is important for sustainable fisheries management (Fisher 1997; Aas et al. 2000; Arlinghaus and Mehner 2003). While there are some examples of coupled social-ecological models that link complex angler behaviour and fish population dynamics (e.g., Cole and Ward 1994; Woodward and Griffin 2003; Massey et al. 2006), to our knowledge only McConnell and Sutinen (1979) and Anderson (1993) considered heterogeneity either in angler preferences or fishing practices in a bioeconomic modelling context. In both cases, the modelling frameworks differed substantially from that presented here. In particular, these earlier studies did not use random-utility models to predict angler participation under different management scenarios, and the complexity of the biological and angler-behaviour components were much more simplified.

Our goals of this study are fourfold. First, we present an integrative bioeconomic modelling approach that links the ecological, socioeconomic and management components driving angler-effort dynamics to a fish population model, and that allowed optimal harvest regulations for various angler types to be predicted. Second, we demonstrate the importance of assumptions about angler-effort dynamics in fisheries management by contrasting predictions from models that make traditional assumptions of static or exclusively catch-based dynamic angler behaviour with models that assume more complex, multi-attribute dynamic behaviour. In this study, complexity in angler behaviour is characterized by whether angler-effort dynamics rely on a single fishery attribute to drive angler behaviour or on multiple fishery attributes. Third, by incorporating heterogeneity in angler behaviour into a bioeconomic modelling framework by accounting for the perceived utility a fishery provides to an angler population,, we examine how angler diversity (i.e., heterogeneity of angler types) and the composition of the angler population (in terms of these angler types) influence predictions about optimal management strategies. Finally, we explore how different management objectives, represented by different measures of social welfare, alter predicted optimal management regulations. Rather than simulating a particular fishery, our approach is stylized in nature and is intended to demonstrate the suitability of an integrated bioeconomic modelling approach for investigating coupled angler-fish population dynamics.

Methods

We developed an integrated model in which angler-type-specific utility derived from both catch- and non-catch-related attributes of the fishing experience was linked to a deterministic age-structured fish population model for a single-species, single-lake fishery. Our modelling framework had three components: (*i*) a management component that described the regulations applied to the fishery system, (*ii*) a socioeconomic component that described the effort dynamics of different angler types, and (*iii*) a biological component that described the fish population dynamics. Angler utility was used to determine changes in angling effort in the dynamic angler-behaviour scenarios, and to make predictions about optimal harvest regulations. The resulting impacts on the fish population under different management policies were investigated to determine whether management for social optima also conserved the fish population. All model equations are summarized in Table 1 and illustrated in Figure 1; model parameters are listed in Tables 2 and 3.

Insert
Figure 1

Management component

Traditional harvest-control measures have focused on regulating the harvest rates of individual anglers to achieve biological sustainability (Radomski et al. 2001). However, in open-access systems, which are typical for many recreational fisheries (Post et al. 2002), output-control measures that do not directly limit angler numbers cannot constrain total fishing mortality (Radomski et al. 2001; Cox and Walters 2002a; Cox and Walters 2002b). The failure of traditional output-control measures to preserve some recreationally exploited fish populations (Post et al. 2002) has led to a call for input-control measures that more directly limit angling effort (Cox and Walters 2002a; Cox and Walters 2002b). Therefore, we investigated two types of regulatory policies over a range of values (Table 2): a traditional output-control regulation, expressed in terms of a minimum-size limit, and an input-control regulation, expressed in terms of the number of angling licenses issued.

Socioeconomic component

Angler utility

Economic utility theory assumes that human agents make choices that will maximize their personal utility (alternatively termed benefits or satisfaction; Perman et al. 2003). For example, from a set of potential alternatives, recreational anglers will choose to fish a fishery that provides them with the greatest possible utility (Hunt 2005). Multiple attributes contribute to an individual angler's utility function, and the relative importance of fishery attributes (such as fish size or crowding), called part-worth utilities, for total angler utility vary substantially among different angler types (Aas et al. 2000; Oh et al. 2005a; Oh and Ditton 2006). Choice models based on random-utility theory (McFadden 1974; Manski 1977) can be calibrated with actual (revealed) or hypothetical (stated) empirical site-choice data. Such models constitute one approach that can be used to predict recreational-angler behavior, which can then be used to predict and understand how anglers will react to changes in the attributes of a fishery (Paulrud and Laitila 2004; Massey et al. 2006; Wallmo and Gentner 2008).

Three scenarios of angler behaviour were investigated. In the first scenario, we simulated static angler behaviour, characterized by anglers that did not respond to changes in a fishery's attributes (such as fish size, catch rate or congestion level), but instead, participated at the maximum effort level allowed. Predictive recreational-fisheries models often assume constant exploitation rates and ignore angler dynamics when evaluating regulation impacts (e.g., Dunning et al. 1982). The static scenario mimics this situation by keeping angling effort constant. In our two other scenarios, anglers were allowed to behave dynamically, i.e., they chose to fish or not to fish depending on the time-varying utility provided by the fishery. Utility functions that described the preferences of a particular angler type for the fishing attributes experienced were used to simulate angler-type-specific behavioural decisions. In the second scenario, the utility of fishing was based on the utility gained from catch rates alone (Table 1, equation 1a; and Table 3), an approach used in previous recreational-fishing models (Cox et al. 2003; Post et al. 2003). In the third scenario, utility was based on a more realistic multi-attribute utility function (Table 1, equation 1b; and Table 3). Attributes included in this utility function were catch rates, average size of fish caught, maximum size of fish caught, angler congestion, minimum-size limit regulations and license costs, all of which have been shown to affect anglers' fishing decisions about participating in a particular fishery (Hunt 2005). Although the multi-attribute utility function was not used to determine angling effort in the static scenario, for comparative purposes it was used to evaluate the quality of the fishery at the end of the simulations (Table 1, equation 1b) (Figure 1).

Insert
Table 1

Angler-effort dynamics

In our second and third scenarios, anglers responded dynamically to their perception of fishery quality by changing the amount of effort they devoted to the fishery. In these scenarios, the utility gained from a fishing experience determined the angler's probability of an angler choosing to fish over the alternative of not fishing (Table 1, equation 2a). This probability was calculated as is typical in empirical choice models (Oh et al. 2005b; Massey et al. 2006). The probability of fishing based on angler utility, as well as the maximum time anglers would fish in a year irrespective of fishing quality, were then used to determine realized annual effort of anglers (i.e., the amount of time they actually fished; Table 1, equations 2b-2e; Figure 1). To account for the fact that anglers make decisions based on previous experiences and habits, and not exclusively based on their most recent experiences (Adamowicz et al. 1994), a fishing-behaviour persistence term (Table 2) was introduced to the effort dynamics (Table 1, equation 2b). This term described the relative influence of last year's realized fishing probability on the current year's realized fishing probability.

We assumed that the realized annual angling effort (Table 1, equation 2e) was limited by three factors: the realized probability of fishing, the desired maximum effort that an individual angler would fish irrespective of angling quality (Table 1, equation 2c), and the input-control measure expressed in terms of the number of angling licenses issued (Table 1, equation 2d). The instantaneous fishing effort of a given angler type was assumed to be constant throughout the fishing season, and to equal zero after the fishing season ended (Table 1, equation 2f).

Insert
Table 2

Angler heterogeneity

Angler heterogeneity was introduced into our model by defining three different angler types – generic, consumptive, and trophy anglers – that differed in their degree of angling specialization (Bryan 1977; Ditton et al. 1992; Table 3). Our parameterization of angler behaviour was based on recreational specialization theory (Bryan 1977; Ditton et al. 1992). Bryan (1977) described four general angler types ranging from the casually involved to the technique- and setting-specialist. As specialization levels increase, skill levels improve, fish size is of greater importance, and harvesting fish is of lesser importance (Bryan 1977). This can lead to differing propensities to perform voluntary catch-and-release (Arlinghaus 2007), and to an increased ability to catch more and larger fish (Dorow et al. 2010). Angler preferences also change with specialization: for example the value of solitude relative to the social aspects of the fishing experience varies with specialization (Ditton et al. 1992; Connelly et al. 2001). Based on pioneering work by Bryan (1977) and subsequent applications and refinements (e.g., Quinn 1992; Allen and Miranda 1996; Fisher 1997) we devised qualitatively realistic angler-type-specific part-worth-utility functions for the various attributes of the fishing experience. Figure 2 illustrates qualitative differences in preferences and tolerances for different fishery attributes among angler types, while Figure 3 illustrates the resultant utility functions.

Insert
Figure 2

Parameters for three stylized angler types were chosen to reflect differential skill, consumptive orientation and overall dedication to the recreational fishing experience (Table 3). Angler types differed in both their fishing practices, and their preferences for various attributes of the fishing experience (Figure 2; Table 3). Generic anglers were assumed to be the least specialized, consumptive anglers were intermediate, and trophy anglers were the most specialized. By definition, consumptive anglers had the greatest consumptive orientation. Accordingly, generic anglers were assumed to (*i*) be least likely to participate in angling activities, (*ii*) be intermediate in their tolerance of restrictive minimum-size limits, (*iii*) be the most affected by license costs, (*iv*) have an intermediate interest in catch rates and be least interested in the challenge of catching fish, (*v*) be least interested in average fish size and be intermediately interested in trophy-sized fish, (*vi*) be most tolerant of angler crowding, (*vii*) be least skilled, and to (*viii*) practice some voluntary catch-and-release of harvestable fish (Table 3). In contrast, consumptive anglers were assumed to (*i*) participate at an intermediate level in angling activities, (*ii*) be least tolerant of restrictive minimum-size limits, (*iii*) be intermediately affected by license costs, (*iv*) be most interested in catch rates and intermediately interested in the challenge of catching fish, (*v*) be intermediately interested in average fish size and least interested in trophy-sized fish, (*vi*) be intermediately tolerant of angler crowding, (*vii*) have intermediate skills, and (*viii*) practice no voluntary catch-and-release of harvestable fish (Table 3). Finally, trophy anglers were assumed to (*i*) participate the most in angling activities, (*ii*) be most tolerant of restrictive minimum-size limits, (*iii*) be least affected by license costs, (*iv*) be least interested in catch rates but most interested in the challenge of catching fish, (*v*) be most interested in average fish size and trophy-sized fish, (*vi*) be least tolerant of angler crowding, (*vii*) have the greatest skills, and (*viii*) practice the most voluntary catch-and-release of harvestable fish (Table 3). Trophy anglers were also assumed to target larger fish relative to consumptive and generic anglers (through the use of different fishing gear; Rapp et al. 2008; Table 3). Parameter values and further justification for these assumptions are outlined in Table 3, and the resulting shapes of the angler-type-specific part-worth-utility functions are illustrated in Figure 3. Although these functions might look different for particular fisheries, we believe that their general features adequately reflect the angling behaviour and preferences of differently specialized recreational anglers.

Insert
Figure 3
and
Table 3

The importance of angler heterogeneity for determining optimal fishing regulations was examined by first comparing model results among different homogeneous angler populations, each composed of a single angler type. However, because natural angler populations are likely comprised of a mixture of angler types, we also considered a mixed angler population composed of all three angler types mentioned above. As this aspect increases the model complexity and in an attempt to simplify angler descriptions, recreational-fisheries researchers and managers may wish to simplify angler descriptions by assuming some form of average angler behaviour (Hahn 1991; Aas and Ditton 1998). Therefore, to examine the importance of explicitly accounting for the composition of the angler population on model predictions of optimal regulations, we compare model results for an average angler type population with those for a corresponding mixed angler population composed of three angler types. here, the average angler type was defined by a weighted average of fishing preferences and fishing practices of the three angler types according to their relative frequencies in the mixed angler population (Table 2). It should be noted, that this is a weighted average and therefore depends on the assumptions about the relative abundance of angler types in the mixed angler population. However, this example demonstrates the implications of the simplifying assumption of an average angler.

Biological component

Our study aimed to show how the biological and socioeconomic and management components of recreational-fishery systems could be linked in an integrated modelling framework. For brevity we therefore only describe the essentials of the biological component in terms of growth, reproduction and survival functions.Tables 1 and 2 provide further details about equations and parameters..

In short, an age-structured model was used to describe the fish population being exploited. Individual fish within an age class were assumed to be ecologically equivalent (Tables 1, equations 3a and 3b). The fish population model was parameterized to be representative of a northern pike (*Esox lucius* L.) population. We chose this species due to its importance for recreational fisheries in both North America and Eurasia (Paukert et al. 2001; Arlinghaus and Mehner 2004a). In all scenarios, the fish population reached its demographic equilibrium prior to the introduction of fishing, and the results presented correspond to equilibrium conditions after fishing was introduced (i.e., we investigated long-term dynamics).

The determination of fishing effort (Table 1, equations 2a-2f) and fish reproduction (Table 1, equations 5a-5d) were assumed to occur on an annual basis at the beginning of each year, and population and fishery characteristics were updated annually. However, because recreational fishing is often a size-selective process (Lewin et al. 2006) occurring throughout the year, we described fish mortality and the growth in body size of fish by continuous functions (Table 1, equations 4a-4e). This allowed our model to account for fish to grow into vulnerable size classes within each year, and for the recapture and repeated exposure to hooking mortality of released individuals throughout the fishing season, both of which are important aspects of recreational fisheries (Coggins et al. 2007). These resultant ordinary differential equations were solved numerically using the ODE45 function in Matlab (version 7.0.1 Mathworks, Inc.).

Two crucial density-dependent relationships were included to allow for compensatory responses of the fish population to exploitation (Lorenzen and Enberg 2002): density-dependent biphasic growth in body size (Table 1, equations 4a-4d) (Lester et al. 2004; Dunlop et al. 2007) and density-dependent survival from spawning to post-hatch of fish of age zero. The latter was represented by a Beverton-Holt type relationship, which was assumed to apply at the beginning of each year (Table 1, equations 5c) (Lorenzen 2008). Fish younger than one year were assumed to experience no further natural mortality (Table 2) but could experience fishing mortality if they became large enough. Fish one year and older experienced a constant natural mortality rate in addition to size-dependent fishing mortality (Table 2, equation 7h).

Fishing mortality was assumed to be size-dependent in two ways that quantitatively differed among angler types (see Table 3 for angler specific parameters). First, catch rates were dependent on the size-dependent vulnerability of fish to the specific fishing gear utilized by each angler type. Vulnerability to capture therefore differed among age classes and also changed over the course of the growing season (Table 1, equations 7a and 7b; see Table 3 for parameters). Catch rates were also dependent on fishing effort and the skill level of the anglers (Table 1, equation 7b, see Table 3 for parameters). Second, harvest of fish was regulated by a minimum-size limit (MSL;Table 1, equation 7c). While all fish above the legal MSL were harvestable, a portion of undersized fish were also considered harvestable because of non-compliance with regulations (either through ignorance or choice; Sullivan 2002). Anglers chose to harvest fish based on their catch rates mediated by their propensity to voluntarily release fish (Table 1, equation 7e) determined by the personal limit an angler had on the number of fish they harvested in a day; (see Table 3 for angler-type-specific parameters). Released fish were assumed to experience hooking mortality from handling or injuries (Table 1, equation 7f; Table 3; Arlinghaus et al. 2007, Arlinghaus et al. 2008c). Fish under the legal size limit, which were not part of the pool of illegally harvestable fish, only experienced hooking mortality (Table 1, equation 7g).

After fishing was introduced, the fish population was allowed to equilibrate. The spawning potential ratio (SPR) was used to assess the biological impacts of angling exploitation. SPR, which has previously been used in recreational-fishing models (Coggins et al. 2007; Allen et al. 2009), measures reductions in the fish stock's reproductive output, and can thus serve as an indicator of recruitment overfishing (Goodyear 1993; Coggins et al. 2007; Allen et al. 2009). In our model, we use a weighted SPR (Table 1, equation s 5b and 6). Depending on the life history of a species, values below 0.2-0.3 are considered critically low (Goodyear 1993) and it is commonly assumed that SPR should be maintained above 0.35-0.40 to reduce the risk of recruitment failure (Goodyear 1993; Coggins et al. 2007). We used these values as criterion to assess the risk of recruitment overfishing under different management policies.

Social-welfare measures

Social welfare was used to determine optimal regulations. Social welfare is an aggregation of individual utilities (Perman et al. 2003) and determines the total economic value of a good or service, such as a recreational-fishing experience, as perceived by anglers (Edwards 1991). A social welfare function describes how individual utilities are aggregated based on their social “worth”, and it is assumed that any concerns about equity are accounted for in the aggregation method (Perman et al. 2003). However, maximizing social welfare does not necessarily result in an equitable distribution of resources among individuals, nor is there universal consensus on what constitutes an appropriate social-welfare measure or function (Perman et al. 2003). Managers must therefore carefully decide what social-welfare measures reflect their management objectives (e.g., maximizing angler satisfaction and/or participation).

In most model simulations described below, a utilitarian social-welfare function was used, referred to as total utility (TU), in which individual utilities were weighted equally among angler types. However, in a subset of simulations, three different social welfare functions, representing different management objectives, were used to examine how these differences alter predictions about socially optimal management regulations. The first welfare measure, TU, described the utility gained by an angler type per fishing experience, multiplied by the total annual number of fishing experiences (measured in terms of angling effort, and expressed in angling days) by that angler type, and summed over all angler types (Table 1, equation 8a; similar to McConnell and Sutinen 1979). TU reflects the realized demand for angling experiences. However, TU may be influenced heavily by individuals with disproportionately large utility, and a more equitable distribution of resources among all anglers in the angler population may be desired (Loomis and Ditton 1993). Thus, a second, more equitable utilitarian social-welfare function (EU) was examined. Here, individual utility from a fishing experience was weighted by the relative abundance of angler types in the angler population, to create a weighted mean utility for an individual, which was then multiplied by the aggregate number of angling days (Table 1, equation 8b). Finally, we examined a Rawlsian approach (RU) to utility maximization, where the utility of the worst-off individual was maximized, emphasizing the objective of achieving the most equitable distribution of resources (Perman et al. 2003). Here, the utility from the angler type with the lowest individual utility was used and multiplied by the aggregate number of angling days (Table 1, equation 8c). Naturally, the second and third social-welfare measures only differed from the first measure in the mixed angler population composed of different angler types.

Outline of analysis

Across a range of minimum-size limits and angling-license numbers, three different angler-behaviour scenarios – static, catch-based dynamic and multi-attribute dynamic scenarios – were considered for five different types of angler populations – generic, consumptive, trophy, average, and mixed. Optimal input and output regulations were identified by maximizing one of three measures of social welfare – total utility TU, equitable utilitarian utility EU, and Rawlsian utility RU (Table 1, equations 8a-c). With this approach, we examined the impacts of dynamic angler behaviour, angler heterogeneity, and composition of the angler population on socially optimal regulations and the resulting biological impacts on the fish population. In most analyses presented, TU was used to determine socially optimal management regulations. However, we also examined the EU and RU social-welfare measures in the context of multi-attribute dynamic angler behavior and mixed angler populations, to demonstrate how different management objectives alter socially optimal management regulations.

We used sensitivity analyses to explore the importance of different attributes for determining angler behaviour, optimal regulations and biological impacts, by removing in turn each attribute from the multi-attribute angler-behaviour scenario. However, given the hypothetical nature of the constructed angler types and their part-worth-utility functions (Figure 3), we decided it would be imprudent to derive generalized conclusions about the relative importance of individual attributes in determining optimal regulations. Therefore, sensitivity analyses were not intensified beyond the approach summarized above.

Results

Impacts of dynamic angler behaviour

A comparison of the three angler-behaviour scenarios showed substantial differences in predictions of total utility (left to right in Figure 4). Optimal minimum-size limits were predicted to be highest in scenarios with catch-based dynamic angler behaviour and were generally lower (and similar) for corresponding scenarios with static and multi-attribute dynamic angler behavior for angler populations composed of one angler type (Table 4; Figure 4). Optimal effort regulations were lowest in the static scenarios, intermediate in the multi-attribute scenarios, and highest in the catch-based scenarios (Table 4). In fact, optimal license numbers in the catch-based scenarios were often more than two times larger than the number predicted in the other scenarios. Under predicted optimal regulations, the number of hours that anglers actually fished, termed realized angling effort, were identical in the static and multi-attribute scenarios when the angling population was composed of one angler type, (thus following the pattern of predictions for optimal minimum-size limits). In the catch-based scenario, realized effort followed a trend similar to that of optimal license numbers.

Insert
Figure 4
and
Table 4

The risk of recruitment overfishing and the biological impacts of recreational angling on the modelled pike population were affected by the type of angler behaviour considered (Figure 5). Static angler behaviour caused the most negative impacts on the fish population across the range of minimum-size limits and license numbers examined, compared to the two scenarios in which anglers behaved dynamically. This was because realized angling effort in the static angler-behavior scenario was fixed at the maximum level allowed, whereas in the two dynamic scenarios realized angling effort was less and depended on the utility anglers gained from the fishery. When comparing the two dynamic scenarios, biological impacts of fishing at low to moderate *MSL* levels in the catch-based scenario were generally less severe than in the multi-attribute scenario, with the latter approaching recruitment overfishing and fishery collapse at lower license numbers. At high *MSL* levels, approaching complete catch-and-release conditions, the risk of recruitment overfishing was often greater in the catch-based scenario, although the *SPR* never dropped below 0.4, even when a large number of licenses were issued.

Insert
Figure 5

Impacts of angler heterogeneity

Not only angler dynamics, but also angler heterogeneity substantially affected model-predicted optimal input and output regulations. When the three angler types were compared (first three rows in Figure 4), optimal minimum-size limits were generally intermediate for generic anglers, low for consumptive anglers and high for trophy anglers, with the latter approaching complete catch-and-release conditions, except in the catch-based scenario, in which complete catch-and-release regulations were preferred by all angler types (Figure 4; Table 4). Optimal effort regulations were found to be the lowest for consumptive anglers in the static and multi-attribute scenarios, intermediate for trophy anglers and highest for generic anglers. However, in the catch-based scenario, all angler types preferred a large number of licenses, with generic anglers favouring somewhat fewer angler licenses than the other angler types. Under optimal regulations, consumptive anglers were predicted to fish the least, but generic and trophy anglers invested more (and similar) realized angling efforts in the static and multi-attribute scenarios (Table 4). However, in the catch-based scenario, consumptive anglers invested the most realized angling effort. At their optimum, trophy anglers, as a homogeneous group, derived the highest utility from fishing, exceeding that of the other anglers types by a factor of more than two; generic anglers were intermediate, while consumptive anglers derived the least utility in the static and multi-attribute scenarios (Figure 4).

Differences among the angler types also affected the risk of recruitment overfishing. In all scenarios and across all regulation combinations, consumptive anglers generally had the most negative impact and generic anglers the least, except in the multi-attribute scenario at high MSL levels. This trend was also seen when examining the biological impacts of different angler types under the different regulations they perceived as optimal (Table 4). Under these optimal regulations, the biological impact of consumptive anglers was greatest, occurring close to the threshold levels of recruitment overfishing (0.35-0.40) and at regulation combinations for which small changes in regulations could cause large changes in the risk of recruitment overfishing (Figure 5). At these respective optima, generic and trophy anglers impacted the fish population much less than consumptive anglers and at regulation combination that imply a low risk of recruitment overfishing.

We found the sensitivity of results to individual attributes in the multi-attribute scenario varied in their effect on optimal regulations, realized effort and SPR, and varied greatly with angler type, without any consistent pattern becoming evident

(Table A1). We could tentatively conclude, however, that findings for trophy anglers were strongly dependent on crowding aversion, while findings for consumptive anglers were particularly sensitive to MSL levels and some catch attributes. It was also interesting to notice that the response of mixed angler populations to the removal of a particular fishery attribute sometimes exceeded that of homogeneous angler populations, highlighting the importance of including heterogeneity in angler preferences (Table A1).

Impacts of angler-population composition

Predictions of optimal input and output regulations substantially differed between the average angler and the mixed angler population (bottom two rows in Figure 4). Under optimal regulations, license numbers and realized angling efforts were higher for the mixed angler population than for the average angler population (Table 4). Optimal MSL levels for the mixed angler population were the same as the average angler population in the static scenario, lower in the catch-based scenario and higher in the multi-attribute scenario. In addition, across all scenarios, TU under optimal regulations was greater in the mixed angler population than in the average angler population.

For the average angler population was assumed, minimum-size limits and realized efforts under optimal regulations were identical in the static and multi-attribute scenarios. However, for the mixed angler population, minimum-size limits, license numbers and realized efforts under optimal regulations were substantially higher in the multi-attribute scenario than in the static scenario (Figure 4; Table 4). Furthermore, in the multi-attribute scenario, predictions of optimal license sales and realized efforts were generally higher than in any of the three homogeneous angler populations (Table 4). The mixed angler population was also predicted to have a greater biological impact than the average angler population (Figure 5). However, under optimal regulations, the risk of recruitment overfishing in both cases was low (Table 4).

Changes in the composition of the mixed angler population that fished in the multi-attribute scenario were described by the changes in the proportion total realized angling effort invested by each angler type (Figure 6). This shows that the composition of the angling population varied depending on minimum-size limits and license regulations, with trends predominantly following changes in MSL (Figure 6). At low MSL levels and low license numbers, all angler types fished in approximately equal proportions, whereas at low MSL levels and high license numbers the composition of the angling population resembled that of the entire angler population (i.e., 40% generic, 30% consumptive and 30% trophy). At moderate to high MSL levels the majority of consumptive anglers in the angler population chose not to fish, and thus dropped out of the angling population. Even higher MSL levels resulted in generic anglers dropping out too, and thus in an angling population dominated by trophy anglers. Under optimal regulations, the composition of the angling population in the multi-attribute scenario was heavily skewed toward generic and trophy anglers, with few consumptive anglers being attracted to the fishery (Table 4; Figure 6).

Insert
Figure 6

Impacts of social-welfare measures

In the multi-attribute scenario for the mixed angler population, socially optimal minimum-size limits were highest for total utility (TU), intermediate for equitable utilitarian utility (EU) and lowest for Rawlsian utility (RU) (Figure 7; Table 4). Optimal license numbers were also highest for the TU social-welfare measure, but lower (and similar) for the EU and the RU social-welfare measures, and realized angling efforts under optimal conditions showed the same pattern.

Under optimal regulations, optimal license numbers and realized angling efforts for the average angler population never exceeded those for the mixed angler population, irrespective of the applied social-welfare measure (Table 4). However, the optimal MSL was slightly higher in the average angler population than in the mixed population when a RU social-welfare measure was applied (Table 4). Under optimal regulations, SPR levels were well above 0.40, irrespective of the applied social-welfare measure (Table 4); therefore, all social-welfare measures avoided recruitment overfishing under optimal regulations.

Insert
Figure 7

Discussion

We developed a bioeconomic modelling approach that integrates angler behaviour and angler heterogeneity with age-structured and density-dependent fish population dynamics, to determine socially optimal input and output regulations for a recreational fishery. Using this approach, we have demonstrated how angler behaviour and heterogeneity affect optimal regulations, and how optimal regulations varied with the social-welfare measure applied.

Angler behaviour

The importance of accounting for angler behaviour was demonstrated by the differences observed in predicted optimal regulations (expressed in terms of minimum-size limits and license numbers) among three angler-behavior scenarios that describe, respectively, static, catch-based dynamic and multi-attribute angling dynamics. Predicted optimal minimum-size limits and license numbers were substantially higher for the catch-based scenario than for the other two scenarios. However, most published recreational-fisheries models that incorporated dynamic angler behaviour assumed that anglers respond to catch rates alone or some measure of fish abundance (Johnson and Carpenter 1994; Beard et al. 2003; Post et al. 2003), thus neglecting other attributes known to affect participation decisions of anglers (Hunt 2005).

Our findings call into question the validity of this simplifying assumption and resulting predictions of “optimal” regulations. For example, when catch rate was assumed to be the only attribute determining the fishing decisions of anglers, the catch-based scenario predicted optimal input and output regulations that effectively imply complete catch-and-release regulatory policies at largely unlimited effort levels. This prediction is clearly misleading in many situations and results from an oversimplification of angler preferences. Indeed, because some angler types are strongly harvest-oriented, management conflicts and dilemmas have occurred in some recreational fisheries despite high catch rates, when the possibility for anglers to harvest was constrained (Matlock et al. 1988; Radomski 2003; Sullivan 2003). Perceived harvest constraints may result in the displacement of harvest-oriented anglers to alternative fisheries (Radomski and Goeman 1996; Beard et al. 2003), an important effect that cannot be captured by models that assume angler behaviour to be driven by catch rates alone. In contrast, our investigations of multi-attribute dynamic angler behaviour, presumably allowing a more realistic representation of angling effort, showed that complete catch-and-release regulations were not always socially optimal.

Our sensitivity analyses highlighted that, while most attributes of the fishing experience (such as fish size, catch rate, crowding, aversion to regulations, etc.) were important for determining angler choice and angler welfare, their relative importance varied among angler types (Table A1). This underscores the importance of including all relevant catch- and non-catch-related attributes affecting angler choice in bioeconomic fisheries models to more accurately predict angler behaviour and fishing pressure, and to derive optimal regulations that maximize angler welfare.

A multi-attribute perspective on angler behavior and welfare is also likely to improve predictions of the biological impacts of fishing under different regulations. Historically, angler populations were expected to be self-regulating, as anglers were assumed to leave a fishery when catch rates declined (Cox and Walters 2002a, Radomski 2003). However, because catch rate is just one among many attributes characterizing a fishing experience, such catch-based self-regulation does not necessarily apply (Post et al. 2002; Paulrud and Laitila 2004; Post et al. 2008). Indeed, we found that realized angling effort and the biological impacts were higher in the multi-attribute scenario than in the catch-based scenario at low to intermediate MSL levels. These finding corroborate claims that multi-attribute angler behaviour may put fish populations at risk of overexploitation (Post et al. 2002), since anglers continue to be attracted to particular fisheries even after catch rates have declined because other attributes of the fishery (such as close proximity, social aspects of the experience) provide them with utility, and thereby partly compensate for reduced catch rates. The interesting features of the multi-attribute utility scenario derive from its partial "decoupling" of fish and angler dynamics (Johnson and Carpenter 1994). In contrast, the catch-based scenario is appropriate for describing predator-prey interactions where a predator's fitness is predominantly dependent on prey consumption. Not accounting for the array of attributes that attract anglers to a fishery may therefore lead to an underestimation of the biological impacts of fishing (Post et al. 2002). Consequently, management decisions based on assumptions of purely catch-based angler behaviour will likely be less conservative than intended with regard to limiting biological impacts, and probably also less successful than intended with regard to angler satisfaction and participation.

Angler heterogeneity

Our results have shown that accounting for the complexity of angler behaviour when predicting the amount of angling effort invested in a particularly fishery can fundamentally improve predictions about optimal regulations. However, this improvement alone might not be enough: predictions are likely even more realistic when the heterogeneity of angler behaviour is considered in recreational-fisheries models.

We found that, because of the consumptive orientation and aversion to angling regulations of some angler types, minimum-size limits were particularly important in determining angler utility and optimal regulations. Under less restrictive output regulations, consumptive angling effort was reduced, because the fish population could not support large numbers of harvest-oriented anglers while at the same time maintain high catch rates. In these situations, trophy anglers fished in greater numbers than consumptive anglers, because they were less concerned with harvest constraints and more interested in attributes of the fishery unrelated to catch rates. Despite their greater numbers, at low MSL levels the less consumptive nature and the reduced catch rates of trophy anglers (which occurred because they used gear that targeted fish of larger size) resulted in them imposing less fishing mortality on a fish stock than consumptive anglers.

This demonstrates that both aspects of angler heterogeneity, diversity in angling preferences and differences in fishing practices, are important when determining optimal angling regulations. Furthermore, while managing for angler diversity to enhance the recreational fishing experience of all anglers has been repeatedly called for (Driver et al. 1984; Aas et al. 2000; Arlinghaus and Mehner 2004a), our study is the first to explicitly demonstrate the benefits of such an approach when determining optimal, angler-type-specific regulations to maximize social welfare.

Although the aim of our modelling exercise was to explore the general importance of behavioural complexity and diversity in anglers, our model-based results also highlight some practical implications. In particular, our model findings suggest that some MSL regulations currently used for pike fisheries (45-75 cm in North America; Paukert et al. 2001) are below the optimal levels (53-99 cm) predicted by our model for the different angler types. Implementation of lower-than-optimal minimum size limits could put fish populations at risk of recruitment overfishing. Thus, depending on the composition of the local angler population, special regulations described by Paukert et al. (2001) that are geared toward particular angler types (e.g., maximum-size limits, inverse slot length limits) may perform better than the standard solution of imposing a moderately low minimum-size limit (such as 45-50 cm).

Despite considerable differences among angler types, we found that socially optimal regulations resulted in biologically sustainable exploitation patterns. This is because angler utility is partly dependent on catch-related attributes of the fishery (such as catch rates or fish size), which implicitly requires a productive, biologically sustainable fishery in the long term. Our results therefore indicate that socioeconomic management objectives, such as maximizing social welfare, can account for the state of a fish population through its influence on angler utility and thus provide management advice that results in biologically sustainable exploitation. This supports suggestions for a focus on optimal social yield (OSY) when managing for sustainability (Roedel 1975; Malvestuto and Hudgins 1996; Carpenter and Brock

2004). However, the occurrence of optimal regulations in the vicinity of SPR levels suggestive of recruitment overfishing varied with angler type. Thus, a precautionary approach has to be taken in socially optimal management, to account for the stochastic processes underlying any fishery.

Angler–population composition

The results discussed so far account for the dynamics and heterogeneity in angler behaviour, they are still limited, in the sense that the angler population was assumed to be composed of just one angler type. In reality, angler populations are composed of different types of anglers that vary in their preferences and behaviour (Hahn 1991; Fisher 1997; Connelly et al. 2001). Our study has shown that this composition affects optimal regulations. Moreover, while, managers might be inclined, for the sake of simplicity, to represent angler populations in terms of an average angler (Hahn 1991; Aas and Ditton 1998), we found that such a simplification can lead to misleading predictions of optimal regulations and biological impacts. This is because different angler types dominated the realized angling effort under different regulations, and because optimal regulations were consistently more restrictive for the mixed angler populations than for the average populations. Shifts in the angling population was also important for determining biological impacts, because of differences in fishing practices and participation of the different angler types.

Therefore, our model results underscore the importance of considering not only dynamic angler behaviour and angler heterogeneity in both angling preferences and angling practices in models of recreational-fisheries management (Post et al. 2008) , but also how dynamics and diversity interact in angler populations containing a mixture of angler types. Our findings suggest that current monitoring methods that pool information about anglers need to be modified to account for the heterogeneity of angler types using specific fisheries. This will allow managers to understand better which types of anglers are fishing and why (Radomski et al. 2001), thus yielding insights that our model results suggest could be of crucial importance for determining optimal regulations and for more accurately predicting the biological impacts of the angling population.

Social-welfare measures

A final insight from this study relates to the importance of the management objectives determining optimal input and output regulations. From a welfare-economics perspective, the management objective is to maximize the social welfare a fishery provides to the angling community irrespective of which anglers benefit the most or the least (Cole and Ward 1994; Perman et al. 2003). However, our results suggest, that a strictly utilitarian economic approach may alienate some angling groups from a fishery that is managed for maximum total utility. For example, we found that consumptive anglers interested in fish harvest were no longer attracted to a fishery that was subject to restrictive maximum-size limits. Trophy anglers, in contrast, enjoyed high individual utility at high *MSL* levels, mainly because of their lack of consumptive orientation and the greater importance of fishing to their lifestyle. As a result, trophy anglers gained more utility, which strongly influenced the TU social-welfare measure, and thus optimal regulations. Social-welfare measures that reflected more equitable management objectives, such as equitable utilitarian utility (EU) or Rawlsian utility (RU), rendered optimal regulations in mixed angler populations more restrictive, but resulted in a more diverse composition of anglers attracted to a fishery.

Thus, although there is no universal consensus about which social-welfare functions to use to quantify welfare (Cole and Ward 1994; Perman et al. 2003), our results illustrate how the optimal regulations predicted by bioeconomic models are sensitive to the social-welfare measures applied. Therefore, managers need to be explicit about their underlying management goals and objectives (Barber and Taylor 1990; Aas and Ditton 1998), and ensure that the welfare measure applied closely reflects these objectives, when implementing an OSY approach to recreational-fisheries management.

Limitations and extensions

While we hope that our study provides valuable insights about the importance of angler dynamics and angler heterogeneity when managing for OSY, several limitations need to be highlighted. First, our model results depend on the description of angler behaviour. Application of our modelling approach to local fisheries therefore requires a quantitative assessment of the local and regional angler populations, e.g., using stated and revealed choice models (Hunt 2005; Massey et al. 2006). A second limitation is that we assumed that over time, anglers will follow the same behavioural patterns and will keep occurring in the same proportions, which may be in error (Baerenklau and Provencher 2005). Temporal trends in the behavior of individual anglers or in the composition of the angler population could be examined in future extensions of our model. Changing preferences of anglers over time due to specialization or learning, could also be exciting to investigate, as angler will likely adapt to changes in the fishery by altering their expectations (Arlinghaus 2006a). Third, to simplify an already complex, model we assumed that participation decisions were made on an annual basis, whereas other time steps may be more realistic (Schuhmann and Schwabe 2004; Hunt 2005). However, because we were interested in long-term equilibrium conditions, our simplifying assumption seems warranted. Fourth, our model described a single fishery and therefore did not account for changes in utility offered by substitute sites in the vicinity of the modeled fishery. Clearly, this is an unrealistic assumption, and further research is needed to broaden our modelling approach to fisheries landscapes (Lester et al. 2003).

A final limitation of this study is that we defined social welfare in terms of aggregated utility, rather than aggregated willingness-to-pay. In environmental and resource economics, including recreational-fisheries economics, an aggregate of individuals' willingness-to-pay for an environmental good or service is a commonly used welfare measure (Edwards 1991). In empirical studies of non-marketable goods and services, such as recreational fisheries, this measure of social welfare is calculated using the change in utility provided by attributes of the good (such as catch rate or crowding) from one condition of the fishery to another divided by the marginal utility of income (such as the license cost coefficient in our model) and is expressed in monetary units (Hanemann 1984). Here, we chose not to express utility in monetary units, because this would necessitate making an additional assumption about the baseline condition used for comparison, and because it was felt to be imprudent to put a monetary value on hypothetical scenarios. However, such calculation could be carried out if appropriate empirically derived parameters were available from stated- or revealed-preference models for angler-type-specific part-worth-utility functions (e.g., Massey et al. 2006). This would also ensure that the welfare measure has a cardinal scale avoiding the potential debate of how comparable utility is among individuals (Perman et al. 2003).

Despite these limitations, by coupling socioeconomic and biological models our modelling framework is among the few that addresses the often-touted need for an interdisciplinary approach to recreational-fisheries management (e.g., Anderson 1993) (Johnson and Carpenter 1994; Radomski et al. 2001), and provides a basis for future research. There are numerous directions in which our model can be extended, including incorporating environmental stochasticity and a multi-species biology. These extensions are important because deterministic models (Carpenter et al. 1994) and single-species models (Worm et al. 2009) may result in erroneous conclusions about appropriate management strategies. In multi-species models, incorporating angling preferences for different species and indirect effects of angling on the aquatic food webs (Roth et al. 2007) are promising options for complementing the predictions presented here.

Further avenues for future research include, exploring the part-worth-utility functions driving angler behaviour, examining the sensitivity of model predictions to changes in fishery attributes, and investigating an even larger numbers of prototypical angler types and their interactions in mixed angling populations Because multi-lake fisheries opportunities (Parkinson et al. 2004; Post et al. 2008) are more realistic than the simplified single-lake perspective have adopted here, exploration of angler choice within a landscape of fishing opportunities (Carpenter and Brock 2004) may be the most important extension of our modelling approach.

Implications

Even though we have just scratched the surface, we hope that readers share our optimism that the interdisciplinary approach to modeling recreational fisheries introduced here constitutes a sound and extensible theoretical framework. The approach builds on choice theory from welfare economics, angler-specialization theory from leisure sciences and traditional ecological theory, and provides unique insights into recreational-fisheries management.

A key finding of this study and related work (Carpenter and Brock 2004) is that “one-size-fits-all” policies are likely to produce suboptimal management outcomes, because they cannot account for the diversity and complexity of angler behaviour that is inherent to most of the world's recreational fisheries (Cox et al. 2003; Arlinghaus et al. 2008a; Post et al. 2008). Furthermore, we have shown that misleading predictions about optimal management can result from the omission of dynamic angler behaviour and angler heterogeneity from recreational-fisheries models; this can put fish populations at risk of overfishing, in line with what has been suggested by other studies (Carpenter et al. 1994; Parkinson et al. 2004). In contrast, although managers need to be aware that socially optimal regulations strongly depend on the applied measure of social welfare and the management objectives upon which it is based, managing for socially optimal regulations resulted in both social and biological sustainability.

Managers are likely to encounter difficulties in jointly satisfying the interests of the entire angling public. Decisions therefore need to be made about how to best distribute access to scarce resources across angler types (Loomis and Ditton 1993; Daigle et al. 1996). The benefit of an interdisciplinary bioeconomic modelling approach, such as the one presented here, is that it enables managers to quantify welfare changes resulting from alternative management scenarios, and to predict how these regulations will affect different segments of the angling public, as well as the fish population. A decision-support tool such as this one, built on clear objectives and quantitative descriptions, thereby fostering transparency and defensibility in the management process, can facilitate decision taking and clarify when managing for diverse angling opportunities is the best strategy. Ideally, accounting for angler dynamics and angler diversity in fisheries-management models will provide more accurate and realistic predictions of optimal regulations that maximize angler satisfaction, minimize conflicts among angling groups and result in the sustainable management of recreational fisheries.

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Table 1 Model equations. The modelled species was pike (*Esox lucius* L.). Variables, parameters, parameter values and their sources are listed in Tables 2. Angler types are specified in Table 3.

Number	Equation	Description
	Individual-angler utility	
1a	$U_{\mathrm{f}j} = U_{\mathrm{c}j}$	Conditional indirect utility gained by an angler of type j from choosing to fish in the catch-based scenario only
1b	$U_{\mathrm{f}j} = U_{0j} + U_{\mathrm{c}j} + U_{\mathrm{s}j} + U_{\mathrm{x}j} + U_{\mathrm{a}j} + U_{\mathrm{r}j} + U_{\mathrm{o}j}$	Conditional indirect utility gained by an angler of type j from choosing to fish in the static and multi-attribute scenarios
	Angler-effort dynamics	
2a	$p_{\mathrm{f}j} = \dfrac{\exp(\hat{U}_{\mathrm{f}j})}{\exp(U_{\mathrm{n}}) + \exp(\hat{U}_{\mathrm{f}j})}$	Probability that an angler of type j chooses to fish, over the alternative to not fish, where $(\hat{U}_{\mathrm{f}j})$ applies to the previous year
2b	$p_{\mathrm{F}j} = (1-\varphi) p_{\mathrm{f}j} + \varphi \hat{p}_{\mathrm{F}j}$	Realized probability that an angler of type j chooses to fish, where $\hat{p}_{\mathrm{F}j}$ applies to the previous year
2c	$D_j = p_{\mathrm{F}j} D_{\max}$	Number of days an angler of type j chooses to fish during a year
2d	$A_{\mathrm{L}j} = A_{\mathrm{L}} \rho_j$	Number of licensed anglers of type j
2e	$E_j = D_j A_{\mathrm{L}j} \Psi / \phi$	Total annual realized fishing effort per unit

		area of all anglers of type j
2f	$e_{jt} = \begin{cases} E_j / S_\mathrm{F} & \text{if } t \le S_\mathrm{F} \\ 0 & \text{if } t > S_\mathrm{F} \end{cases}$	Instantaneous fishing effort per unit area at time t of all anglers of type j
	Age-structured fish population	
3a	$N_\mathrm{total} = \sum_{a=0}^{a_\mathrm{max}} N_a$	Total fish population density
3b	$B_\mathrm{total} = \sum_{a=0}^{a_\mathrm{max}} N_a W_a$	Total fish biomass density
	Growth	
4a	$h = \dfrac{h_\mathrm{max}}{1 + B_\mathrm{total} / B_{1/2}}$	Maximum annual growth of a fish dependent on the biomass density at the beginning of the year
4b	$p_a = \begin{cases} 1 - \dfrac{G}{3+G}(1 + L_{a0} / h) & \text{if } a \ge a_\mathrm{m} - 1 \\ 1 & \text{if } a < a_\mathrm{m} - 1 \end{cases}$	Proportion of the growing season during which a fish of age a allocates energy to growth
4c	$g_{at} = \begin{cases} h / S_\mathrm{G} & \text{if } t \le p_a S_\mathrm{G} \\ 0 & \text{if } t > p_a S_\mathrm{G} \end{cases}$	Instantaneous growth rate in length of a fish of age a at time t
4d	$L_{at} = L_{a0} + g_{at} t$	Length of a fish of age a at time t
4e	$W_{at} = w L_{at}^{l}$	Mass of a fish of age a at time t
	Reproduction	
5a	$R_a = \begin{cases} \delta W_a GSI / W_\mathrm{e} & \text{if } a \ge a_\mathrm{m} \\ 0 & \text{if } a < a_\mathrm{m} \end{cases}$	Annual fecundity of a female fish of age a

5b	$b = \Phi \sum_{a=a_\mathrm{m}}^{a_\mathrm{max}} R_a N_a$	Annual population fecundity density, pulsed at the beginning of the year
5c	$s_0 = \frac{\alpha}{1 + b / b_{1/2}}$	Survival probability from spawning to post-hatch of fish of age zero, applied at the beginning of the year
5d	$N_0 = s_0 b$	Density of age zero fish at the beginning of the year
6	$SPR = b_\mathrm{F} / b_\mathrm{U}$	Spawning potential ratio (= relative reduction in egg production under fishing relative to the corresponding unfished condition)
	Mortality	
7a	$v_{ajt} = [1 - \exp(-y_j L_{at})]^{z_j}$	Proportion of fish of age a that are vulnerable to capture by anglers of type j at time t
7b	$c_{ajt} = q_j e_{jt} v_{ajt}$	Instantaneous per capita catch rate of fish of age a by anglers of type j at time t
7c	$H_{ajt} = \begin{cases} 1 & \text{if } L_{at} \geq MSL \\ f_{\mathrm{n}j} & \text{if } L_{at} < MSL \end{cases}$	Proportion of fish at age a that are harvestable by anglers of type j at time t
7d	$C_{jt} = \sum_{a=0}^{a_\mathrm{max}} c_{ajt} N_a H_{ajt}$	Instantaneous catch rate of harvestable fish by anglers of type j at time t
7e	$C_{\mathrm{H}jt} = \min(C_{jt}, c_{\max j} e_{jt} / \Psi)$	Instantaneous harvest rate by anglers of type j at time t

7f	$f_{\mathrm{H}jt} = \frac{C_{\mathrm{H}jt}}{C_{jt}} + f_{\mathrm{h}j}\frac{C_{jt}-C_{\mathrm{H}jt}}{C_{jt}}$	Proportion of vulnerable harvestable fish killed by anglers of type j at time t
7g	$m_{\mathrm{f}ajt} = f_{\mathrm{H}jt} c_{ajt} H_{ajt} + f_{\mathrm{h}j} c_{ajt} (1 - H_{ajt})$	Instantaneous per capita fishing mortality rate of fish of age a imposed by anglers of type j at time t
7h	$d_{at} = m_{\mathrm{n}a} + \sum_{j} m_{\mathrm{f}ajt}$	Instantaneous per capita mortality rate of fish of age a at time t
7i	$\frac{dN_a}{dt} = -d_{at} N_a$	Continuous rate of change in the density of fish of age a at time t
	Social-welfare measures	
8a	$U_{\mathrm{TU}} = \sum_{j} U_{\mathrm{f}j} D_j A_{\mathrm{L}j}$	Annual total utility
8b	$U_{\mathrm{EU}} = \sum_{j} (U_{\mathrm{f}j} \rho_j) \sum_{j} (D_j A_{\mathrm{L}j})$	Annual equitable utilitarian utility
8c	$U_{\mathrm{RU}} = \min_{j}(U_{\mathrm{f}j}) \sum_{j} (D_j A_{\mathrm{L}j})$	Annual Rawlsian utility

Table 2 Model variables, parameters, parameter values and their sources. The modeled species was pike (*Esox lucius* L.). Equations are listed in Table 1. Angler types are specified in Table 3.

Symbol	Description (unit, where applicable)	Equation	Value or range	Source
Index variables				
j	Angler type		Generic, consumptive, trophy, or average	
a	Age class (y)		0 - $a_{\max}$	
$a_{\max}$	Maximum age of a fish (y)		15	(1)
t	Time within the year (y)		0 - 1	
Angling regulations				
MSL	Minimum-size limit (cm)	7c	0 - 120	
A_L	Number of angling licenses (= number of licensed anglers)	2d	0 - 100	
Angler population				
ρ_j	Proportion of the angler population that is composed of anglers of type j	2d, 8b	Non-mixed: 1.0 for one j ; 0.0 for the others Mixed: (0.4, 0.3, 0.3, 0.0)	
Angler-effort dynamics				
U_n	Conditional indirect utility gained by an angler from choosing not to fish	2a	0	

φ	Persistence of fishing behaviour (= the relative influence of last year's realized fishing probability on the current year's realized fishing probability)	2b	0.5	
Ψ	Average time an angler will fish in a day (h)	2e	4	*
$D_{\max}$	Maximum number of days that an angler would fish per year irrespective of fishing quality	2c	40	*
ϕ	Lake area (ha)	2e	100	
S_F	Annual duration of the fishing season (y)	2f	9/12	
Age-structured fish population				
N_a	Density of fish of age a (ha^{-1})	3a, 3b, 5b, 5d, 7d	0 - ∞	
Growth				
$h_{\max}$	Maximum growth increment (cm)	4a	24.0	†
$B_{1/2}$	Total fish biomass density at which the growth increment if halved (kg^{-1}• ha)	4a	100.0	†
G	Annual reproductive investment	4b	0.58	†

a_m	Age at first spawning (y)	4b, 5a	2	(4)
L_{a0}	Length of fish of age a at the beginning of a year (cm)	4b		
L_0	Length of fish at hatch (cm)	4b	0.8	(2)
S_G	Annual duration of the growing season (y)	4c	1.0	
w	Scaling constant for length-mass relationship (g•cm^{-l})	4e	0.0048	(6)
l	Allometric parameter for length-mass relationship	4e	3.059	(6)
Reproduction				
GSI	Gonadosomatic index (= gonadic mass/somatic mass)	5a	0.17	(3)
W_e	Average egg mass (g)	5a	0.0050	(3)
δ	Proportion of eggs that hatch	5a	0.75	(4)
Φ	Proportion of female fish in the spawning population	5b	0.5	(5)
α	Maximum proportion of offspring surviving from spawning to post-hatch	5c	$4.75 \bullet 10^{-4}$	‡
$b_{1/2}$	Annual population fecundity density at which survival of offspring from	5c	20,325	‡

	spawning to post-hatch is halved (ha)			
b_F	Annual population fecundity under fishing	6	0 - ∞	
b_U	Annual population fecundity under unfished conditions	6	0 - ∞	
Mortality				
m_{na}	Instantaneous natural mortality rate of fish of age a (y^{-1})	7h	0.00 if $a = 0$ 0.42 if $a > 0$	(4)

Sources: (1) Craig and Kipling 1983; (2) Frost and Kipling 1967; (3) Hubenova et al. 2007; (4) Kipling and Frost 1970; (5) Le Cren et al. 1977; (6) Willis 1989.

* Estimated from average participation rates and average lengths of fishing trips obtained from diary data of recreational anglers in Mecklenburg-Vorpommern, Germany (Dorow and Arlinghaus, *unpublished data*) and other literature (van Poorten and Post 2005; Post et al. 2008).

† Estimated from empirical length-at-age and biomass density data from various pike studies (Kipling and Frost 1970; Kipling 1983a; Tresurer et al. 1992; Pierce et al. 2003; Pierce and Tomcko 2003; Pierce and Tomcko 2005) by minimizing the sum of squares using the ‘solver’ function in Excel (Microsoft® Office Excel 2003).

‡ Estimated from modified data on female biomass and age-2 abundance in Lake Windermere (Kipling 1983b). Egg density was determined using the relative fecundity relationship reported in (Craig and Kipling 1983) and adult biomass (Kipling 1983b), and

natural mortality information from Kipling and Frost (1970) was used to calculate age-1 abundance from age 2 abundance.

Table 3 Angler types and their angling behavior. Parameters describe four angler types (generic, consumptive, trophy, and average) in terms of the basic utility they gain from fishing, their tolerances with regard to managerial constraints, their preferences with regard to attributes of the fishing experience, and their fishing practices. Parameter values for the average angler type are weighted averages of the corresponding parameter values for the three prototypical angler types, weighted by the proportion of each angler type in the angler population (0.4 generic; 0.3 consumptive; 0.3 trophy). Parameters values for the angler-type-specific part-worth-utility (PWU) functions (Figure 3) were chosen based on assumptions about differences among angler types reported in the angler-specialization literature. Figure 1 illustrates qualitative differences in angler preferences, and Figure 3 illustrates the angler-type-specific utility functions based on the parameters listed here.

Variable	Symbol and defining equation (affected equation); rationale for general shape (source)	Rationale for angler-type-specific shape (source)	Parameters values describing angler types			
			Generic	Consumptive	Trophy	Average
Importance of fishing to angler lifestyle						
Basic utility gained by an angler of type	U_{0j} (equation 1b); Constant function: the propensity to fish when all	As specialization increases: basic utility of fishing increases (4, 16); the assumed annual participation	Lowest $U_{0j} = -0.405$ (40%	Intermediate $U_{0j} = 0.000$ (50%	Highest $U_{0j} = 0.405$ (60%	$U_{0j} = -0.041$ (49%

j from choosing to fish	other attributes are as expected; see **†‡ for expected values.	is generally consistent with study findings (7, 10).	probability of fishing)	probability of fishing)	probability of fishing)	probability of fishing)
Tolerances with regard to managerial constraints						
PWU of minimum-size limit for an angler of type j	$U_{\mathrm{r}j} = u_{1j} r + u_{2j} r^2 + u_{3j}$ (equation 1b), where r is the standardized MSL*; Dome-shaped quadratic function: anglers may prefer moderate minimum-size regulations, but object to too low and to too high levels (10, 16, 17).	As specialization increases: anglers become less consumptive and have a greater acceptance of stricter minimum-size regulations (6, 16), but consumptively oriented anglers are averse to harvest regulations that limit their ability to harvest fish (1, 8, 12).	Intermediate $u_{1j} = 2.321$ $u_{2j} = -3.869$ $u_{3j} = 0.271$	Lowest $u_{1j} = 3.766$ $u_{2j} = -9.414$ $u_{3j} = 0.471$	Highest $u_{1j} = 2.534$ $u_{2j} = -2.534$ $u_{3j} = -0.228$	$u_{1j} = 2.819$ $u_{2j} = -5.132$ $u_{3j} = 0.181$
PWU of annual license cost for an angler of	$U_{\mathrm{o}j} = u_{4j} o$ (equation 1b), where o is the relative license cost**;	As specialization increases: cost aversion decreases (4, 16).	Lowest $u_{4j} = -0.015$ €$^{-1}$	Intermediate $u_{4j} = -0.011$ €$^{-1}$	Highest $u_{4j} = -0.008$ €$^{-1}$	$u_{4j} = -0.012$ €$^{-1}$

type j	Linear function: license costs usually have a negative effect on angler utility (14, 21).					
Preferences with regard to attributes of the fishing experience						
PWU of daily catch rate for an angler of type j	$U_{cj} = u_{5j} c_{\mathrm{D}} + u_{6j} c_{\mathrm{D}}^2$ (equations 1a and 1b), where c_{D} is the relative daily catch rate†; Dome-shaped quadratic function: greater utility is gained from increasing catch rates (2, 3, 15), but marginal benefits decrease at high catch rates due to the lack of challenge (1, 2, 9).	As specialization increases: focus shifts from quantity to quality and to the challenge of the catch (2, 6, 15).	Intermediate interest in catch	Highest interest in catch	Lowest interest in catch	
			Lowest interest in challenge	Intermediate interest in challenge	Highest interest in challenge	
			$u_{5j} = 0.968$	$u_{5j} = 1.318$	$u_{5j} = 0.825$	$u_{5j} = 1.030$
			$u_{6j} = -0.121$	$u_{6j} = -0.220$	$u_{6j} = -0.206$	$u_{6j} = -0.176$

PWU of average size of fish captured annually for an angler of type j	$U_{sj} = u_{7j}\bar{l} + u_{8j}$ (equation 1b), where $\bar{l}$ is the relative size of fish caught†; Linear function: anglers have a general preference for catching larger fish (2, 10, 11).	As specialization increases: importance attached to the size of fish increases (2, 6, 10).	Lowest $u_{7j} = 2.476$ $u_{8j} = 0.000$	Intermediate $u_{7j} = 3.389$ $u_{8j} = 0.000$	Highest $u_{7j} = 4.394$ $u_{8j} = -0.220$	$u_{7j} = 3.326$ $u_{8j} = -0.066$
PWU of maximum size of fish captured annually for an angler of type j	$U_{xj} = \begin{cases} u_{9j} l_x^2 & \text{if } l_x \ge 0 \\ -u_{9j} l_x^2 & \text{if } l_x < 0 \end{cases}$ (equation 1b), where l_x is the relative maximum size (= the 95th percentile in the size distribution of fish caught†); Piecewise quadratic function: increasing when the relative maximum size† is positive and	As specialization increases: utility gained from large-sized fish increases (2, 6, 17), but the least specialized, generic anglers gain more utility than consumptive anglers in the unlikely event that they catch a large fish (8).	Intermediate $u_{9j} = 9.414$	Lowest $u_{9j} = 6.878$	Highest $u_{9j} = 12.207$	$u_{9j} = 9.491$

	decreasing when it is negative; anglers gain greater utility from larger fish (18), and the relative value of large-sized fish is nonlinear (12).					
PWU of crowding for an angler of type j	$U_{\mathrm{aj}} = u_{10j}A + u_{11j}A^2 + u_{12j}$ (equation 1b), where A is the expected daily congestion ‡; Dome-shaped quadratic function: anglers gain utility from the social aspects of fishing, but avoid congested sites (22).	As specialization increases: desire for solitude increases (6, 7, 22); consumptive anglers recognize that areas with high catch rates will attract other anglers (13).	Highest $u_{10j} = 0.244$ $u_{11j} = -0.031$ $u_{12j} = 0.610$	Intermediate $u_{10j} = 0.149$ $u_{11j} = -0.025$ $u_{12j} = 0.396$	Lowest $u_{10j} = 0.136$ $u_{11j} = -0.034$ $u_{12j} = 0.712$	$u_{10j} = 0.183$ $u_{11j} = -0.030$ $u_{12j} = 0.577$
Fishing practices						
Skill level of an	q_j (equation 7b);	As specialization increases: skill	Lowest	Intermediate	Highest	

angler of type j	Measured in terms of catchability.	level increases (8, 10).	$q_j = 0.011$ ha•h^{-1}	$q_j = 0.020$ ha•h^{-1}	$q_j = 0.025$ ha•h^{-1}	$q_j = 0.018$ ha•h^{-1}
Size selectivity for an angler of type j	y_j and z_j (equation 7a) Measured in terms of parameters for the size-dependent vulnerability to capture (modified from 20).	As specialization increases: type of fishing gear used changes (2, 6), and gear used by more specialized anglers catches larger fish (21).	Small $y_j = 0.21$ cm^{-1} $z_j = 406$	Small $y_j = 0.21$ cm^{-1} $z_j = 406$	Large $y_j = 0.21$ cm^{-1} $z_j = 4636$	$y_j = 0.21$ cm^{-1} $z_j = 1675$
Threshold for practicing voluntarily catch-and-release fish for an angler of type j	$c_{\max j}$ (equation 7e) Measured in terms of the desired average number of fish an angler will harvest daily.	As specialization increases: propensity to harvest fish decreases (6).	Highest $c_{\max j} = 2$	Lowest $c_{\max j} = \infty$	Intermediate $c_{\max j} = 0.5$	$c_{\max j} = \infty$

Hooking mortality for an angler of type j	f_{hj} (equations 7f and 7g) Measured in terms of the proportion of fish dying from hooking mortality.	As specialization increases: no differences in hooking mortality levels (5) were assumed.	$f_{hj} = 0.05$	$f_{hj} = 0.05$	$f_{hj} = 0.05$	$f_{hj} = 0.05$
Non-compliance mortality for an angler of type j	f_{nj} (equation 7c) Measured in terms of the proportion of fish under the minimum-size limit (MSL) that are harvested illegally.	As specialization increases: no differences in non-compliance were assumed; because values reported in the literature vary widely (19, 23, 24), a conservative constant value of 5% was assumed.	$f_{nj} = 0.05$	$f_{nj} = 0.05$	$f_{nj} = 0.05$	$f_{nj} = 0.05$

Sources: (1) Aas and Kaltenborn 1995; (2) Aas et al. 2000; (3) Arlinghaus 2006b; (4) Arlinghaus and Mehner 2004b; (5) Arlinghaus et al. 2008c; (6) Bryan 1977; (7) Connelly et al. 2001; (8) Dorow et al. 2010; (9) Fedler and Ditton 1994; (10) Fisher 1997; (11) Gillis and Ditton 2002; (12) Jacobson 1996; (13) Martinson and Shelby 1992; (14) Massey et al. 2006; (15) Oh and Ditton 2006; (16) Oh et al. 2005a; (17) Oh et al. 2005b; (18) Paulrud and Laitila 2004; (19) Pierce and Tomcko 1998; (20) Post et al. 2003; (21) Rapp et al. 2008; (22) Schuhmann and Schwabe 2004; (23) Sullivan 2002; (24) Walker et al. 2007.

* $r = MSL / L_{\max}$ is the relative minimum-size limit, standardized to range between 0 and 1, where $L_{\max}$ is the maximum size that a fish can attain at the maximum age allowed in the absence of density dependence (equations 4a-d).

** $o = (O_{\mathrm{o}} - O_{\mathrm{e}})$ is the annual fishing-license cost relative to a baseline expected value, where O_{o} and O_{e} are the observed and expected values, respectively.

† Attributes related to the fish population represent the proportional difference scaled relative to a baseline expected value as follows: $c_{\mathrm{D}} = C_{\mathrm{Do}} / C_{\mathrm{De}} - 1$, where C_{Do} and C_{De}, respectively, are the observed and expected average daily catch rates; $\overline{l} = \overline{L}_{\mathrm{o}} / \overline{L}_{\mathrm{e}} - 1$, where $\overline{L}_{\mathrm{o}}$ and $\overline{L}_{\mathrm{e}}$, respectively, are the observed and expected average sizes of caught fish in a year; $l_{\mathrm{x}} = L_{\mathrm{xo}} / L_{\mathrm{xe}} - 1$, where L_{xo} and L_{xe}, respectively, are the observed and expected the maximum sizes of caught fish in a year (with the latter defined as the 95th percentile of the size distribution of caught fish). Expected values are based on the literature and on unpublished data from pike fisheries. We assumed an expected daily catch rate of 0.5 fish (Kempinger and Carline 1978; Goeman et al. 1993; Arlinghaus et al. 2008c) and that anglers fished 4 h in an angling day, an expected average size of 51 cm (Kempinger and Carline 1978; Pierce et al. 1995 (harvested fish); Arlinghaus et al. 2008c), and an expected average maximum size of 69 cm (Dorow and Arlinghaus, *unpublished data*).

‡ $A = \sum_{j}(D_j A_{\mathrm{L}j}) / (365 S_{\mathrm{F}})$ is the expected average number of anglers fishing in a day (see equations 2c-d).

Table 4 Predicted optimal regulation and their implications. Optimal input and output regulations maximized social welfare for various angler types and for different assumptions about angler behaviour and social-welfare measures. Implications are shown in terms of resulting angling efforts and biological impacts (with the latter being measured by the spawning-potential ratio SPR). Three social-welfare measures were examined for the mixed angler population: total utility (TU), an equitable utilitarian utility (EU) and a Rawlsian utility (RU) (Table 1, equations 8 a-c). For the non-mixed angler populations, results for the EU and R were identical to those for TU and are therefore not repeated.

Scenario	Angler population				
	Generic	Consumptive	Trophy	Average	Mixed
Optimal minimum-size limit (cm)					
Static – TU	80	53	99	69	69
Catch-based – TU	104	102	101	106	98
Multi-attribute – TU	80	53	99	69	93
(EU; RU)					(69; 63)
Optimal angler-license number					
Static – TU	38	27	36	31	36
Catch-based – TU	92	100	99	100	100
Multi-attribute – TU	52	36	39	44	66
(EU; RU)					(48; 48)
Annual realized angling effort under optimal regulations ($h \cdot ha^{-1}$)					
Static – TU	61	43	58	50	58
Catch-based – TU	80	112	93	94	97
Multi-attribute – TU	61	43	58	50	65

(EU; RU)					(57; 57)
Composition of anglers fishing in the mixed angler population under optimal regulations					
Static – TU	0.40	0.30	0.30	n.a	n.a
Catch-based – TU	0.34	0.37	0.29	n.a	n.a
Multi-attribute – TU	0.41	0.14	0.45	n.a	n.a
(EU; RU)	(0.38; 0.37)	(0.27; 0.29)	(0.35; 0.34)		
Spawning-potential ratio under optimal regulations					
Static – TU	0.74	0.38	0.73	0.61	0.57
Catch-based – TU	0.78	0.54	0.61	0.67	0.63
Multi-attribute – TU	0.74	0.39	0.73	0.61	0.73
(EU; RU)					(0.57; 0.48)

Figure captions

Figure 1 Simplified flow diagram illustrating interactions among the three model components of our bioeconomic modelling approach: the biological component, the socioeconomic component, and the management component. The model included three angler-behavior scenarios: (a) static angler behavior, where anglers fish at the maximal rate; (b) catch-based dynamic angler behavior, where anglers responded to the fishery based on catch rates; (c) multi-attribute dynamic angler behavior, where anglers responded to the fishery based on a multi-attribute utility function. Black, solid arrows depict influences that apply across all scenarios, while gray arrows apply to the catch-based scenario only and black dashed arrows apply to either the static or multi-attribute scenarios as is also indicated by labels along the arrows. Factors in round-cornered boxes dynamically change throughout model runs, while parameters for factors in square-cornered boxes were held constant.

Figure 2 Qualitative differences in angler preferences for fishery attributes among the three different prototypical angler types (generic, consumptive, and trophy anglers). Gray circles indicate the relative preference levels or tolerance levels (low, intermediate, or high) of angler types for a particular fishery attribute.

Figure 3 Part-worth-utility functions describing the preferences of generic, consumptive, trophy and average anglers for various attributes of the fishery.

Figure 4 Total utility (TU) over a range of input (license number) and output (minimum-size limit) regulations. Columns illustrate results for three angler-behaviour scenarios (left column: static angler behaviour, where anglers fished at the maximal rate; middle column: catch-based dynamic angler behaviour, where anglers responded to the fishery based on catch rates; right column: multi-attribute dynamic angler behaviour, where anglers responded to the fishery based on a multi-attribute utility function). Rows illustrate results for five different angler populations (first row: generic anglers; second row: consumptive anglers; third row: trophy anglers; fourth row: average anglers; and fifth row: mixed angler population composed of 40% generic, 30% consumptive, and 30% trophy anglers). Blue diamonds indicate the optimum regulations at which total utility was maximized.

Figure 5 Spawning-potential ratio (SPR) of fished populations over a range of input (license number) and output (minimum-size limit) regulations. SPR values below 0.35-0.4 indicate a potential for recruitment overfishing. Columns show results for three angler-behavior scenarios (left column: static angler behaviour, where anglers fished at the maximal rate; middle column: catch-based dynamic behaviour, where anglers responded to the fishery based on catch rates; right column: multi-attribute dynamic behaviour, where anglers responded to the fishery based on a multi-attribute utility function). Rows show results for five different angler populations (first row: generic anglers; second row: consumptive anglers; third row: trophy anglers; fourth row: average anglers; fifth row: mixed angler population composed of 40% generic, 30% consumptive, and 30% trophy type anglers). Blue diamonds indicate the optimum regulations at which total utility was maximized.

Figure 6 Proportion of the total realized angling effort contributed by each angler type in a mixed angler population over a range of input (license number) and output (minimum-size limit) regulations. The mixed angler population was composed of

40% generic, 30% consumptive, and 30% trophy type anglers. Anglers responded to the fishery based on a multi-attribute utility function; see (o) panels in Figures 4 and 5. Blue diamonds indicate the optimum regulations at which total utility was maximized.

Figure 7 Social-welfare measures in a mixed angler population with multi-attribute dynamic angler behavior over a range of input (license number) and output (minimum-size limit) regulations. The mixed angler population was composed of 40% generic, 30% consumptive, and 30% trophy anglers. Results are shown for three social-welfare measures (total utility, TU;, egalitarian utilitarian utility, EU; Rawlsian utility, RU; see Table 1, equations 8a-c). Blue diamonds indicate the optimum regulations at which the social-welfare measures were maximized.

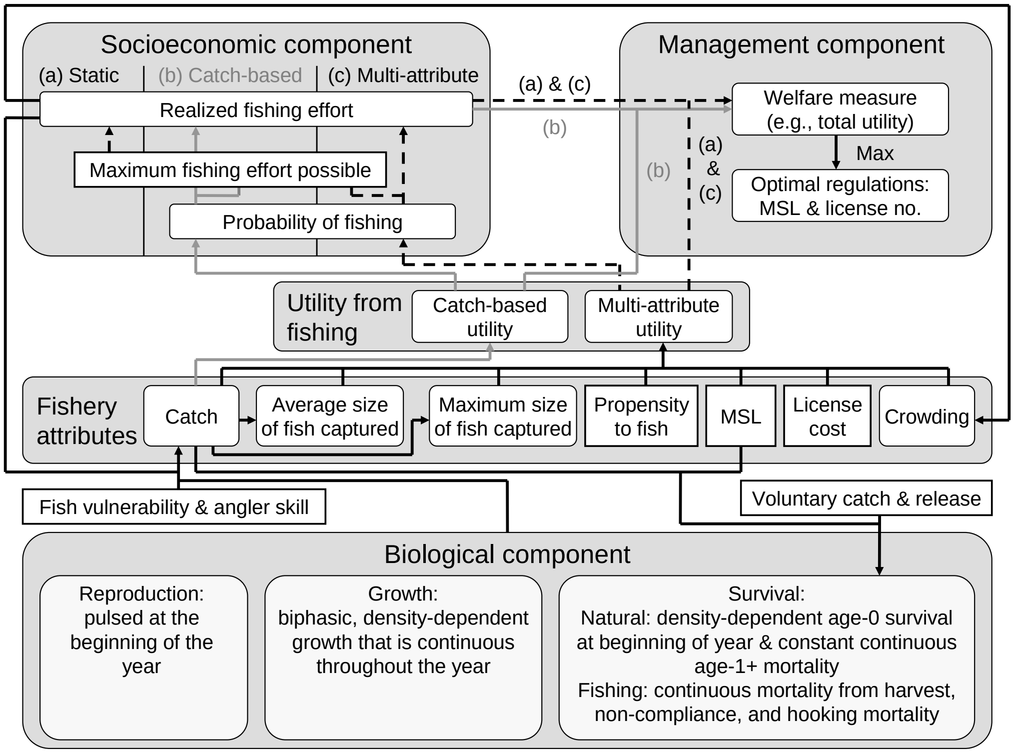
Socioeconomic component
(a) Static
(b) Catch-based
(c) Multi-attribute
Realized fishing effort
Maximum fishing effort possible
Probability of fishing
Management component
(a) & (c)
(b)
Welfare measure (e.g., total utility)
Max
Optimal regulations: MSL & license no.
(b)
(a) & (c)
Utility from fishing
Catch-based utility
Multi-attribute utility
Fishery attributes
Catch
Average size of fish captured
Maximum size of fish captured
Propensity to fish
MSL
License cost
Crowding
Fish vulnerability & angler skill
Voluntary catch & release
Biological component
Reproduction: pulsed at the beginning of the year
Growth: biphasic, density-dependent growth that is continuous throughout the year
Survival: Natural: density-dependent age-0 survival at beginning of year & constant continuous age-1+ mortality
Fishing: continuous mortality from harvest, non-compliance, and hooking mortality

Figure 1

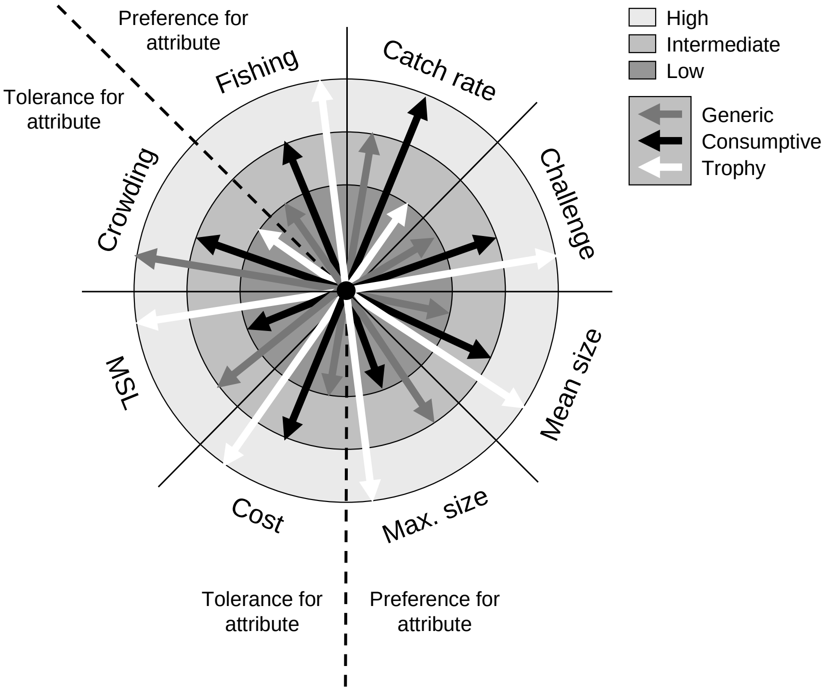
Preference for attribute
Tolerance for attribute
Fishing
Catch rate
Challenge
Mean size
Max. size
Cost
MSL
Crowding
Tolerance for attribute
Preference for attribute
High
Intermediate
Low
Generic
Consumptive
Trophy

Figure 2

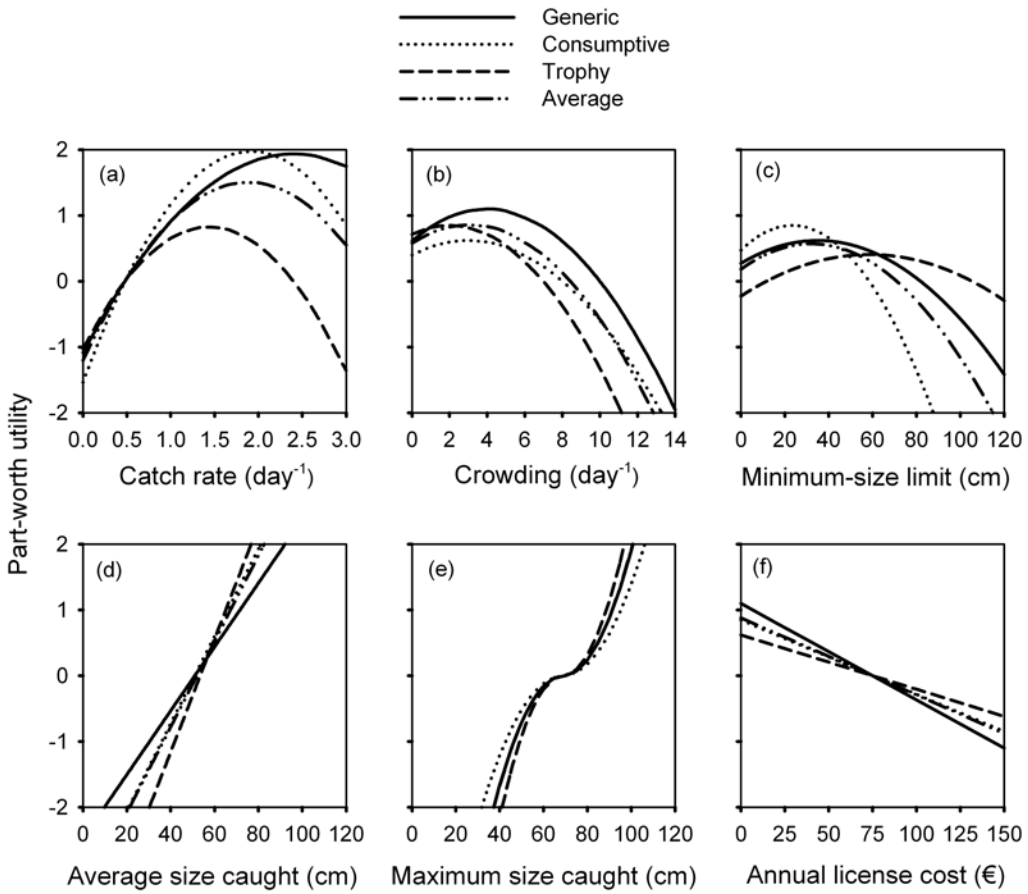
Generic
Consumptive
Trophy
Average
Part-worth utility
(a)
(b)
(c)
(d)
(e)
(f)
2
1
0
-1
-2
0.0 0.5 1.0 1.5 2.0 2.5 3.0
Catch rate (day^{-1})
0 2 4 6 8 10 12 14
Crowding (day^{-1})
0 20 40 60 80 100 120
Minimum-size limit (cm)
0 20 40 60 80 100 120
Average size caught (cm)
0 20 40 60 80 100 120
Maximum size caught (cm)
0 25 50 75 100 125 150
Annual license cost (€)

Figure 3

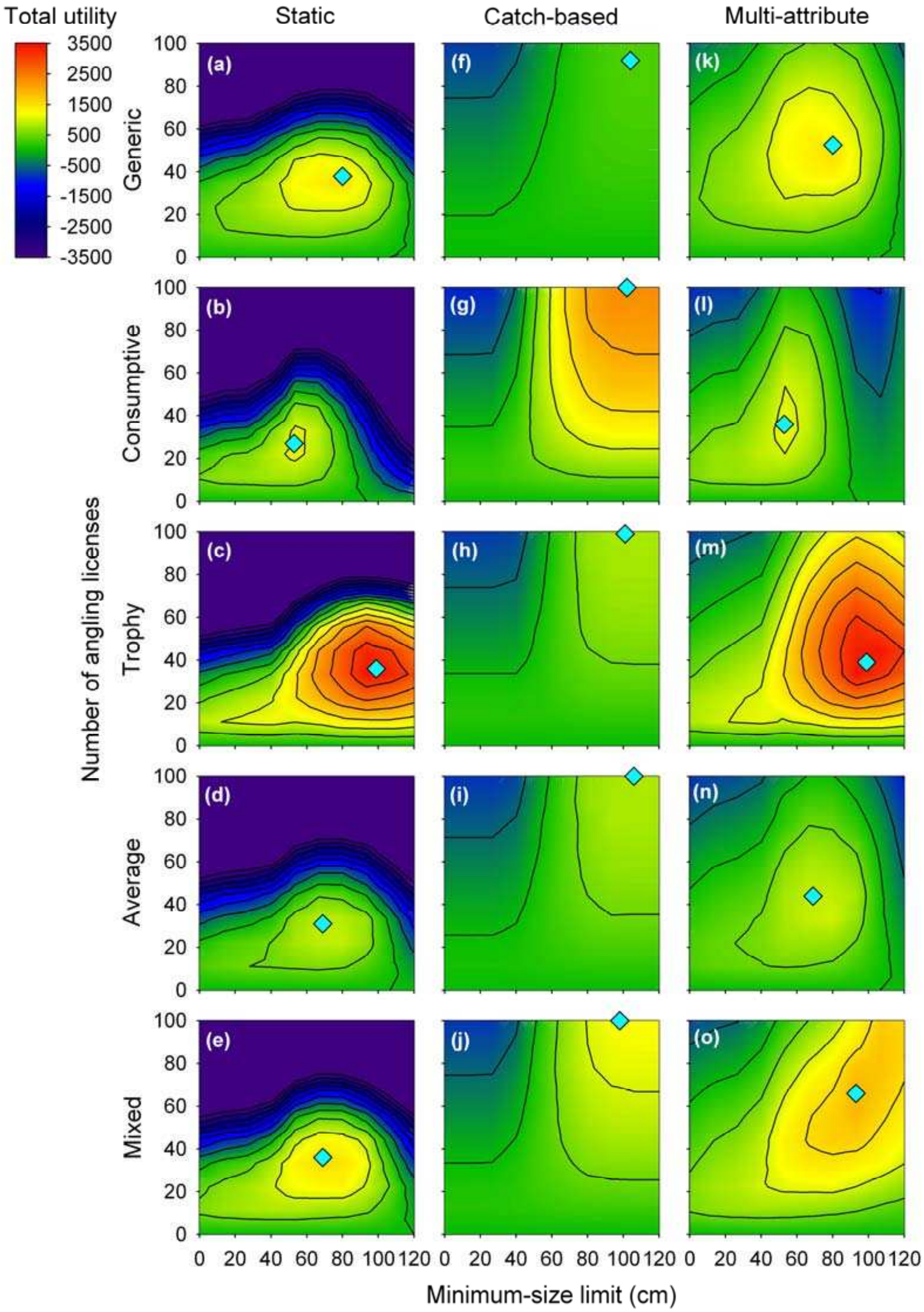
Total utility
3500
2500
1500
500
-500
-1500
-2500
-3500
Static
Catch-based
Multi-attribute
Generic
Consumptive
Trophy
Average
Mixed
Number of angling licenses
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
(o)
0
20
40
60
80
100
120
Minimum-size limit (cm)

Figure 4

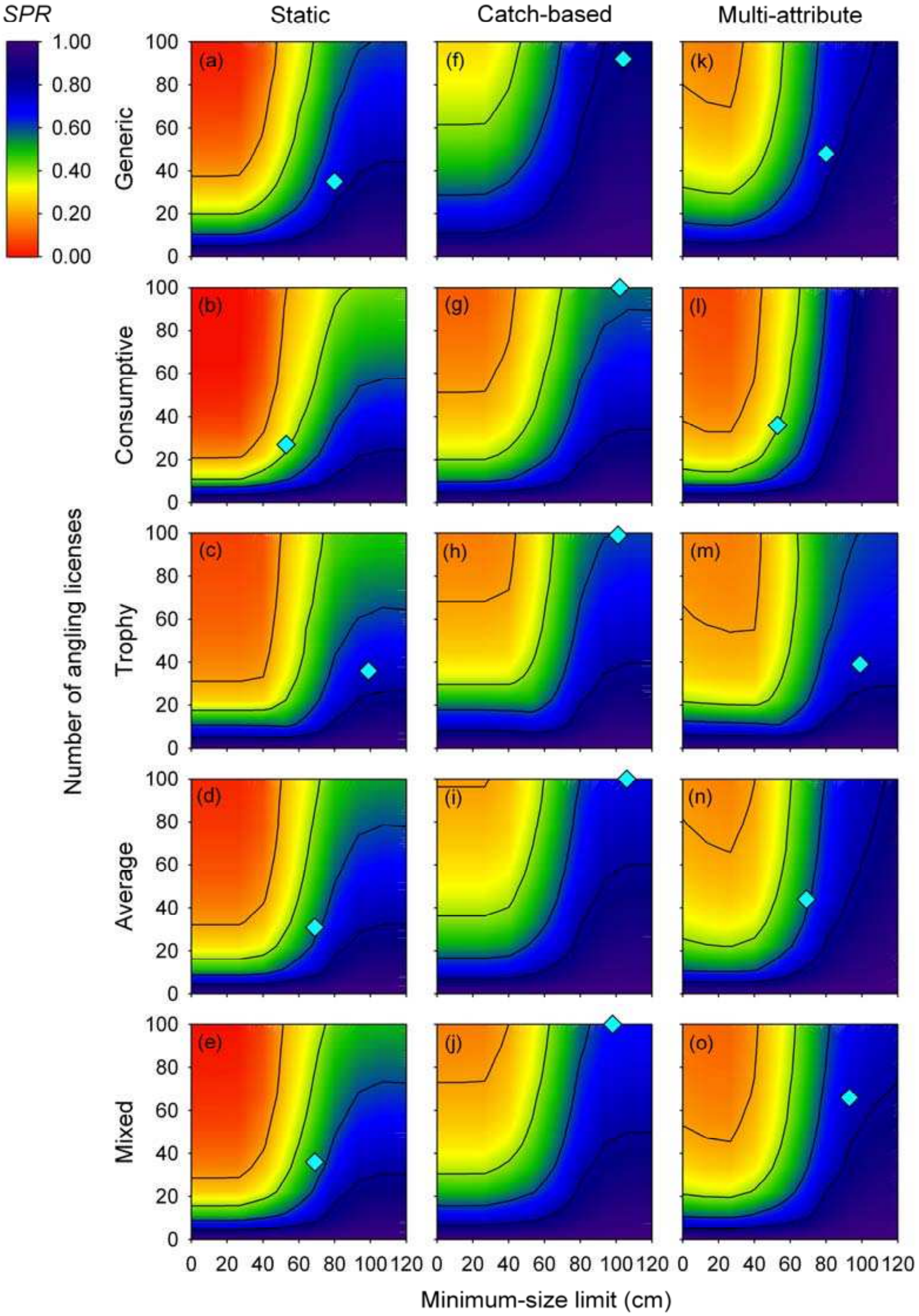
SPR
1.00
0.80
0.60
0.40
0.20
0.00
Static
Catch-based
Multi-attribute
Generic
Consumptive
Trophy
Average
Mixed
Number of angling licenses
Minimum-size limit (cm)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
(o)
0
20
40
60
80
100
120

Figure 5

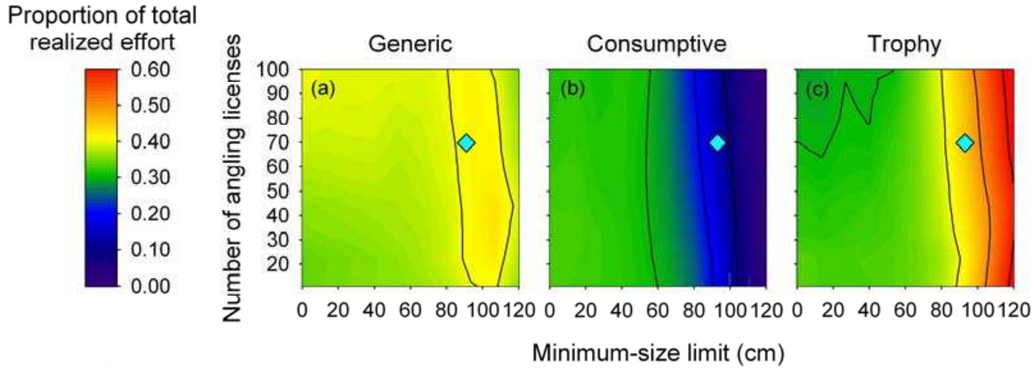
Proportion of total realized effort
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Generic
Consumptive
Trophy
(a)
(b)
(c)
Number of angling licenses
100
90
80
70
60
50
40
30
20
0
20
40
60
80
100
120
Minimum-size limit (cm)

Figure 6

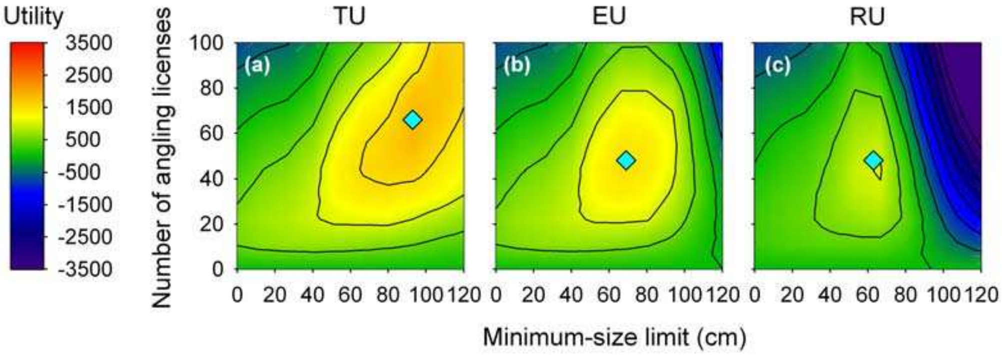
Utility
3500
2500
1500
500
-500
-1500
-2500
-3500
TU
EU
RU
(a)
(b)
(c)
Number of angling licenses
100
80
60
40
20
0
0 20 40 60 80 100 120
Minimum-size limit (cm)

Figure 7

Appendix A Sensitivity of predicted optimal regulations to fishery attributes

Table A1 Sensitivity of predicted optimal regulations, and of the conditions that occur under these regulations, to the removal of single fishery attributes from the multi-attribute utility function (Table 1, equation 1b). Results shown are for the multi-attribute scenario, assuming total utility (TU) as the maximized social-welfare measure. Parentheses show changes relative to results for the multi-attribute scenario with all fishery attributes being included (Table 4).

Removed attribute	Angler population				
	Generic	Consumptive	Trophy	Average	Mixed (TU)
Optimal minimum-size limit (cm)					
Minimum-size limit	104 (+30.0%)	103 (+94.3%)	104 (+5.1%)	105 (+52.2%)	99 (+6.5%)
Crowding	60 (–25.0%)	51 (–3.8%)	96 (–3.0%)	50 (–27.5%)	99 (+6.5%)
Catch	51 (–36.3%)	23 (–56.6%)	100 (+1.0%)	52 (–24.6%)	93 (0.0%)
Average size	55 (–31.3%)	53 (0.0%)	101 (+2.0%)	61 (–11.6%)	61 (–34.3%)
Maximum size	62 (–22.5%)	52 (–1.9%)	86 (+13.1%)	69 (0.0%)	69 (–25.8%)
Optimal angler-license number					
Minimum-size limit	49 (–5.8%)	50 (+38.9%)	41 (+5.1%)	45 (+2.3%)	53 (–19.7%)
Crowding	20 (–61.5%)	31 (–13.9%)	88 (+125.6%)	12 (–72.7%)	100 (+51.5%)
Catch	56 (+7.7%)	40 (+11.1%)	42 (+7.7%)	47 (+6.8%)	75 (+13.6%)
Average size	55 (+5.8%)	44 (+22.2%)	42 (+7.7%)	48 (+9.1%)	46 (–30.3%)
Maximum size	51 (–1.9%)	39 (+8.3%)	44 (+12.8%)	44 (0.0%)	50 (–24.2%)
Annual realized angling effort under optimal regulations (h•ha^{-1})					
Minimum-size limit	61 (0.0%)	67 (+55.8%)	60 (+3.4%)	61 (+22.0%)	68 (+4.6%)
Crowding	19 (–68.9%)	33 (–23.3%)	114 (+96.6%)	13 (–74.0%)	70 (+7.7%)

Catch	63 (+3.3%)	44 (+2.3%)	59 (+1.7%)	49 (–2.0%)	64 (–1.5%)
Average size	64 (+4.9%)	55 (+27.9%)	59 (+1.7%)	53 (+6.0%)	57 (–12.3%)
Maximum size	58 (–4.9%)	46 (+7.0%)	61 (+5.2%)	49 (–2.0%)	59 (–9.2%)
Composition of anglers fishing in the mixed angling population under optimal regulations					
Minimum-size limit	0.35 (–14.6%)	0.31 (+121.1%)	0.34 (–24.9%)	n.a.	n.a.
Crowding	0.31 (–23.8%)	0.09 (–38.7%)	0.60 (+34.1%)	n.a.	n.a.
Catch	0.45 (+8.6%)	0.06 (–55.6%)	0.49 (+9.7%)	n.a.	n.a.
Average size	0.38 (–7.2%)	0.30 (+111.2%)	0.32 (–28.6%)	n.a.	n.a.
Maximum size	0.38 (–7.9%)	0.27 (+91.6%)	0.35 (–21.8%)	n.a.	n.a.
Spawning-potential ratio under optimal regulations					
Minimum-size limit	0.83 (+11.7%)	0.68 (+77.0%)	0.73 (–0.6%)	0.76 (+25.7%)	0.72 (–1.2%)
Crowding	0.76 (+2.2%)	0.42 (+10.0%)	0.56 (–23.1%)	0.66 (+9.3%)	0.71 (–2.3%)
Catch	0.42 (–43.8%)	0.13 (–65.6%)	0.72 (–0.7%)	0.38 (–37.3%)	0.74 (+0.8%)
Average size	0.43 (–41.8%)	0.34 (–12.5%)	0.72 (–0.9%)	0.49 (–18.5%)	0.48 (–34.7%)
Maximum size	0.56 (–24.5%)	0.37 (–3.9%)	0.68 (–7.2%)	0.61 (+0.2%)	0.57 (–22.3%)