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Efficacy of harvest and minimum size limit regulations for controlling short-term harvest in recreational fisheries

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Abstract It is important to consider the potential effectiveness of regulations for reducing total harvest levels when developing fishery management plans. A random forest (RF) modelling approach was used to examine how changing per-angler harvest or minimum size limit regulations affected sport fishery harvest in US Atlantic coast recreational fisheries. Harvest limits per angler (i.e. bag limits) were typically high initially and subsequently reduced, whereas almost half of minimum length limits were initially below the length-at-maturity and subsequently increased. Across most fisheries examined, extreme reductions in harvest limits (e.g. from unlimited to catch-and-release) were largely ineffective at limiting total fishery harvest. Increasingly restrictive minimum length limits caused a greater average harvest reduction than per-angler harvest limits. Some regulation changes were associated with higher angling effort and thus increased harvest, which suggests that when effort cannot be constrained, more direct harvest limitations should be considered.

KEYWORDS: harvest, harvest limit, management regulation, minimum size limit, random forest, recreational angling.

Introduction

A growing recreational angling sector increases the total contribution of recreational fisheries to many local economies (Bartholomew & Bohnsack 2006), prompting calls for reallocating more total allowable catch to the recreational sector (Mcphee *et al.* 2002; Ihde *et al.* 2011). It is therefore not surprising that recreational harvest represents a growing source of mortality for a large number of marine fish species, often overtaking mortality rates caused by commercial fisheries (Ihde *et al.* 2011; Coleman *et al.* 2004; Cooke & Cowx 2004). In developed countries, commercial fishery catch and effort are typically monitored as part of the requirement for owning a licence through a combination of portside monitoring and on-board observers. In principle, such close and timely monitoring of commercial fisheries allows for reasonably tight control of total harvest and thus fishing mortality. Recreational fisheries, on the other hand, are much more difficult to monitor for total catch, harvest and effort because reporting is generally not required of licence holders and access points for observers are diffuse across the coastal landscape (Cooke & Cowx 2006). Although agencies such as the US National Marine Fisheries Service (NMFS) routinely conduct recreational fishery surveys, it is often not possible to analyse the data, make in-season regulation changes and enforce those regulations fast enough to close fisheries when total allowable recreational catch is exceeded. These difficulties with output harvest controls typically force agencies to rely on regulating angling efficiency (i.e. input controls) to a point where it is unlikely that allowable catches will be exceeded given the estimated number of anglers in a fishery (Coleman *et al.* 2004). Although specific regulatory objectives vary among fisheries (Radomski *et al.* 2001), recreational angling regulations are generally aimed at limiting angler efficiency and/or limiting harvest on sensitive size-classes and age-classes of fish populations (Scrogin *et al.* 2004; Dawson & Wilkins 1981; Homans & Ruliffson 1999). Therefore, for our purposes, we define a short-term (i.e. a few years) decline in harvest as the mark of an effective management regulation.

In both marine and freshwater recreational fisheries, two of the most common fishing regulations are size

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limits and per-angler harvest limits, where the latter includes mandatory catch-and-release (Cooke & Cowx 2006; Woodward & Griffin 2003; Coggins *et al.* 2007). In general, harvest limits attempt to control the total allowable harvest by individual anglers of one or more fish species. Particular variations in harvest limits include daily individual harvest limits of a single species (commonly referred to as bag or creel limits in inland fisheries), aggregate limits on the harvest of a group of taxonomically or ecologically similar species and possession limits on the number of one or more species harvested per group of anglers (usually on a single boat). In some cases, harvest limits are expected to limit harvest by exceptionally skilled anglers so as to reduce total mortality and to distribute catch more equitably among as many recreational anglers as possible (Radomski *et al.* 2001). However, as critics of harvest limits point out, most anglers catch well below their limit of fish, and therefore, the regulations affect a small minority of anglers (Mcphee *et al.* 2002; Radomski 2003). Even where it is reasonable to expect reductions in the number of fish retained on each fishing trip, such regulations sometimes have no effect on total catch because the total number of anglers, as well as the number of trips per angler (Post *et al.* 2002; Cox *et al.* 2002), may increase in response to new fishing regulations if those regulations increase the perceived attractiveness of the fishery (Cook *et al.* 2001; Radomski *et al.* 2001; Post *et al.* 2002; Coleman *et al.* 2004; Beard *et al.* 2003). Regulating individual catch per angler could also easily fail in situations where the number of recreational anglers and/or trips per angler is increasing as a part of underlying social, economic or political trends. Understanding the circumstances under which particular input control regulations may or may not work is therefore important if management agencies are to develop regulations aimed at achieving particular goals.

Size limits are generally intended either to prevent growth overfishing, prevent harvest of immature members of a species to ensure the maximum number of fish reach maturity (Noble & Jones 1999), or to create a 'trophy' fishery where individual fish are allowed to survive to large body sizes (Homans & Ruliffson 1999). Length limits are arguably the most common regulation used in fisheries management (Coggins *et al.* 2007) and can be quite effective at preventing overharvest in many situations. Fish life history plays an important role in determining when size limits are appropriate and what the optimal limit should be for a particular fishery (Cooke & Cowx 2006); notably, long-lived, slow-growing species may be particularly well suited for minimum size limit protection. However, studies of inland systems demonstrate that shifting a fish population's size structure via selective harvesting may combine with density-dependent processes and inter-cohort interactions to cause unintended consequences such as increased cannibalism or reduced food resources because of the increased consumption requirements of larger individuals (Radomski 2003; Johnson & Martinez 1995).

Clearly, the choice of recreational fishing regulations needed to achieve a particular management goal will be context specific. There are many situations where one regulation will work as intended, while others will not (Lewin *et al.* 2006 and references therein). This is true not just from a biological perspective, but also from a social-scientific perspective; for example, regulations may be ineffective in certain contexts where anglers are unable or unwilling to comply with regulations (Reynard & Hilborn 1986; Aas *et al.* 2000; Johnson & Martinez 1995). While much effort is currently put into estimating both the absolute size and productivity of fish populations, as well as the total impact of different fishing sectors on these resources, few studies have examined the contexts and factors influencing how effective size and harvest limit regulations are at limiting total removals across a range of fish populations.

In this paper, how harvest and minimum size limit regulations help to limit total harvest in recreational fisheries are evaluated. Fishing regulations are often imposed on fisheries where latent effort is high because of various reasons or where the target species has life history traits (growth rate, maximum size, age at maturity, population productivity) that make them particularly vulnerable to overharvesting. Therefore, this evaluation will specifically include variables on fishing effort and species life history traits as well as environmental and demographical variables. Data from the US Atlantic recreational fishery (excluding the coast of the Gulf of Mexico) across all species and management jurisdictions for which either of these two regulations exists were used. The aim is to elucidate the relative importance of various factors when considering imposing fishing regulations to limit harvest and provide direction for further investigation.

Methods

Data collection

Summaries of recreational fishing harvest (including harvested and dead releases combined) and angling effort for US Atlantic fisheries were obtained from the NMFS marine recreational fisheries survey (NMFS, Fisheries Statistics Division, NOAA Office of Science and Technology, Silver Spring, MD, *personal communication*).

These data are collected using two complementary surveys (for details, see Hicks *et al.* 1999). The first is a Coastal Household Telephone Survey used to estimate the total number of fishing trips made by coastal residents (who also happen to own a telephone). Interviews are conducted based on randomly chosen telephone numbers in the first 2 weeks of every bi-monthly wave (six waves per year). In the second survey, an access-point angler intercept survey is conducted at randomly chosen public marine fishing access points, where angler demographics, catch and species composition are collected by trained personnel. The two surveys combined are expected to provide an accurate estimate of total fishing effort including non-coastal anglers and coastal anglers without a telephone (Hicks *et al.* 1999).

Estimated mortality data from a combination of landed harvest and discarded mortalities were obtained through a search over all species on the Atlantic Coast (excluding the Gulf of Mexico coast) based on queries limited to year (1985–2010), time of year (by wave), geographical area (Atlantic Coast by State), fishing mode (by mode) and area (all areas by area). Total fishing effort data in a given time and area were obtained using the same search criteria as above. Within these two databases, wave represents bi-monthly time period of the year, fishing mode represents different groups of anglers (e.g. shore anglers, private, charter or party boats), and area is composed of either areas under state jurisdiction (≤ 3 nautical miles from shore; ≤ 10 nautical miles from shore in Florida) or areas under federal jurisdiction (all exclusive economic zone [EEZ; waters 200 nautical miles from shore] except state jurisdictions). Charter operations are often managed using different fishing regulations than other fishing modes, so estimates of harvest and effort for modes that included charter operations were excluded. Data were retained on individual species only, so that catch estimates on species groupings were removed.

Regulations for fisheries under state jurisdiction were obtained from individual state websites, the Atlantic States Marine Fisheries Commission, and direct contact with fisheries managers from several state agencies. Regulations for fisheries under federal jurisdiction were obtained from the New England Fishery Management Council (NEFMC, including Maine, New Hampshire, Massachusetts, Rhode Island and Connecticut), the Mid-Atlantic Fishery Management Council (MAFMC, including New York, New Jersey, Pennsylvania, Delaware, Maryland, Virginia and North Carolina) and the South Atlantic Fishery Management Council (SAFMC, including North Carolina (in addition to MAFMC), South Carolina, Georgia and eastern Florida to Key West). Regulation information included the year, wave, state and area (state or federal jurisdictions) in which regulation change was enacted, the species being regulated and the exact regulation with respect to harvest or minimum size limits.

Life history traits for each fish species in the data set were obtained from FishBase (Froese & Pauly 2011) and included length-50% maturity, Brody's coefficient, k, the asymptotic maximum length, L_∞, and primary habitat occupied by adults. An additional parameter, ω, was calculated as $L_\infty \cdot k$ to account for the dependence and interaction of the von Bertalanffy parameters L_∞ and k (Gallucci & Quinn 1979). This parameter has been suggested as an alternative to k and has a less correlation with L_∞. Habitats used by species included in the analysis were characterised as either benthopelagic, demersal, pelagic–neritic, pelagic–oceanic or reef. When more than one record for a species existed in FishBase, the most current record whose geographical location was nearest the mid-US Atlantic coast was chosen.

Data analysis

The ways in which different variables influence harvest following the implementation of a harvest regulation, including non-linear relationships and interactions among explanatory factors, are largely unknown and difficult to predict, especially across species and fisheries. Therefore, data were analysed using a non-parametric random forest (RF) method from machine learning. The RF method is generally robust to unknown model structure, lack of independence and pseudoreplication (Breiman 2001; Prasad *et al.* 2006; Davidson *et al.* 2009). Random forests are an extension of classification and regression trees (CART), whereby the data are partitioned into two nodes by a single-class variable (for classification trees) or a particular value of a continuous variable (for regression trees) using an optimisation algorithm designed to maximise both homogeneity within a node and heterogeneity between nodes (Cutler *et al.* 2007). Exact details of the random forest method are more fully described elsewhere (Breiman 2001; Cutler *et al.* 2007). Briefly, the RF algorithm proceeds as follows: (1) n replicate bootstrap data sets are drawn and a tree is grown for each replicate; (2) at each node of each tree, a random sample of m variables is drawn from all classification variables and is used to make the decision on where to split the data; (3) each tree in the forest is then used to make predictions for the out-of-bag (OOB) data that were not included in the original bootstrap data set (Breiman 2001); (4) the predicted class of each observation is calculated by majority vote of the OOB predictions across the forest with ties split randomly (Cutler *et al.* 2007); (5) accuracies and error rates are computed for each observation based on the OOB predictions and averaged across all observations. An important aspect of the random forest approach is that because the OOB observations are not used to fit the trees but essentially cross-validate the model accuracy, there is no need to hold some data back to validate the model (Cutler *et al.* 2007). In ecological applications, the RF approach outperforms or is closely competitive with a wide range of alternative methods (e.g. Perdiguero-Alonso *et al.* 2008; Cutler *et al.* 2007; Knudby *et al.* 2010a,b; Prasad *et al.* 2006).

Along with providing a predictive model, the RF also provides measures of variable importance, which may be defined in several ways (Breiman 2001). The most commonly used metric, permutation accuracy importance which is defined as the increase in mean squared error when OOB data for a variable are permuted was chosen, while all others are left unchanged (Breiman 2001; Liaw & Wiener 2002; Cutler *et al.* 2007). The randomised approach to computing permutation accuracy importance also accounts for among-variable interactions.

The RF analysis was used to identify and rank key factors that are associated with changes in total harvest following either an individual harvest limit or minimum size limit regulation change. The two regulations were analysed simultaneously based on factors listed in Table 1. Harvest limits are often ambiguously defined, so instances where either an individual bag limit or aggregate bag limit was imposed were defined as the harvest limit. In cases where both bag and aggregate limits were imposed, the lesser of the two (i.e. fewest number of fish allowed) was used as the harvest limit. Within each regulation-type data set, the number of bimonthly waves since a particular regulation was enacted or changed was calculated for each species, state and area (state or federal jurisdiction). Years and waves where no harvest was estimated were removed from the data set. To remove the influence of seasonality and differences in scale of harvest among different states and species, harvest was transformed and expressed as

$$t(H_{y,w}) = \ln\left(\frac{H_{y,w}}{\mu_{H(w)}}\right)$$

where $t(H_{y,w})$ is the transformed harvest for a particular year (y) and wave (w), $H_{y,w}$ is the observed harvest for that year and wave, and $\mu_{H(w)}$ is the mean harvest for the same wave across the 5 years prior to regulation change to the current regulation. Fishing effort was expressed in the same way. This has the dual role of helping to make the distributions of harvest and effort symmetrical while also showing if harvest and effort increased or decreased following a regulation change. Harvest and minimum length limits at a particular time were expressed as a deviation from the previous harvest (in numbers of fish allowed) or minimum length limit (in cm). If no harvest limit was in place, it was set to 200 fish per day; if no minimum length limit was in place, it was set to 1 cm. Results were found to be insensitive to these choices. Both of these regulations will do nothing to limit harvest by an individual angler in virtually all fisheries examined. Additionally, to examine only short-term responses of harvest to regulation change, harvest records that occurred more than 5 years following a management regulation were removed.

The data were analysed using a RF algorithm run in R (Core Development R Team 2011) using the

Table 1. Variables used to predict the proportional change in harvest following the implementation of a management regulation

Predictor	Type	Description
Contextual Predictor		
State	Categorical (14)	State jurisdiction from which catch was taken
Area	Categorical (2)	Area (Federal or State) from which catch was taken
Year	Categorical (26)	Year of catch record
Wave	Categorical (6)	2-month period of within a year catch record
Time of regulation	Continuous	Number of waves since regulation was enacted
Harvest Limit	Continuous	Current minus previous harvest limit for the relevant species, state and area
Minimum length limit	Continuous	Current minus previous minimum length limit for the relevant species, state and area
Effort	Continuous	Number of fishing trips estimated for each state, area and time
Biological Predictor		
Length-at-50% maturity	Continuous	Length at which 50% of individuals are mature
von Bertalanffy L_∞	Continuous	Asymptotic length of species captured
von Bertalanffy k	Continuous	Brody 'growth' coefficient of species captured
von Bertalanffy ω	Continuous	Early growth rate of species captured
Habitat	Categorical (5)	Habitat type in which species captured is reported to be frequent

The number of levels for categorical predictors is given in parentheses.

RandomForest package (Liaw & Wiener 2002). Random forests have only three parameters that may be tuned to improve prediction accuracy. These include the total number of trees in the forest (n), the number of randomly chosen variables examined at each node (P) and the minimum node size (m). The default value for P is one-third the number of predictor variables and the default value for m is five. To ensure that the best fit to the data were obtained, P and m were initially varied on both the harvest limit and minimum size limit data sets using a forest of 250 trees to determine the combination that resulted in the lowest residual mean squared error before running the final analysis. The final analysis was run using n = 1000 trees, which preliminary analysis showed to be appropriate.

Results

The final data set included 1759 records from 14 Atlantic coast states. The data set included 85 instances where harvest limits were changed and 52 instances where minimum length limits were changed. Twenty-one species had changes to minimum length limit or harvest limit regulations. Exact species included are listed in Appendix 1.

On the basis of regulation information from federal fisheries management councils, state agencies and the Atlantic States Marine Fisheries Commission, initial harvest limits (including individual bag limits and possession limits) over the past few decades are most frequently set to ten fish or more (Fig. 1). Note that this does not take into account other regulations that may be in place at the same time. Note that Figures 1 and 2 show untransformed ratios of harvest or minimum size limits (in numbers of fish or cm, respectively) following change in regulation relative to before change in regulation. Instances where bag limits were changed typically resulted in harvest limits decreasing by up to 90%, although some instances of substantial increases in harvest limits also occurred (Fig. 1). This most often is accompanied by a change in another regulation type, typically a more conservative minimum length limit (not shown). To reflect the common use of minimum size limits to protect immature fish, size limits relative to the size-at-maturity are presented in Figure 2. Minimum size limits ranged from one-half the size-at-maturity to over twice as large with more than 40% of all initial minimum length limits set below the length-at-maturity (Fig. 2; top panel). When minimum size limits changed over time, they were typically adjusted to be marginally larger, making them more conservative. Relatively few changes resulted in smaller minimum size limits (Fig. 2; bottom panel).

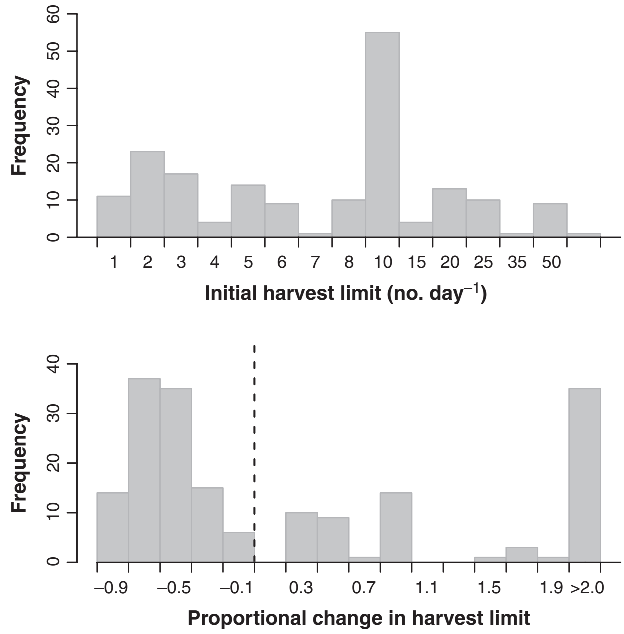

Figure 1. Initial harvest limits for marine recreational fisheries along the US Atlantic coast (top panel) and subsequent proportional change in harvest limits (new limit – previous limit)/previous limit (bottom panel). Vertical dashed line represents the break between an increase and decrease in proportional harvest limit.

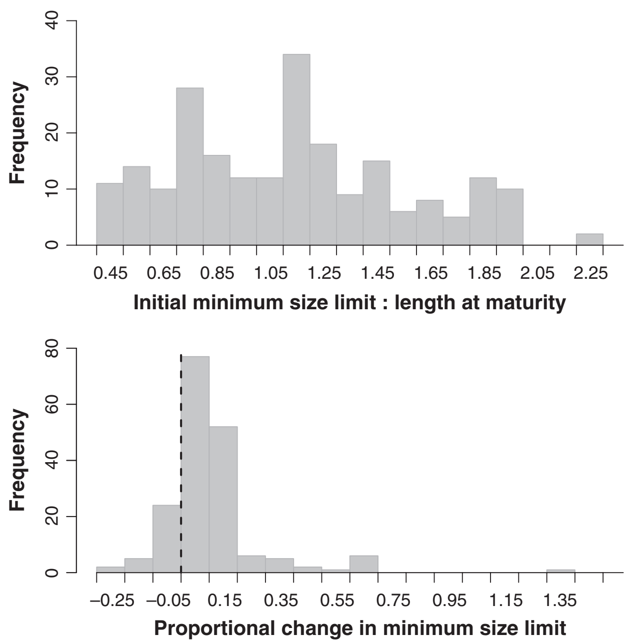

Figure 2. Ratio of initial minimum size limit to length at maturity for marine recreational fisheries along the US Atlantic Coast (top panel) and subsequent proportional change in minimum size limit (previous limit – new limit)/previous limit (bottom panel). Dashed vertical line represents the break between an increase and decrease in minimum size limit.

Tuning the random forest model slightly improved the fit for both harvest limit and minimum size limit models (Table 2). Overall, however, the RF model explained a low proportion of the total variance in the data set (12%), which mainly reflects the large amount of uncertainty in recreational harvest data and the course scale of our analysis.

The change in total harvest following a change in management regulation is strongly associated with both contextual and biological variables (Fig. 3). State was the most important variable influencing mean proportional harvest change. No particular latitudinal pattern was evident, indicating that spatial location was less important than individual state characteristics, leading to greater changes in total harvest in some states than others (Fig. 4a). Note that Figure 4 shows mean transformed harvest with respect to a predictor variable with all other variables marginalised. For brevity, this is referred to as mean proportional harvest. Changes in harvest limits were most correlated with changes in harvest where smaller declines in harvest limits were correlated with greater reductions in harvest (Fig. 4b). Habitat was the third-most important variable, primarily because of benthopelagic species having positive mean proportional harvest following changes in management regulations (Fig. 4c). All increases in the minimum length limit were correlated with declines in mean proportional harvest, whereas decreasing minimum length limits generally were correlated with increases in mean proportional harvest (Fig. 4d). The parameters L_∞, length-at-50% maturity (L_m), ω and transformed fishing effort all had approximately equal importance in affecting mean proportional harvest (Fig. 3). Changes in fishing regulations appear to be correlated with a larger effect on harvest in larger-bodied fish, indicated by declining mean proportional harvest with increasing L_∞ (Fig. 4e). Species with smaller size-at-maturity generally have larger decline in harvest following changes in harvest limits, although species with very low size-at-maturity were relatively insensitive to the regulation changes examined with respect to changes in harvest (Fig. 4f). The von Bertalanffy parameter ω influenced change in harvest but no clear pattern was evident (Fig. 4g). There is a near linear relationship between transformed effort and mean proportional harvest (Fig. 4h). In fisheries where effort increases following management change, there is a greater chance of harvest increasing.

Table 2. Effect of the random forest tuning procedure on the mean squared error (MSE) and percent variance explained (PVE) of the harvest limit and minimum size limit analyses with respect to the number of predictors (P) and minimum node size (m). Baseline values are determined as P = P/3 and m = 5

Parameter	Baseline	Tuning	Best fit
N	250	250	1000
P	4	2	2
m	5	9	9
MSE	2.5	2.5	2.5
PVE (%)	11.4	12.1	12.1

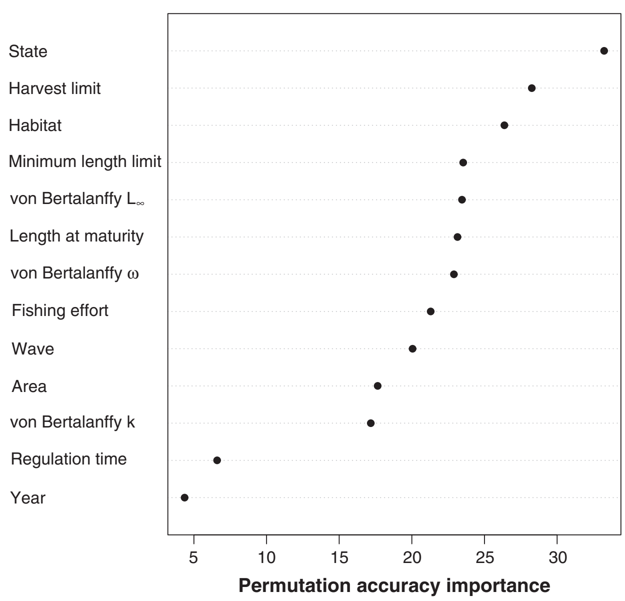

Figure 3. Variable importance for predicting changes in harvest following changes to management regulations. Variable importance is defined as permutation accuracy importance (see text for details).

Discussion

The objective of this study was to examine the ability of harvest and size limit regulations to limit total harvest in US Atlantic coast recreational fisheries. An attempt was made to account for particular contextual and biological factors that could influence the efficacy of these regulations by modelling changes in proportional harvest using a random forest approach. The random forest analysis was specifically chosen because it routinely outperforms similar analyses aimed at similar types of questions (Cutler *et al.* 2007; Perdiguero-Alonso *et al.* 2008; Davidson *et al.* 2009). The harvest data set assembled appears to include substantial amounts of variability, most of which remained unexplained by the random forest model. Nevertheless, several interesting patterns emerged that can help to focus further investigations into how and when harvest or minimum size limit regulations might be useful management tools in recreational fisheries, or when they might be avoided in favour of more direct forms of harvest control.

First, state was the most important variable determining changes in harvest following regulation changes. At

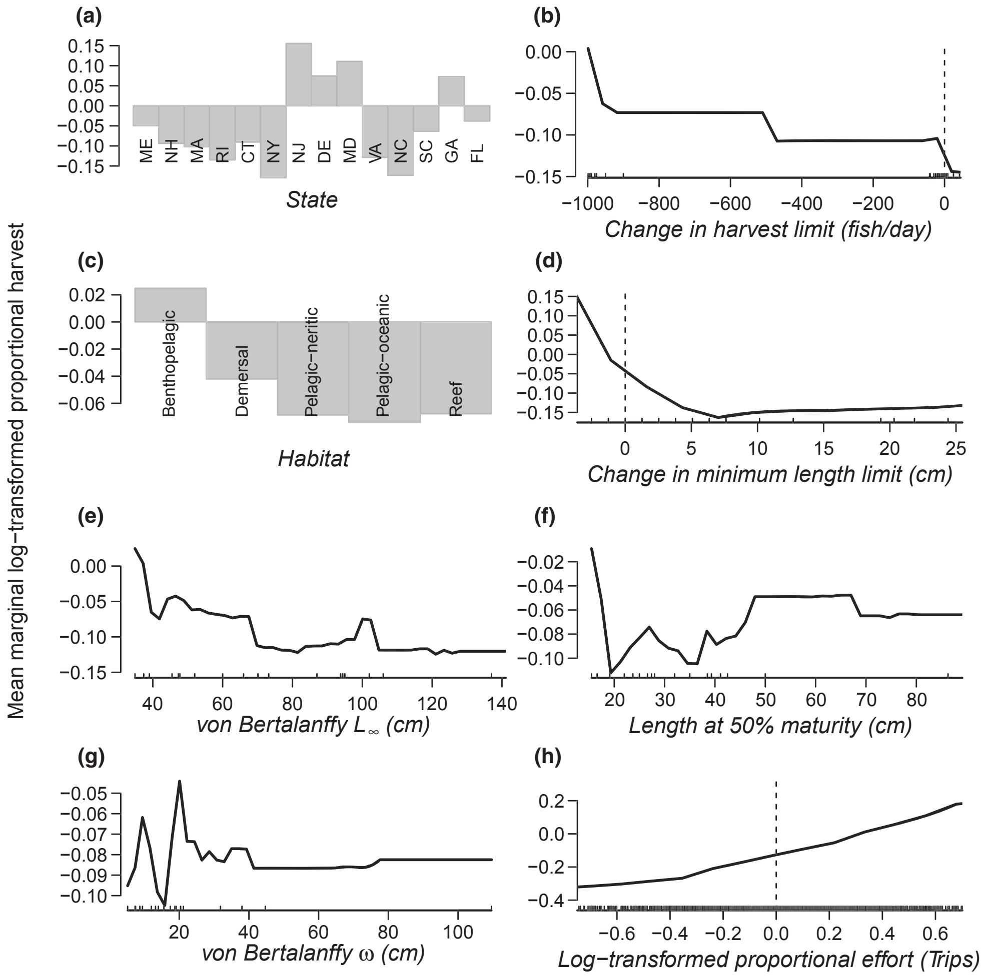

Figure 4. Marginal dependence plots of proportional harvest following changes to management regulations. Proportional harvest is given as log-transformed harvest following regulation change as a proportion of the 5-year mean prior to regulation change. Ticks on plots of continuous variables represent 5th percentiles of the data. The eight most important variables predicted using permutation accuracy importance are displayed.

first glance, it may appear that four states of the 14 examined are ineffective at implementing management regulations in a way that significantly influences harvest. However, this is unlikely because many fisheries are jointly managed by either the Atlantic States Marine Fisheries Commission (in State waters) or federal Fishery Management Councils. The exact reasons why these states appear to stand out as having a mean positive change in proportional harvest, while all others are negative, are unclear. For example, if a particular regulation is imposed that is unattractive to the angling public, this could lead to non-compliance with regulations and a lack of direct connection between management intentions and results (Reynard & Hilborn 1986). Thirteen factors were included that may influence harvest in recreational fisheries, yet together these factors accounted for only 12% of total variation in transformed change in harvest following regulation changes. Although understanding and incorporating contextual information on species productivity and life history is important, they are insufficient to explain much variation in harvest.

Second, progressively strong changes in harvest limits (e.g. from unlimited harvest to very small harvest limits) resulted in weak declines in harvest. A large number of changes to harvest limits were dramatic declines from unlimited harvest, or very high limits, to very low limits. These regulations may often be ‘too little, too late’, so that although the fishery was previously unregulated, few fish were being caught and the new intended limits on harvest do little to limit individual harvest because few fish are being caught. This is not to say that harvest limits are ineffective in general, but the initial change was large and ineffective. Although all changes to harvest limits resulted in a mean reduction in marginal proportional harvest, the results suggest that incremental increases to harvest limits are the most effective. This counterintuitive result is likely due to two factors. First, while the initial implementation of harvest limits may not do much to affect harvest across many fisheries, smaller subsequent changes will help to 'fine-tune' limits in a way that increasingly have the desired effect of limiting harvest. Second, the observed decline in harvest following small increases in harvest limits is likely due to management agencies beginning to abandon harvest limits as the sole management tool in favour of concurrently strengthening other types of regulation, particularly more restrictive size limits. This suggests that although harvest limits reduce mean harvest across all fisheries, the importance of other regulations used in concert must be considered (Woodward & Griffin 2003; Pine *et al.* 2008). Equally important, it points to the difficulty in limiting total harvest via per-angler harvest limits alone given that total angling effort is still unrestricted (Cox *et al.* 2002; Post *et al.* 2002).

In contrast to harvest limit regulations, implementing increasingly restrictive size limit regulations resulted in reductions in harvest as would be expected. This result suggests that minimum size limits generate more predictable effects on harvest changes despite a wide range of contextual and biological variation. Part of this effect could be that minimum size limits are actually an extreme form of harvest limit (i.e. harvest limit equal to 0 for fish below the size limit) that is relatively insensitive to changes in total fishing effort. Imposing conservative minimum size limits (e.g. greater than size-at-maturity) throughout their Atlantic coast range was apparently quite effective in helping to recover striped bass in the 1980s and 1990s (Grout 2006). On the other hand, the summaries of regulation changes over time suggest that perhaps minimum size limit regulations are not being used as effectively as they could. Ideally, size limits are set to reduce or eliminate mortality risk caused by fishing prior to first reproduction (Walters & Martell 2004; Noble & Jones 1999). Therefore, it was surprising that so many fisheries set minimum size limits at levels considerably below the size-at-maturity of particular fish species. As the number and sizes of fish protected by a size limit increase, the proportion of fish caught and released increases, and therefore so too should release mortality. Some fisheries may experience higher rates of release mortality than others depending on factors such as gear used, fishery specialisation, capture depth and water temperatures (reviewed in Bartholomew & Bohnsack 2006). Thus, even if minimum size limit regulations are effective in the short term at limiting total harvest, factors that are likely to increase release mortality should be considered when imposing regulations (Coggins *et al.* 2007).

Finally, fishing effort plays a role in the ability of a management regulation to limit total harvest and mortality. The results indicate that regulations that can help to reduce effort are more likely to reduce harvest. This result makes qualitative sense if smaller fisheries are small because of socioeconomic or accessibility constraints on total fishing effort, while larger fisheries are more open to entry and exit from larger angler populations (Cox & Walters 2002). Limiting the number of fish harvested per trip must eventually fail to control harvest at conservative levels as the number of trips taken increases (Post *et al.* 2002). Indeed, while many anglers see harvest limits as an effective means of managing a fishery, managers recognise that limits strict enough to affect total harvest are almost always socially unacceptable (Radomski *et al.* 2001; Cook *et al.* 2001) and therefore are generally expected to be ineffective. Furthermore, harvest limits rarely deter anglers (Radomski *et al.* 2001) and may even be used as a means of evaluating the attractiveness of a fishery (Radomski *et al.* 2001; Cook *et al.* 2001; Beard *et al.* 2003; Noble & Jones 1999). No similar finding has been investigated for minimum length limits, but presumably high minimum limits may attract anglers seeking 'trophy' fisheries and so the same will likely hold true.

A typical fishery response to input management regulations involves the following steps: decreased harvest; possibly a decrease in effort as anglers move to fisheries with higher attractiveness; recovery of the fish population; improved catch and harvest of legal fish; increased fishing effort as the attractiveness of the fishery improves relative to other fisheries (Walters & Martell 2004). If the fishery becomes too attractive, or if harvests from other similar fisheries decline, effort could increase to the point where overexploitation returns. This is an important consequence of using input controls such as harvest and minimum length limits that do nothing to limit access to the fishery. Examination of short-term responses (within 5 years of regulation changes) were chosen to isolate the immediate impacts of these regulations from the effects of recovery of the fish population. Although factors that may be helpful in deciding when these regulations may be effective in the short term were chosen, there is no guarantee that they will ensure long-term sustainability (Cox *et al.* 2002).

It is increasingly clear that management of capture fisheries needs to take uncertainty into account when setting harvest regulations (Hilborn & Walters 1992). Predictability of the effects of management regulations is an important component of the total uncertainty in any fishery management system, yet there are few broad-scale examinations of the efficacy of fishery management regulations, particularly for recreational fisheries. The results demonstrate that the short-term outcome of regulation changes, and especially those involving harvest limits, may be difficult to predict based on readily observable characteristics of a fishery. Given the limited total predictive power of our random forest model, which is typically among the most powerful methods for these problems (Cutler *et al.* 2007; Perdiguero-Alonso *et al.* 2008; Davidson *et al.* 2009), the effects of harvest and size limit regulations should probably be viewed as highly uncertain in all but the smallest, most effort-constrained fisheries. Thus, although harvest and minimum size limit regulations are among the most common regulations across recreational fisheries (Cooke & Cowx 2006; Woodward & Griffin 2003; Coggins *et al.* 2007), other types of regulations, including gear restrictions, temporal and spatial closures, may be predictably more effective (Hilborn *et al.* 2004). Some of the fisheries examined also incorporated these regulations, but they could not be included because their occurrence was often at a finer scale than our data (e.g. temporal closures of a few weeks; spatial closures in small areas within state jurisdictions). Where these more restrictive regulations are not feasible, realistic assessments of the likely outcome of harvest and size limit regulations should become a mandatory component of recreational fishery management plans.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix1. Species included in random forest analysis of factors influencing recreational harvest across Atlantic states fisheries.