# Protecting Marine Biodiversity: A Comparison of Individual Habitat Quotas (IHQs) and Marine Protected Areas

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**Summary**

Fisheries managers in the United States are required to identify and mitigate the adverse impacts of fishing activity on essential fish habitat (EFH). There are additional concerns that the viability of noncommercial species, animals that are habitat dependent and/or are themselves constituents of fishery habitat may still be threatened. We consider a cap-and-trade system for habitat conservation, individual habitat quotas for fisheries, to achieve habitat conservation and species protection goals cost effectively. Individual quotas of habitat impact units (HIUs) would be distributed to fishers with an aggregate quota set to maintain a target habitat "stock" of EFH conservation. Using a dynamic, spatially explicit fishery simulation model we explore the efficiency and cost effectiveness of an IHQ policy versus alternative marine protected area (MPA) configurations, at reducing the risk of extinguishing a habitat dependent species of unknown spatial distribution. Our findings indicate that an IHQ policy with a conservatively established habitat target is better suited to the protection of non-target species than a rotating or fixed MPA policy.

**Keywords:** Fisheries management, Individual transferable quota, ITQ, Individual habitat quota, IHQ, Essential fish habitat, EFH, Marine protected areas, MPA, Non-target species

**JEL Classification:** Q20, Q22

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## Introduction

The provisions added to the Magnuson-Stevens Fisheries Conservation and Management Act (MSFCMA) in 1996 require the eight regional fishery management councils to identify and describe essential fish habitat in each fishery management plan (FMP); minimize to the extent practical the adverse effects of fishing on EFH; and identify actions to encourage the conservation and enhancement of EFH. Essential fish habitat (EFH) is defined in the (MSFCMA) as “those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity.” This description was amended to the MSFCMA in 1996 when Congress added a provision to protect EFH within the United States. In addition, councils are instructed to “consider the nature and extent of the adverse effect on EFH and the long and short term costs and benefits of potential management measures to EFH, associated fisheries, and the nation” (50 CFR §600.815). Requirements to protect EFH were motivated by the finding (stated in the reauthorization of the MSFCMA) that “one of the greatest long-term threats to the viability of commercial and recreational fisheries is the continuing loss of marine, estuarine, and other aquatic habitats.”

A predominant source of habitat damage is commercial fishing which can reduce the complexity of the benthic structure, increase the resuspension of benthic sediments, and alter the community and trophic structure within an ecosystem (Engel and Kvitek 1998; Greenstreet 1999; Jennings and Reynolds 2000; Johnson 2002; McConnaughey et al. 2000; Pilskaln et al. 1998; Rice 2000; Schratzberger et al. 2002 to name a few). These impacts may vary with the type of gear utilized (Collie et al. 2000; Johnson 2002) as well as with the benthic structure (Ball et al. 2000; Bergman and Santbrink 2000; Bradshaw et al. 2000; Hall-Spencer and Moore 2000; Johnson 2002).

Habitat impact also create concerns for the viability of non-target species, the primary focus of this paper (Kaiser and de Groot 2000; Pope et al. 2000). One type of non-target species is habitat areas of particular concern (HAPC), which may require enhanced protection. HAPCs are “those areas within EFH that are of particular ecological importance to the long-term sustainability of a managed species, are of a rare type, or are especially susceptible to degradation or development.” The North Pacific Fisheries Management Council (NPFMC), responsible for managing Alaskan fisheries, has identified three habitat types as HAPC: areas with living substrates in shallow waters (e.g., eelgrass, kelp, etc.); areas with living substrate in deep waters (e.g., sponges, corals etc.); freshwater areas used by andronomous fish (NPFMC-EIS 2004). Therefore HAPC may be characterized as sessile organisms with low rates of reproduction and diffusion which are highly susceptible to habitat damage. The difficulty in managing HAPC is that the component species are not commercially targeted and directly managed with catch limits. For instance, species which constitute HAPC such (corals, sponges, kelp, rockweed, and mussels) have been labeled "prohibited" species by the NPFMC in order to prevent the establishment of an active market for them (NPFMC-EIS 2004). Therefore management instruments intended to mitigate the impacts of commercial fishing may not fully internalize the damage done to HAPC.

Proposed actions to mitigate the impacts of commercial fishing consist mainly of gear restrictions, temporary area closures, gear/area restrictions, permanent area closures (Marine Protected Areas (MPAs) (Horwood 2000; Lindeboom 2000)) and rotational closures (Rotating MPAs). However, the impacts of these policies may parallel or diverge from the observed commercial benefits, depending on the dynamic response taken by fishermen and the ecological community interactions present. In particular, there are concerns that EFH protection based on area closures may shift to and intensify effort in other areas threatening species that exist primarily or solely in those areas. This may have an adverse impact on HAPC and other non-target species. As an alternative approach, we propose a rights-based habitat management regime, using individual quotas for habitat impacts, to provide habitat protection and to protect non-target species which are habitat dependent.

The development of an individual habitat quota (IHQ) management regime is premised on expanding individual transferable quotas (ITQs), currently in use within a number of fisheries, to the management of habitat. ITQs have proven effective at increasing the profitability and sustainability of fisheries (OECD 1997). The success of an ITQ program hinges on the economic incentives it generates and its property rights structure. A fully transferable, exclusive, and well defined ITQ program will force fishermen to internalize the externalities present in an open-access fishery. However, not all the externalities of their behavior will be captured in the ITQ program, i.e. habitat damage, unless property rights are extended to incorporate these components. Extending rights based fishery management to include habitat damage can be achieved either through the bundling, or division of resource rights (Edwards 2003). Vernon Smith, was one of the first economists to realize that the separation of these rights may be the most appropriate method. He recommended that a two-tiered water allocation right be applied to water resources within the arid Southwest. One property right would exist for the renewable flow of water provided via aquifer recharge and the second right would apply to the non-renewable component of the aquifer resource. This separated the resource into its two most important components: a non-renewable and a renewable flow (Smith 1977). The development of a nested IHQ and ITQ market would behave in a similar fashion. However, the two components would both be renewable with different rates of regeneration.

Under our proposed individual habitat quota (IHQ) regime individual quotas of habitat impact units (HIU) based on a proxy for marginal habitat damage would be distributed to fishers with an aggregate quota set to maintain a target habitat "stock" within the fishery. An integrated IHQ and ITQ management regime would provide a more complete and efficient property rights structure but may still not completely internalize the externalities imposed by commercial fishing. Although the IHQ system would provide incentives to reduce habitat impacts, the impacts on non-target species would not be fully incorporated into the economic incentive structure. Theoretically the ITQ system could be expanded to encompass all the components of the ecosystem managed, both target and non-target species (Arnason 2000) and could be synthesized with a minimum information ITQ regime (Arnason 1991). However, this management regime may be operationally difficult to implement (Holland 2004) and potentially infeasible given the lack of accurate biological information. Therefore, understanding the degree to which a nested IHQ and ITQ system, based on a simple and easily monitored proxy for habitat impacts, will mitigate these externalities when non-target species are captured and/or harmed via habitat damage is of increasing importance.

To investigate how the IHQ system might perform, we develop a dynamic spatially explicit fishery and habitat simulation consisting of three primary components: a target species, a habitat stock and a non-target habitat dependent species. The survival rate of the habitat dependent species depends on the habitat quality in the surrounding area and varies depending on the habitat threshold specified. This corresponds with the documented belief that habitat degradation may yield species extinction (Powles et al. 2000). Given that we currently do not have accurate information with regard to the biological characteristics of the non-target species and that they may possess varying degrees of growth and spatial growth and recruitment we model a number of non-target species by pairing alternative growth rates with varying degrees of spatial growth and recruitment.

The performance of the IHQ model is compared to two alternative management regimes, fixed and rotating MPA policies. Policies are compared to each other based on their ability to mitigate their impact on non-target species and their cost-effectiveness under various degrees of uncertainty, diffusion, and ecological structure of the non-target species. We find that an IHQ system, with a conservatively specified habitat target "stock" level is not only the most cost-effective management instrument it is also successful at mitigating the effects of commercial fishing on non-target species relative to the alternative management regimes.

## Methodology

An IHQ management regime requires definition and monitoring of the habitat impacts that will be allocated and traded. Because it is unlikely to be feasible or cost-effective to directly monitor habitat impacts, we propose that a proxy for habitat impacts, denominated in habitat impact units (HIU), be utilized. HIU would represent the marginal damage that the ecosystem incurs from a single fishing event and would vary depending on the ecological characteristics of the region fished as well as the amount of fishing that has recently occurred within the region. For instance, suppose that empirical research has shown that a heavily fished area takes 10 years to regenerate to a "pristine" level and that each fishing event reduces the quality by 80%. In addition, assume that HIU are denominated in square meters of the benthic structure. A vessel towing a trawl over 10,000 square meters of "pristine" habitat would incur 8,000 HIU and leave the habitat proxy at 2,000 HIU. The next vessel to follow would incur a HIU of 1,600 HIU and leave 400 HIU. Assuming that the second vessel was last to fish in the area and an annual recovery rate of 10% of the “pristine” level, the habitat would recover to 1,400 HIU by the following year.

The number of HIU allocated each year would be determined by the managing body according to a habitat “target” which characterizes the minimum desired level of habitat quality within the fishery. All HIUs that exceed this threshold, due to the dynamic recovery rate of the habitat, would be allocated to vessels within the fleet. The HIUs would operate in the same manner as a traditional ITQ system. They would be transferable and quota holders would possess an ongoing right to a proportional share of the total quantity of HIU allocated each year. Alternatively HIU might be allocated in proportion to ITQ. A given total stock of HIU might be made up of a combination of totally and partially regenerated areas and once an area achieves a “pristine” level the marginal addition to the HIU stock is capped.

Monitoring of HIU use and enforcement could be achieved with a vessel monitoring system (VMS) that would continually monitor the vessels’ location and rate of movement. This would create a real-time management regime in which a vessel would incur HIU at any time they fished in a given area. Determining when they were fishing could be conducted by monitoring the speed of the vessel or linking the VMS to a gear deployment mechanism that would indicate when they were actively fishing. To be effective this system would need to be linked to a continually updated database that could be accessed by fishermen in real-time to determine the state of the habitat in a particular area and the HIU use that would be incurred by fishing there. This would not be the true physical state of the habitat but a proxy for the habitat quality within the region. Given the sophistication of the standard electronic mapping equipment on board many vessels, compliance with even a high resolution IHQ system should be feasible.

***Simulation Model***

To investigate the performance of an IHQ regime we use a spatially explicit fishery simulation model with fish stock, habitat, fishing effort and the non-target species modeled on a (25 x 40) two dimensional grid of 1000 cells. Following Sanchirico (2004), each grid is honeycomb shaped with diffusion of the target and non-target population occurring over each of the grid’s six edges (Figure 1). To ensure that each cell has the same level of connectivity, we connect the edges of the grid (i.e., fish can move from the right edge to the left edge and from the top to the bottom and visa versa). This form of connectivity eliminates the possibility of edge effects, fish and habitat aggregating at the edge of the simulation grid. Although this reduces the parallelism with real world fisheries it does provide a template for comparing the four management regimes simulated without biasing the results towards any one policy. While edge effects are not likely to be important for the IHQ model, the results from the MPA models would likely be affected by the location of the MPAs vis-à-vis the grid edges. Within the simulation model the target and non-target species move from one cell to another depending on their corresponding rates of diffusion while fishermen choose a single cell to fish in each fishing event based on expected profitability.

There are four primary components to the simulation model: target and non-target species dynamics, habitat dynamics and fleet dynamics. All four behave according to the same rules under the four alternative management regimes simulated with the exception that fleet dynamics are influenced by the use of HIU in the IHQ model and by constraints on where they can fish in the MPA models. We model four alternatives management: a fixed MPA, a rotating MPA and two IHQ policies; one utilizes a habitat target of 30% (IHQ_30) and the other a 50% habitat target (IHQ_50). Performance is measured according to a least cost criterion as well as the policies' capacity to protect a non-target species under four separate characterizations of a non-target species and varying degrees on habitat dependence. Although our model would allow us to explore various forms of spatial heterogeneity in the fishery, we assume a homogeneous fleet cost and productivity across all cells to simplify the analysis and avoid confounding effects.

***Target and Non-Target Species Dynamics***

The population of the target and non-target species are similarly modeled as a single cohort and therefore we need only track the weight of each species within each cell of the simulated grid. Each year is divided into 50 periods ($T=50$). The total catch from cell $i$ in year $y$ and period $t$ is determined by the removals by the vessels, $v$, that choose to fish in location $i$. The $V$ vessels in the fleet are deployed consecutively within period $t$, and the population of target and non-target species is adjusted after each vessel is deployed (Figure 2). The net change in the target species, $x^{Tar}$, and non-target species, $x^{Non}$, accounts first for the commercial harvest, then for growth and recruitment and lastly for net population diffusion. The capture of the target and non-target species from each cell *i* in period *t* is determined according to

$$x^{M}_{i,y,t,V} = x^{M}_{i,y,t,0} \prod_{v=1}^{V} (1 - q_M e_{i,y,t,v}) \tag{1}$$

where the weight of fish, *x*, is indexed by cell *i*, year *y*, period *t,* and vessel deployment *v*, the superscript *M* indicates target (*Tar*) or non-target (*Non*) species and $x^{M}_{i,y,t,0}$ represents the respective target and non-target populations before any fishing takes place. The catchability coefficients for the target and non-target species, $q_{Tar}$ and $q_{Non}$ respectively, determines the percentage of the cells fish population removed by one fishing event and $e_{i,y,t,v}$ takes a value of 1 if vessel *v* fishes in cell *i* in year *y* and period *t* and value of 0 otherwise. Note that if one vessel chooses to fish in a given location, the population of the target and non-target species is reduced before the next vessel is deployed. Therefore, the subsequent capture of both species by a vessel which follows another vessel within the same time period *t* is lower than the preceding vessel. A description of how the location choice of each vessel is modeled is discussed under the subheading, "Fleet Dynamics."

Total annual growth for the target and non-target population, $G^{Tar}$ and $G^{Non}$ respectively, is assumed to follow a logistical growth function at the end of the final time step of the year *T*,

$$G^{M}_{y+1} = \delta_M \sum_{i=1}^{N} x^{M}_{i,y,T,V} \left[ 1 - \frac{\sum_{i=1}^{N} x^{M}_{i,y,T,V}}{K^M} \right] \tag{2}$$

where $x^M{}_{i,y,T,V}$ is biomass of the target or non-target species respectively in cell $i$, in the final time period $T$, at the end of year $y$, and $\delta_M$ and $K^M$ are their respective intrinsic growth rates and carrying capacities.

The spatial distribution of the adult population growth will invariably be correlated with the spatial distribution of the adult stock. However, the spatial distribution of recruitment may be completely random. The ratio between the amount of total growth associated with growth of the adult stock and that via randomly distributed recruitment is an important characteristic of the non-target species modeled. A locally recruiting species is modeled by distributing all growth proportionately to the adult population. A broadcast spawning species is simulated by allowing a share of total growth to be distributed randomly over the entire model grid. For a local recruiter, spillover benefits will only be realized via emigration of adults from one region to another. For a broadcast spawner, spillover also occurs through recruitment, effectively increasing leakage areas where the population is concentrated.

In the simulation model, the total annual growth is divided into two components, growth from recruitment and growth of the existing population. Parameters $\alpha_M$ *(M=Tar, Non)* determine the share of the total growth $G^M$ for the target and non-target species respectively, that occurs through the growth of its constituent population. Growth resulting from the existing population of the adult target and non-target population is distributed evenly throughout the year and amongst the cells in direct proportion to their share of the overall population. This is represented by the second piece in equation 3. Growth from the recruitment of the target and non-target population is distributed randomly, both over space and through the year and is captured by the third piece in equation 3. Total aggregate growth is determined as follows

$$x^M_{i,y,t+1,0} = x^M_{i,y,t,V} + \alpha_M \left[ \left( \frac{G^M_y}{T} \right) \frac{x^M_{i,y,t,V}}{\sum_{i=1}^{N} x^M_{i,y,t,V}} \right] + (1-\alpha_M) \frac{G^M_y z^M_{i,y,t}}{\sum_{i=1}^{N} \sum_{t=1}^{T} z^M_{i,y,t}} \tag{3}$$

where, $T$ is the number of time steps modeled in each year (50), $N$ is the number of locations within the simulation grid (1000) and $z_{i,y,t}$ is a randomly distributed number between 0 and 1 assigned to each cell, year and period and captures the random settlement of recruits. In order to ensure that the random distributions of the target and non-target populations were uncorrelated separate "seeds" were used within the random number generator. The last common modeling feature of the target and non-target species is the net diffusion. Net diffusion for each group is modeled as

$$x^{M}_{i,y,t+1,0} = x^{M}_{i,y,t,V} + d_{M}\left(\sum_{k=1}^{6} x^{M}_{k,y,t,V} - 6x^{M}_{i,y,t,V}\right) \qquad (4)$$

where, $d_M$ represents the diffusion rates for the target and non-target species respectively and $x^{M}_{k,y,t,V}$ are the target and non-target population levels in the six surrounding cells.

The spatial distributions for the target and non-target species were initialized differently. The target species was randomly distributed throughout the 1000 grid cells within the simulation model and then "smoothed" by repeating the diffusion process expressed in equation 4 until the spatial distribution possessed only a small degree of variability. The non-target spatial distribution was created by randomly assigning the entire non-target population (totaling 50% of the carrying capacity) to 5 cells and then repeating the same "smoothing" process but curtailing it to allow 5 distinct peaks in the spatial distribution to persist (Figure 3). Our rationale for distributing the non-target species in this manner was to create a spatial distribution that was random but clumpy. This distribution would presumably correspond with an ecologically sensitive non-target species with a limited and spatially defined niche in the ecosystem.

The spatial dynamics of the non-target species possesses one additional complexity, the degree of habitat dependence of the species. Utilizing a habitat threshold variable, $\xi$, the survivability of a non-target species is determined by

$$x^{Non}_{i,y,t,v} = \begin{Bmatrix} x^{Non}_{i,y,t,v} \cdots if \cdots H^{Non}_{i,y,t,v} \geq \xi \\ 0 \cdots if \cdots H^{Non}_{i,y,t,v} < \xi \end{Bmatrix} \text{ where, } H^{Non}_{i,y,t,v} = h_{i,y,t,v} + \sum_{j=1}^{6} h_{j,y,t,v} \tag{5}$$

where $h_{i,y,t,V}$ represents the habitat level in location $i$, time period $t$, year $y$ and following vessel deployment $v$. The survivability of the habitat dependent non-target species depends on the habitat quality within cell $i$ and the six surrounding cells. Within the simulations $\xi$ is varied between 5% and 15% of the "pristine" habitat level.

***Simulation Habitat Dynamics***

The habitat stock $h$ in each cell is modeled simply. We assume that each cell has a homogeneous maximum habitat stock level of $h_{MAX}$ and that habitat regenerates at a fixed rate of recovery, $r$, per a year which is capped at the maximum habitat stock level. As was the case with the target and non-target populations, the habitat stock is consecutively depleted by each vessel that chooses to fish within the location

$$h_{i,y,t+1,0} = h_{i,y,t,0} + \min[(h_{MAX} - h_{i,y,t,V}), r] - \sum_{v=1}^{V} \gamma e_{i,y,t,v} h_{i,y,t,v} \tag{6}$$

where $\gamma$ is the marginal rate of habitat damage, $h_{i,y,t,0}$ is the habitat quality in cell $i$ in year $y$, time period $t$ prior to any fishing activity, whereas $h_{i,y,t,v}$ is corresponding habitat quality following fishing event $v$ and $e_{i,y,t,v}$ is as defined earlier. Within each year of the IHQ model a total quota for habitat is set equal to the projected habitat level at the end of the year in the absence of fishing less the target level for the habitat stock. This maintains the habitat stock at the "target" level, yet allows for its spatial distribution to be endogenously determined by the fleet. The habitat, which is distributed evenly among the fleet is calculated as

$$THQ_y = -H^{Target} + \sum_{i=1}^{N} \left\{ h_{i,y-1,T,V} + \min\left[ \left( h_{MAX} - h_{i,y-1,T,V} \right), r \right] \right\} \tag{7}$$

***Simulation Fleet Dynamics***

Vessels are motivated solely by profit and their location choice decisions do not depend on the effect they have on the non-target species. The only species they are commercially interested in is the target species. Each year a total allowable catch (TAC) for the target species is set equal to the growth of the target population, $G^{Tar}$, plus any residual unfished quota from the previous year. This assures that the fleet captures between 99.5% and 100% of the target species TAC each year. Fish quota is divided evenly among fleet. Therefore, each vessel possesses the same amount of target fish quota and habitat quota at the beginning of each year. The spatial distribution of effort within the fishery is determined by a looping process. Initially the price of habitat is set equal to zero and the vessels are consecutively distributed to the areas within the fishery that possess the highest profit, the difference between HIU costs and relative expected revenues rates. The profits observed by each vessel are calculated as

$$\pi_{i,y,t,v} = p^f q_{Tar} X^{Tar}_{i,y,t,v} \exp(\sigma \varepsilon_{i,y,t,v}) - p^h \gamma h_{i,y,t,v} \tag{8}$$

where $p^f$ and $p^h$ are the price of fish and habitat respectively, $\sigma$ is an uncertainty multiplier and $\varepsilon_{i,y,t,v}$ is a normally distributed random number with mean zero and a standard deviation of one times the uncertainty multiplier $\sigma$. The larger uncertainty multiplier, the greater is the uncertainty each vessel faces with respect to the expected catch and revenues realized within a given location thereby increasing the probability that vessel's spatial choice deviates from the true optimum. However, this multiplier only affects a vessel's expectations, the actual catch realized is deterministic.

If the target TAC is not completely used up because the THQ is exhausted first the HIU price is increased and the year is simulated again. This looping process continues until a price for HIU is found which allows the fleet to catch the entire TAC without exhausting the total quota for habitat. Although our primary interest is the impact that the IHQ has on the viability of the non-target species it is still integrally important that we determine the optimal HIU price because different prices yield different spatial distributions of effort. Alternative spatial distributions result in different impacts on the habitat and non-target species than that which corresponds with the optimal HIU value. The MPA simulations allows the fleet size to change so that the fleet size is adequately large, but the minimum size necessary to take the TAC. The minimum fleet size is determined through a looping process similar to that used to determine the price of HIU for the IHQ policy scenarios.

***Simulation Policy Evaluation***

All simulations begin with the same initial distribution and size of fish population and habitat resulting from running the model for 20 years with a TAC equal to that used for subsequent years, but no habitat regulations. The habitat management policy is then implemented and the simulation continues for an additional 50 years. After year 20 if the habitat quality is incapable of reaching the habitat target specified by the policy (either 30% or 50%) following its incremental growth, the IHQ model sets the initial target for the total habitat stock equal to the current habitat stock plus an increment of 10% of the virgin level. The habitat target is then increased in this way each year until it reaches the final habitat target (either 30% or 50%) where it remains for the rest of the simulation. For the fixed MPA model, after the 20 year initialization, a vertical (25 x 40) strip of cells encompassing 20% of the fishery is then closed to fishing and remains closed for the duration of the simulation. Five separate fixed MPAs were simulated corresponding to the five MPAs used in rotating MPA model (Figure 4). In order to ensure that we are not biasing the results away from the fixed MPA model, we have chosen to present results only for MPA 5 which provides the best non-target species protection. This would be expected given the initial spatial distribution of the non-target species (see Figure 3). The rotating MPA model functions similarly but rotates the closed area every 10 years of the simulation. The rotating closures are ordered such that each new closure is non-adjacent to the last (see Figure 4).

To test the sensitivity of our simulations we vary three key parameters: the non-target species habitat threshold $\xi$, the rate of diffusion of the target species and the degree of uncertainty about relative catch rates faced by fishers. Other target species parameters are fixed (see Table 1) for all simulations. For the four non-target species biological parameters were fixed for a given species but diffusion and the ratio of adult growth to recruitment are different across the species (see Table 2). The sessile species both have very low diffusion rates, but SESS 1 recruits locally while for SESS 2 two-thirds of the net growth is assumed to be from recruitment that is distributed randomly over the model grid. DEM1 and DEM2 represent two alternative classifications of non-target demersal species. DEM 1 possesses a low rate of diffusion and DEM 2 possesses a diffusion rate 3 times that of DEM 1 and both are assumed to be broadcast spawners with 50% of total growth associated with recruitment. Otherwise the species within the two sub-classifications remain identical. The parameters were selected not to mimic a specific non-target species but to represent species which possess asymmetric biological characteristics to develop a broad class of species representations.

## Results

The cost effectiveness of the four policies can be evaluated by comparing the catch-per-unit effort (CPUE) obtained under each of the four policies. Since total catch and its value is constant under all policies and harvest costs are solely a function of nominal effort, a higher CPUE directly translates to a proportionally lower harvest cost and proportionately higher profitability. Because CPUE varies with the diffusion rate and uncertainty with no habitat protection in place, we present the average CPUE for the four policies simulated ($21 \leq y \leq 70$) as a percentage of the average CPUE obtained within the simulation prior to the policy implementation ($20 \leq y$).

CPUE is only marginally reduced by implementation of the IHQ regime and this result is robust both to the rates of diffusion and uncertainty (Figure 5). In the IHQ model with a 30% habitat target, CPUE was maintained at more than 99% of the pre-IHQ level regardless of the rate of diffusion or uncertainty. With a 50% habitat target, CPUE was maintained at more than 97% of the pre-IHQ level. The greatest reduction was with the highest level of uncertainty.

CPUE results for the MPA regimes (fixed and rotating MPAs) are always below that of either IHQ regime, but the rotating MPA policy maintains higher CPUE than the fixed MPA (Figure 5). CPUE with the rotating MPA is maintained at 93% to 96% of pre-MPA levels while it ranges from 46% to 90% for the fixed MPA. Higher diffusion tends to result in a somewhat larger decrease in CPUE for the rotating MPA policy, while higher uncertainty has the opposite effect, but neither result in large differences in CPUE. Diffusion has a much more pronounced impact on CPUE for the fixed MPA models (Figure 5a ). The percentage of pre-policy CPUE with no uncertainty rises from 46% to 90% as the diffusion rate rises from 0.01 to 0.03 (Figure 5a). At the lowest rates of diffusion the fleet size required to capture the TAC with a fixed MPA doubles within the first 20 years, both reducing the CPUE and greatly increasing the total nominal effort required to take the TAC. This results because the target species concentrates within the MPA and little spills over into the fishing grounds. Uncertainty has a relatively small impact on CPUE with the fixed MPA, causing it to fall from 46% to 45% of the pre-MPA level as the rate of uncertainty increases from 0.0 to 0.25 while maintaining the diffusion rate at 0.01 (Figure 5b).

Although the quota price may be irrelevant from a public cost-benefit perspective, because it represents only a wealth transfer rather than an increase in real cost, it may be of great importance to an individual who has to purchase HIU or has the opportunity to lease or sell their allocation. With no uncertainty, the price of HIU is very low, but it rises steeply with increasing uncertainty resulting in a 19-32 fold increase in the habitat quota price depending on the diffusion rate (Figure 6). Diffusion rates also influences the price of the habitat quota, with high diffusion rates causing the price of habitat quota to fall (Figure 6). Uncertainty has the largest impact on the price of habitat quota. Increasing the habitat target also results in substantially higher habitat quota price, $p^h$. Holding the level of target species diffusion at 0.01 the habitat quota price increases between 200% and 300%, depending on the uncertainty level present, as the habitat target is increased from 30% to 50%.

Our primary focus is on the ability of different habitat protection policies to preserve non-target populations, and we provide a detailed discussion of those results below. However, it is notable that the different policies also lead to significantly different levels of average habitat quality. The IHQ regime sets and maintains an absolute target for average habitat quality though it does not dictate the spatial distribution of habitat impacts and quality. In contrast, the average habitat quality with the fixed and rotating MPA regimes varies with the diffusion rate of the target species and uncertainty. Average habitat quality with fixed MPAs varies between 20% and 40% of the maximum depending on the level of diffusion and uncertainty. With the lowest diffusion rate, average habitat quality for the entire grid is maintained at a minimum of 20% by the MPA, but habitat quality outside the MPA approaches zero. This is because to the increased level of effort required to take the TAC when diffusion is low. The rotating MPA results in an average habitat quality ranging from 25% to 33% of the maximum. As with fixed MPAs, higher diffusion rates lead to higher average habitat quality. However, average habitat quality fluctuates, falling substantially in the 2-3 years after rotation and then rebuilding until the next rotation.

***Non-Target Species Impacts***

Although the non-target species populations are initialized at 50% of their capacity, they are already substantially reduced by year 20 when the habitat policy is introduced. Since the catchability coefficient on the non-target species is quite low, this is primarily a result of habitat loss rather than fishing mortality. The higher the habitat threshold, $\xi$, the more the non-target species populations are reduced before any of the four policies are implemented (Figure 7). Population levels prior to habitat protection are also affected, though less dramatically, by the diffusion rate of the target species and uncertainty in its distribution. In some cases, when the non-target species has a 15% habitat threshold, it has been pushed close to extinction even before the policy is implemented. Although this is true for a number of the parameterizations, there still exist substantial differences in the pre-policy and post-policy populations across species (see Table 3). The greatest reduction in non-target species population prior to habitat protection occurs with the DEM 2 population and the least with the SESS 1 population. This is driven by the diffusion rate of the target species and the degree of local recruitment. DEM 2 has the highest diffusion rate of all the non-target species populations increasing the probability of moving from areas of sufficient habitat quality to areas of poor habitat quality where they can not survive. The SESS 1 population has a very low diffusion rate and local recruitment so movement or recruitment to areas of low habitat quality is reduced.

These pre-policy impacts illustrate that for extremely sensitive non-target species it is paramount that habitat protection be implemented early to avoid substantial reductions in their population levels from which they may fail to recover regardless of the means of habitat protection. For most of the non-target species, with the habitat threshold set at 15%, the mean population over the duration of the policy ($21 \leq y \leq 70$) fell relative to the mean at the beginning of the policy's implementation and in no case did it substantially recover (Table 3). The only cases where the population did not show further decline are the fixed MPA for SESS 1 and the IHQ_50 model for SESS 1, SESS 2 and DEM 1. The IHQ_50 model yields a larger increase in SESS 1 than the fixed MPA for all but the lowest target species diffusion rate. With lower habitat thresholds, the non-target species are maintained at more healthy levels. As we discuss in more detail, the results vary significantly by non-target species and policy. Target species characteristics also impact non-target populations, particularly the diffusion rate of the target species.

***Sessile Organisms***

Results for the two sessile organisms simulated, SESS 1 and SESS 2 respectively, are illustrated as the habitat threshold, $\xi$, of the non-target species increases from 5% to 15% of the pristine habitat level (Figure 8 and 9). Results are expressed in terms of the mean population over the duration of the policy simulated ($21 \leq y \leq 70$) as a fraction the non-target species' carrying capacity. The top row of each figure illustrates the role that the target species diffusion has on the population of the sessile organism assuming the median uncertainty level ($\sigma = 0.125$). The bottom row illustrates the role of uncertainty assuming the median target species diffusion rate ($d_{Tar} = 0.02$). As we noted above the population of the sessile organisms is most influenced by the habitat threshold. Increasing the habitat threshold from 5% to 15% yields a reduction in the non-target species population from nearly 60% of the carrying capacity to below 0.01% of the carrying capacity for some combinations of habitat protection policy and fishery characteristics (Table 3). This would be expected because only a small amount of effort is required to reduce to habitat level below the 15% threshold given that the habitat catchability coefficient is 80% ( $\gamma = 0.80$).

The target species diffusion rate has different impacts on the results for the fixed and rotating MPA models as compared to the IHQ management regimes. For the fixed and rotating MPA models increased diffusion increases the mean population level of the SESS 1 and SESS 2 organisms. The percentage increase in the non-target species populations as the diffusion rate increases from 0.1 to 0.3 is most pronounced when the habitat threshold is 15% (Table 3). For SESS 1 the population increases 655.83% and 1640.00% for the fixed and rotating MPA models respectively. However, despite the large percentage increase, with a rotating MPA the sessile species populations still remains below 1% of the carrying capacity. At the lowest habitat threshold (5%) the percentage increases are substantially smaller (27.25% and 5.07% respectively) although the absolute increases in the population size are larger. For SESS 2 the corresponding increases are 1116.13% for the fixed and 502.44% for the rotating MPA, assuming a 15% habitat threshold and 44.76% and 5.14% respectively, assuming a 5% habitat threshold. However, it is important to note that the absolute population levels are substantially smaller under the higher habitat threshold. These reductions often exceed 87% of the population maintained at the 5% threshold.

Diffusion has the opposite effect with the IHQ regimes, when the habitat threshold is low to moderate. For both the IHQ_30 and IHQ_50 model increased diffusion decreases the mean population of SESS 1 and SESS 2. However, these reductions never exceed 0.5% of the mean population indicating that the performance of both regimes is only marginally influenced by the diffusion rate of target species. When the habitat threshold equals or exceeds 10%, increased diffusion actually increases the mean population of the non-target species for SESS 1 and SESS 2 under the IHQ regimes.

Uncertainty in the distribution of the target species has a unilaterally negative effect on SESS 1 for all of the policies simulated and habitat thresholds less than 15%. Fixing diffusion at 0.02 and varying uncertainty from 0 to 0.25 results in a 2.33% to 24.48% reduction in the SESS 1 population for the fixed MPA model, a 2.04% to 46.98% reduction for the rotating MPA, a 0.78% to 32.76% for the IHQ_30 model and 0.69% to 21.48% reduction for the IHQ_50 model as the habitat threshold increases from 5% to 12.5%. The largest of these reductions occur at the 12.5% habitat threshold. When the habitat threshold is 15% increased uncertainty results in an increase in the SESS 1 population for fixed and rotating MPAs and for the IHQ_50 policy. These increases are 54.95%, 5.88% and 7.06% for the fixed and rotating MPAs and the IHQ_50 model respectively. Uncertainty has a similar role on the SESS 2 population, yet the relative reductions in population are slightly greater than those indicated for the SESS 1 species. Under the IHQ_30 policy increasing uncertainty results in a unilateral decrease in the population, but for the IHQ_50 policy it results in small increases in the population for the median range of habitat thresholds (10% and 12.5%).

While there are some parameter combinations under which the fixed MPA policy leads to equal or higher sessile population levels, the IHQ_50 model generally provides the greatest protection for both sessile species. It is only at low habitat thresholds with moderate to high levels of diffusion and uncertainty that the fixed MPA model provides more protection than the IHQ_50 policy and both policies maintain the sessile populations around 60% in those cases. The relative performance of the fixed MPA and the IHQ_50 policy is generally reversed when the habitat threshold increases to 10% or higher. When the habitat threshold ranges from 12.5% to 15% the populations of SESS 1 and SESS 2 with the fixed MPA are between 15% and 58% of the population maintained under the IHQ_50 regime, with one exception. With the highest habitat threshold combined with low diffusion and moderate uncertainty the SESS 1 population with a fixed MPA is 103.5% of the IHQ_50 level.

The rotating MPA provides less protection to the sessile species than either fixed MPAs or IHQs in nearly every case. It is only at low habitat thresholds that this policy performs moderately well, but as the habitat threshold increases the mean population of the sessile organisms dramatically decreases in absolute terms and relative to other policies. When both the diffusion rate and the habitat threshold are low, the rotating MPA does outperform the fixed MPA, but not the IHQ policies. Comparing the IHQ_50 regime to the alternative habitat quota regime, IHQ_30, indicates that for habitat thresholds from 5% to 10% the IHQ_30 model maintains a population of the non-target sessile species between 94.30% and 99.33% of the population under the IHQ_50 regime. However, for higher habitat thresholds the IHQ_50 policy results in significantly higher sessile species populations.

*Demersal Organisms*

The habitat threshold has a similar effect on DEM 1 and DEM 2 as it did on SESS 1 and SESS 2. Increasing the habitat threshold dramatically reduces the population size regardless of the form of habitat protection. For all of parameterizations of the DEM 1 and DEM 2 simulations, assuming a 15% habitat threshold, only two models yielded a mean population level greater than 0.5% of the carrying capacity and both instances occurred in the IHQ_50 for DEM 1 (Table 3).

The effects of diffusion on the ability of each management regime to protect the demersal species is similar to the effects on the sessile species. For the fixed and rotating MPA models the mean population of DEM 1 and DEM 2 increases with diffusion. Within the IHQ_30 and IHQ_50 models diffusion decreases the mean population level at low habitat threshold, $\xi \leq 10\%$, and increases the mean population at higher habitat thresholds, $\xi > 10\%$. In addition, the relative increase in the mean population for both demersal species increases as the habitat threshold increases. For instance at the 12.5% habitat threshold, the population of DEM 1 increases 328.23%, 493.75%, 187.14% and 124.15% for the fixed MPA, rotating MPA, IHQ_30 and IHQ_50 models respectively as the level of diffusion increases from 0.01 to 0.03. Although these appear to be substantially large gains it is important to note that the mean populations are small, never exceeding 26.19% of carrying capacity. For the IHQ models, when the habitat threshold is 5% the mean population levels decrease between 1.25% and 1.66% for the IHQ_30 and IHQ_50 models. However, this marginal reduction is less important given that the population levels are always above 50% of the carrying capacity.

Uncertainty of the target species has a similar impact on both DEM 1 and DEM 2 causing the mean population of the non-target species to decrease. The negative effect of uncertainty is more pronounced in the fixed and rotating MPA models than the IHQ models. For instance, an increase in uncertainty from 0 to 0.25, assuming a habitat threshold of 10% yields a reduction in mean population of 66.70%, 64.67%, 13.90% and 8.85% for the fixed, rotating, IHQ_30 and IHQ_50 models respectively for DEM 1. For DEM 2 the corresponding reductions are 82.14%, 77.81%, 19.33% and 11.87% for the four respective policy simulations. Comparing IHQ_30 to IHQ_50 it is easy to see that the IHQ_50 is better able to absorb the adverse impact of uncertainty. For both DEM 1 and DEM 2 the IHQ_50 yielded a smaller reduction in the mean population as uncertainty increased and it maintained a substantially larger population of the non-target species.

Contrasting DEM 1 and DEM 2 it is evident that the higher diffusion rate of DEM 2 makes it more difficult for all of the four policies to protect the species. For nearly all of the parameterizations the mean population of DEM 1 exceeds that of DEM 2. Comparing the four policies to each other it is evident that both of the IHQ models protect the non-target species better than either the fixed or rotating MPA models. In addition, when the habitat threshold is low to moderate, $\xi \leq 10\%$, the IHQ_30 yields a mean population level that is usually within 5% of the population level maintained under the IHQ_50 regime for both DEM 1 and DEM 2. However, as the habitat threshold increases the mean population level under the IHQ_50 is nearly double that under the IHQ_30 regime. The comparisons between the fixed and rotating MPA models made for SESS 1 and SESS 2 are reversed for DEM 1 and DEM 2. The rotating MPA model either outperforms or tracks the mean population of the fixed MPA model, which is substantially different than its performance within the SESS 1 and SESS 2 simulations.

## Discussion

The policy simulations conducted illustrate a number of general findings regarding the relative performance of the four policies simulated and the sensitivity of their performance to both the biological characteristics of the target species as well as those of the non-target species. We discuss seven general findings that may be drawn from the policy simulations.

*General Finding One: An Individual Habitat Quota (IHQ) management regime is more cost-effective than either a fixed or rotating MPA policy at maintaining a given level of habitat quality.*

The CPUE results for the four policies simulated indicate that an IHQ management regime is the most cost-effective alternative. The higher CPUE achieved under the IHQ regimes is robust to the target species diffusion as well as uncertainty (Figure 5(a) and 5(b)) and is not greatly reduced even when the habitat target is increased to 50%. In contrast, the cost-effectiveness of the fixed MPA is very sensitive to the diffusion rate. The primary negative impact of raising the habitat target is the substantial increase in the habitat quota price within the fishery. This may increase the probability of noncompliance and require more spending to ensure compliance.

*General Finding Two: Higher habitat thresholds make it more difficult to protect the non-target species regardless of the species' biological characteristics and interaction with the target species.*

For the entire habitat thresholds simulated the population unilaterally decreases as the habitat threshold increases (Figure 7). This occurs regardless of the target species diffusion rate or the level of uncertainty within the fishery. This result indicates that protecting an extremely sensitive non-target species is difficult, and even closing large areas to fishing may not provide sufficient protection. An MPA is capable of protecting the population that resides within it but may increase and concentrate effort in the fishing grounds which remain open, thereby further exacerbating the habitat problem. Increasing the size of the closed areas may increase the protection to habitat dependent species if it is correctly located, but it may substantially increase harvest costs. Furthermore it is likely to exacerbate the damage in the smaller area left open increasing the risk to any habitat dependent species that are not provide protection by the MPA.

*General Finding Three: The greater the target species diffusion, the greater is the ability of both MPAs and IHQs to protect the non-target species.*

Diffusion has the most pronounced effect on the fixed and rotating MPA models. For the fixed MPA model, a low diffusion rates dramatically decrease the ability of the fixed MPA to protect the non-target species. This results from the rapid increase in the fleet size that is required to capture the TAC as the target species becomes concentrated within the fixed MPA with little spill over into the fishing grounds. This increase in fleet activity dramatically reduces the habitat level outside of the MPA and causes the non-target species to be virtually wiped out within this region. At higher diffusion rates this does not occur because the required fleet size is significantly smaller because more of the target species migrates out of the MPA.

For the rotating MPA a similar phenomenon occurs but it is temporally dynamic. The fleet concentrates all of its effort in recently opened MPAs because the low diffusion target species concentrates within the MPA prior to being opened. This intense effort within the former MPA causes the habitat to substantially deteriorate and wipes out the non-target species. At higher diffusion rates the target species becomes less temporally concentrated within the MPA. This reduces the adverse impact of fishing in a former MPA as effort is slightly more spread out within the fishery.

For the IHQ regimes, diffusion combined with a low habitat threshold yielded a small reduction in the population. However, with higher habitat thresholds, where the risk to non-target populations is much greater, higher a higher diffusion of the target species generally increases the protection that the IHQ system provides just as it does for MPAs.

*General Finding Four: Higher degrees of uncertainty in target species distribution decrease the ability of each policy to protect the non-target species.*

A higher degree of uncertainty causes the amount of pristine habitat within the fishery to be reduced because it causes effort to by more greatly distributed. For the IHQ regime it results in fishing in areas that would otherwise have remained completely unfished. For instance, as uncertainty increases from 0 to 0.25, holding diffusion at 0.01, the percentage of pristine habitat maintained over the last 20 years of the simulation decreases from 13.52% to 9.26% for IHQ_30 model and 43.71% to 40.23% for IHQ_50. For the MPAs, uncertainty reduces the tendency of vessel to concentrate on the periphery of the closed area. This spreading out of the habitat damage increases the probability that the habitat in a region will not meet the habitat threshold specified for the non-target species, thereby increasing the probability that the non-target species will go locally extinct within that region.

*General Finding Five: The relative performance for the fixed and rotating MPA models to each other depends on the biological characteristics of the non-target species.*

The success of the fixed and rotating MPA models depends on its ability to provide a spatial refuge for the non-target species. However, the degree of spatial refuge they provide hinges on the biological characteristics of the non-target species. For the two sessile organisms modeled the fixed MPA performed much better than for the two demersal species. This fundamental difference was driven by the diffusion rate of the sessile organisms as well as the placement of the MPA. The sessile species have a diffusion rate one-tenth that of DEM 1 and one-thirtieth that of DEM 2. The low diffusion rate of the non-target species reduces leakage, increasing the level of protection provided by the fixed MPA. However, if the MPA is not fixed the population is immediately captured as fishermen flood into the opened area to harvest the target species, which has also utilized the MPA as a spatial refuge. This renders the rotating MPA incapable of protecting either the SESS 1 or SESS 2 species.

An increased degree of global recruitment of the non-target species influences the performance of the fixed and rotating MPA models in a similar way to increased diffusion. This is driven by the fact that habitat damage is concentrated outside of the MPA and this decreases the probability that the non-target species' recruits will survive should they settle within this region. A species that is a local recruiter will concentrate their recruitment effort in the region where abundance is the highest within the MPA. However, the protection provided to the recruits settling in the rotating MPA is only temporary. They are concentrated there and then eliminated when the area is reopened.

*General Finding Six: The degree of protection provided for the non-target species with an IHQ policy is less sensitive to the characteristics of the target and non-target species than either MPA policy.*

The level of protection of each of the non-target species provided by a particular habitat protection policy is sensitive both to the non-target species characteristics and to the target species parameters because it is the distribution of the target species that drives the fleet dynamics and the resulting deleterious effects on the habitat and the non-target species. Finding a policy instrument that is robust to many alternative biological characteristics of the target and non-target species will be extremely useful given the current status of our biological knowledge. The percentage changes for all four non-target species with IHQs were much smaller than the percentage changes cited for the fixed and rotating MPA models as various parameters were changed. This robustness indicates that the IHQ regimes provide better protection of the non-target species when there is uncertainty in the target and non-target species biological characteristics.

*General Finding Seven: A conservatively set THQ, IHQ_50, is better suited to the overall protection of a non-target species than the alternative management regimes regardless of the characteristics of the target and non-target species.*

In general, the IHQ_50 policy appears to provide the greatest protection to the non-target species regardless of its characteristics or those of the target species. This is driven by the high average habitat quality mandated by the IHQ policy (50% of the pristine level). From the simulation results it evident that the IHQ_50 management regime provides the most consistent protection for the non-target species simulated. For all of the DEM 1 and DEM 2 simulations it yielded a higher mean population level than the alternative management regimes. For the SESS 1 and SESS 2 the IHQ_50 outperformed the alternatives for all the simulations except for those with a low habitat threshold. However, given that the IHQ_50 model still performs extremely well under these situations and far outperforms the fixed MPA model under the alternate parameterizations it is a superior policy.

Plotting the mean populations of the sessile and demersal organisms for the fixed and rotating MPA models as a percentage of the mean population maintained under the IHQ_50 regime illustrates its strength (Figure 12). In some cases the fixed MPA performs reasonably well relative to the IHQ_50 policy. This is true for SESS 1 for which the fixed MPA model is able to maintain the SESS 1 population at or above 80% of the IHQ_50 regime's mean population. The fixed MPA model performs less well for SESS 2 and poorly for DEM 1 and DEM 2. The DEM 1 and DEM 2 populations are consistently and significantly below the mean population levels maintained under the IHQ_50 regime. For the rotating MPA model the mean populations of the all four species modeled relative to populations with the IHQ_50 policy are consistent, but never exceed the mean population of the IHQ_50 regime. As the habitat threshold increases the relative performance of the rotating MPA worsens.

## Conclusions

These simulation results suggest that a conservatively set IHQ management regime is not only the most cost-effective means of achieving a given average habitat quality, it is also capable of providing sufficient protection for habitat dependent non-target species. Presumably, it is possible to establish alternative habitat dependent non-target specifications and threshold constraints that will increase the desirability of utilizing MPAs. However, for the parameters illustrated the IHQ models performed remarkably well and they illustrate some of the pitfalls of using MPAs to protect non-target species.

We have assumed a homogeneous habitat type within our simulated fishery and we expect that it may be important to ensure some level of protection for all types of habitat present. This could be achieved by mapping the spatial distribution of alternative habitat types and creating a multi-type habitat quota management regime with habitat targets, as well as degradation and regeneration rates, to manage each type. This would be analogous to an ecosystem based individual transferable quota (ITQ) management regime (Arnason 2000). This should improve the performance of the IHQ regime at protection habitat dependent species assuming that their distributions are correlated with the separate habitat types identified and regulated.

An IHQ system may force fishermen to incur a substantial upfront cost to implement the management regime. However given the cost savings achieved relative to the alternative management regimes the IHQ regime may still be preferable. There will invariably be some objections voiced by fishermen since the IHQ system will require high resolution tracking of their activities and will make that information available to other fishers (though it would not identify which vessels have been fishing where). However, achieving the sufficient protection of benthic habitat, as well as its constituent non-target species, is likely to require a compromise between privacy and preserving a fisherman's freedom to choose where and when to fish.

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**Table 1:** Target species parameters

| Parameter | Value |
|---|---|
| Growth Rate $\boldsymbol{\delta_{Tar}}$ | 0.40 |
| Carrying Capacity $\boldsymbol{K^{Tar}}$ | 2,000,000 |
| Adult Growth Share of Total Growth $\boldsymbol{\alpha_{Tar}}$ | 0.50 |
| Fish Catchability Coefficient $\boldsymbol{q_{Tar}}$ | 0.40 |
| Habitat Catchability Coefficient $\boldsymbol{\gamma}$ | 0.80 |
| Maximum Annual Habitat Regeneration Rate Per Cell $\boldsymbol{rT}$ | $0.1*h_{max}$ |
| Price of fish $p^f$ | 1.00 |
| Diffusion Rates $d_{Tar}$ | 0.01-0.03 |
| Uncertainty Multiplier σ | 0.0-0.25 |
| Fleet Size | 10 for IHQ, Variable for MPA |

**Table 2:** Non-target species parameters. Paremeters in bold font indicate those that varied for each type of species.

| **Parameters** | Sessile One (SESS1) | Sessile Two (SESS 2) | Demersal One (DEM 1) | Demersal Two (DEM 2) |
|---|---|---|---|---|
| Growth Rate, $\boldsymbol{\delta_{Non}}$ | 0.03 | 0.03 | 0.03 | 0.03 |
| Carrying Capacity, $\boldsymbol{K^{Non}}$ | 200,000 | 200,000 | 200,000 | 200,000 |
| Adult Share of Growth, $\boldsymbol{\alpha_{Non}}$ | **1.0** | **0.3333** | 0.5 | 0.5 |
| Catch Rate, $\boldsymbol{q_{Non}}$ | 0.05 | 0.05 | 0.05 | 0.05 |
| Diffusion Rate, $\boldsymbol{d_{Non}}$ | 0.001 | 0.001 | **0.01** | **0.03** |
| Init. Pop. | 100,000 | 100,000 | 100,000 | 100,000 |

**Table 3:** Pre-policy and post-policy non-target population comparisons at the 15% habitat threshold, varying target species diffusion and uncertainty within the fishery (Diff., Unc.).

| Population/Policy | (15%) *y=20* | FIX | % Change | Rotat. | % Change | IHQ_30 | % Change | IHQ_50 | % Change |
|---|---|---|---|---|---|---|---|---|---|
| SESS1 | | | | | | | | | |
| (0.01,0.125) | 0.0057 | 0.0120 | 111% | 0.0005 | -91.2% | 0.0048 | -15.8% | 0.0116 | 104% |
| (0.02,0.125) | 0.0433 | 0.0616 | 42.3% | 0.0044 | -89.8% | 0.0363 | -16.2% | 0.0781 | 44.6% |
| (0.03,0.125) | 0.0657 | 0.0907 | 38.1% | 0.0087 | -86.8% | 0.0525 | -20.1% | 0.1202 | 83.0% |
| (0.02,0) | 0.0516 | 0.0546 | 5.8% | 0.0051 | -90.1% | 0.0392 | -24.0% | 0.0836 | 62.0% |
| (0.02,0.25) | 0.0511 | 0.0846 | 65.6% | 0.0054 | -89.4% | 0.0358 | -29.9% | 0.0895 | 75.1% |
| SESS2 | | | | | | | | | |
| (0.01,0.125) | 0.0052 | 0.0031 | -40.4% | 0.0004 | -92.3% | 0.0036 | -30.8% | 0.0094 | 80.8% |
| (0.02,0.125) | 0.0403 | 0.0221 | -45.2% | 0.0041 | -99.6% | 0.0307 | -23.8% | 0.0709 | 75.9% |
| (0.03,0.125) | 0.0626 | 0.0377 | -39.8% | 0.0084 | -86.6% | 0.0489 | -21.9% | 0.1129 | 80.4% |
| (0.02,0) | 0.0498 | 0.0247 | -50.0% | 0.0057 | -88.6% | 0.0373 | -25.1% | 0.0819 | 64.5% |
| (0.02,0.25) | 0.0475 | 0.0292 | -38.6% | 0.0049 | -89.7% | 0.0305 | -35.8% | 0.0793 | 66.9% |
| DEM 1 | | | | | | | | | |
| (0.01,0.125) | 0.0002 | 0.0000 | Ext | 0.0000 | Ext | 0.0000 | Ext | 0.0002 | 0% |
| (0.02,0.125) | 0.0046 | 0.0007 | -84.8% | 0.0003 | -93.5% | 0.0011 | -76.1% | 0.0049 | 6.5% |
| (0.03,0.125) | 0.0095 | 0.0014 | -85.3% | 0.0006 | -93.7% | 0.0026 | -72.6% | 0.0126 | 32.6% |
| (0.02,0) | 0.0078 | 0.0018 | -76.9% | 0.0007 | -91.1% | 0.0025 | -67.9% | 0.0096 | 23.1% |
| (0.02,0.25) | 0.0051 | 0.0007 | -86.3% | 0.0003 | -94.1 | 0.0010 | -80.4% | 0.0048 | -5.9% |
| DEM 2 | | | | | | | | | |
| (0.01,0.125) | 0.0001 | 0.0000 | Ext | 0.0000 | Ext | 0.0000 | Ext | 0.0000 | Ext |
| (0.02,0.125) | 0.0001 | 0.0000 | Ext | 0.0000 | Ext | 0.0000 | Ext | 0.0001 | 0% |
| (0.03,0.125) | 0.0004 | 0.0000 | Ext | 0.0000 | Ext | 0.0000 | Ext | 0.0003 | -25% |
| (0.02,0) | 0.0065 | 0.0000 | Ext | 0.0000 | Ext | 0.0001 | Ext | 0.0005 | -92.3% |
| (0.02,0.25) | 0.0002 | 0.0000 | Ext | 0.0000 | Ext | 0.0000 | Ext | 0.0001 | -50% |

(Ext indicates that the species went virtually extinct within the simulation because the population did not exceed 0.0000 of the carrying capacity within the fishery)

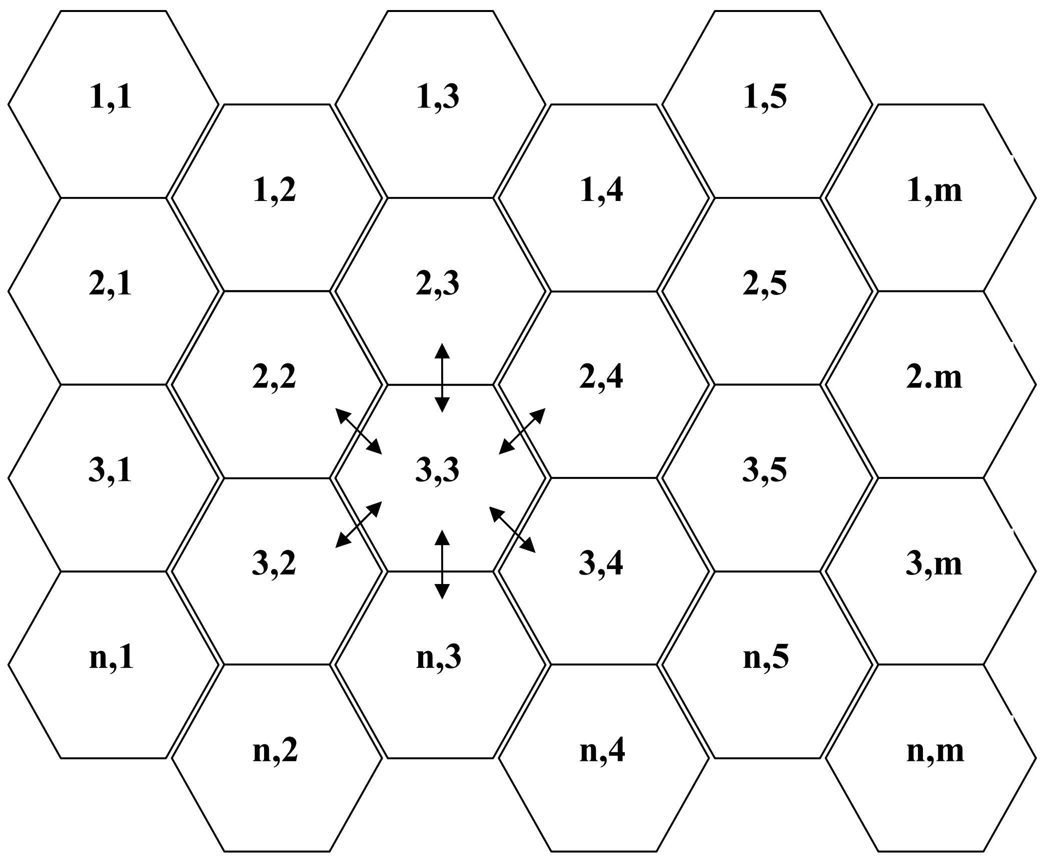



**Figure 1**: Spatial structure of simulation model. Fish diffusion takes place across all edges. All cells have the same degree of connectivity since the right and left edges of the grid are connected as are the top and bottom. For example, in addition to the adjacent cells, cell 2,1 is connected to cells 1,m and 2,m. Corner cells connect opposite sides and opposite corners. For example, cell 1,1 connects with cells n,1; n,2; 1,m; and n,m in addition to the two adjacent cells 2,1 and 1,2.

**Figure 2:** Flowchart of the simulation model

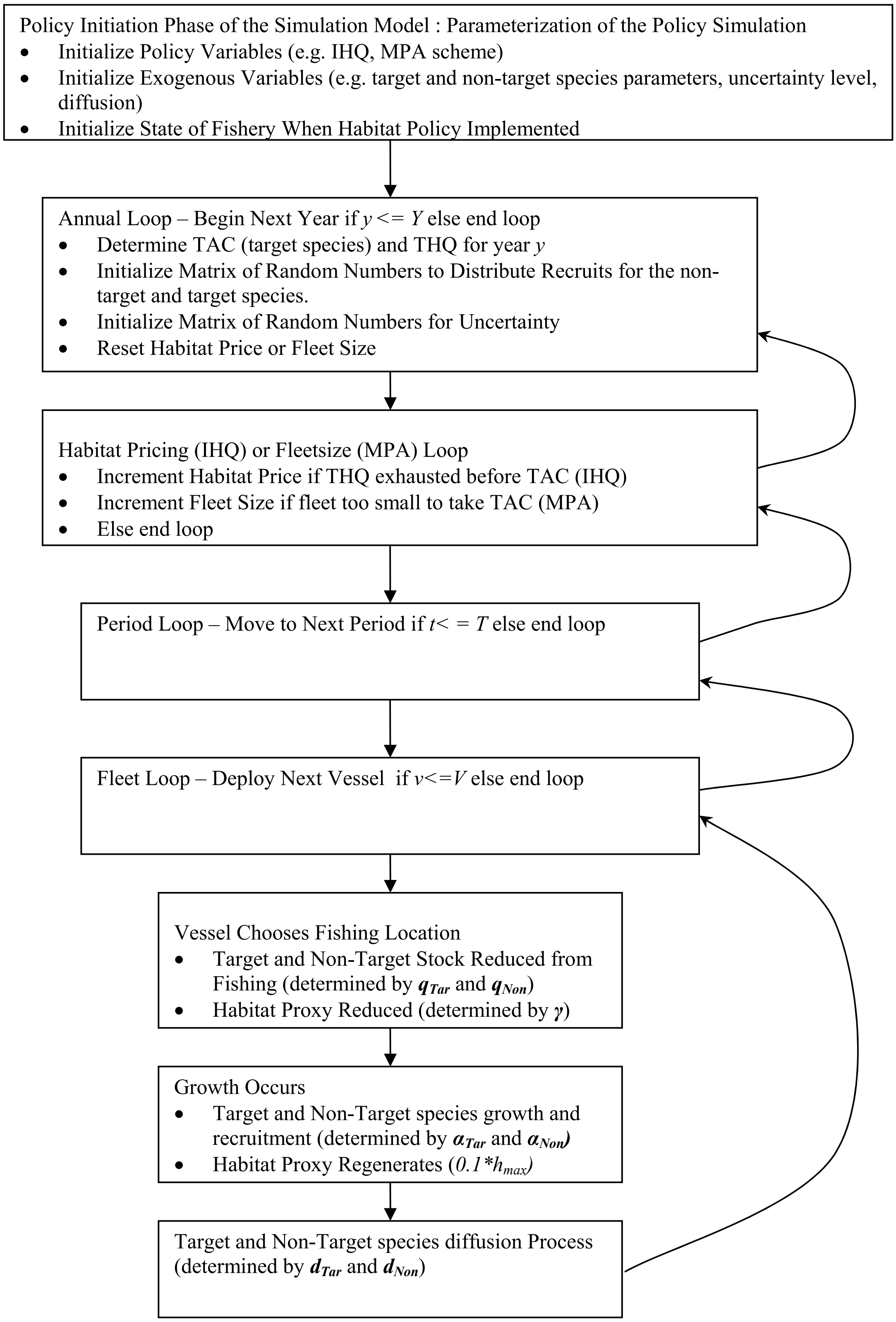


**Figure 3:** Initial spatial distribution of the target and non-target species populations.

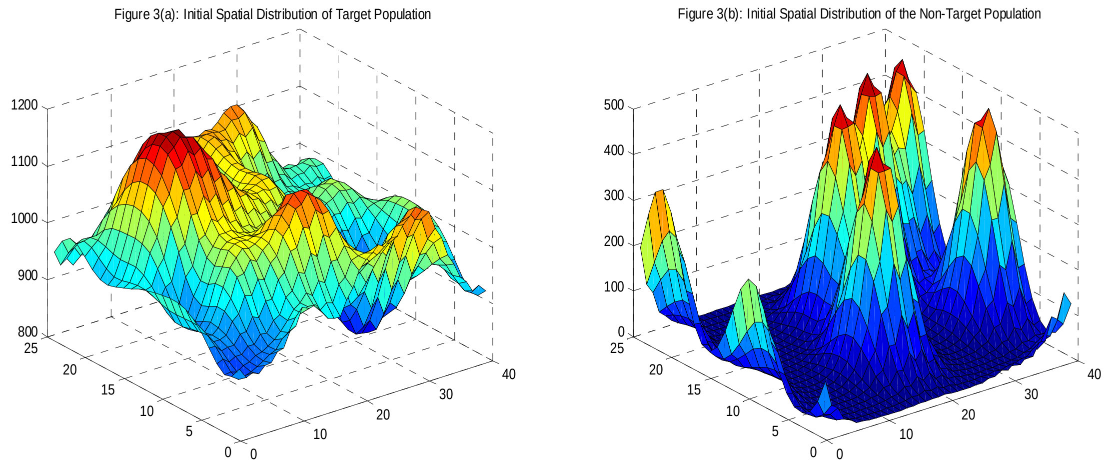


**Figure 4:** Diagram of Area Closures for MPAs. For Fixed MPAs, MPA 5 remains closed the entire simulation. For rotating MPAs, areas are closed for 10 years and then reopened in the order shown.

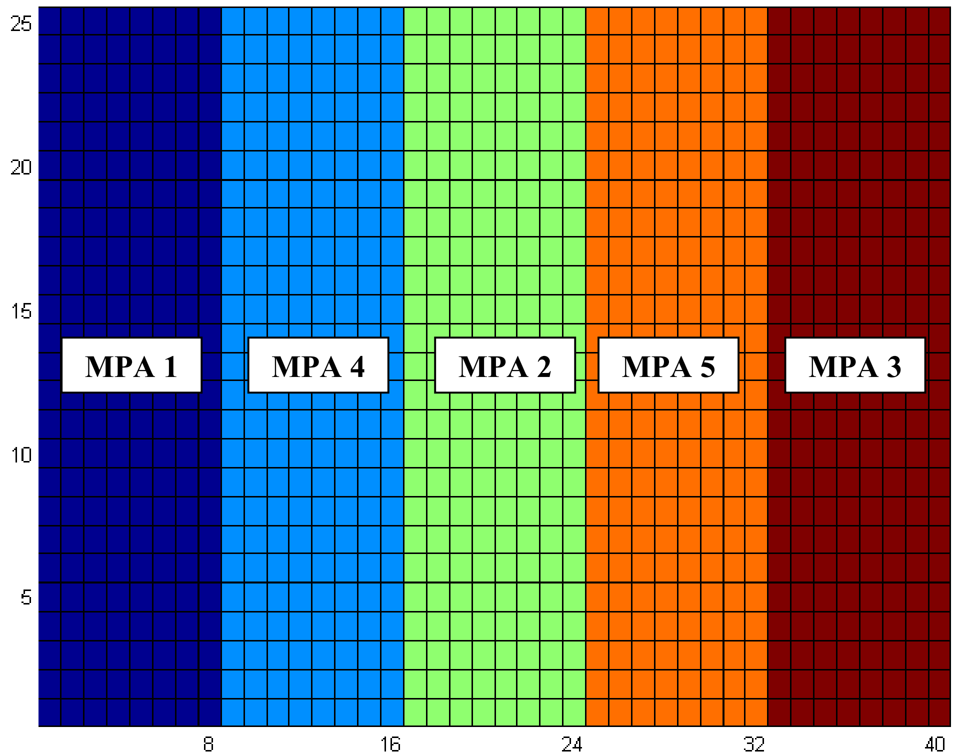


**Figure 5:** Average post-policy CPUE as a percentage of pre-policy CPUE with (a) varying rates of diffusion and no uncertainty, and (b) the lowest diffusion rate and varying uncertainty.

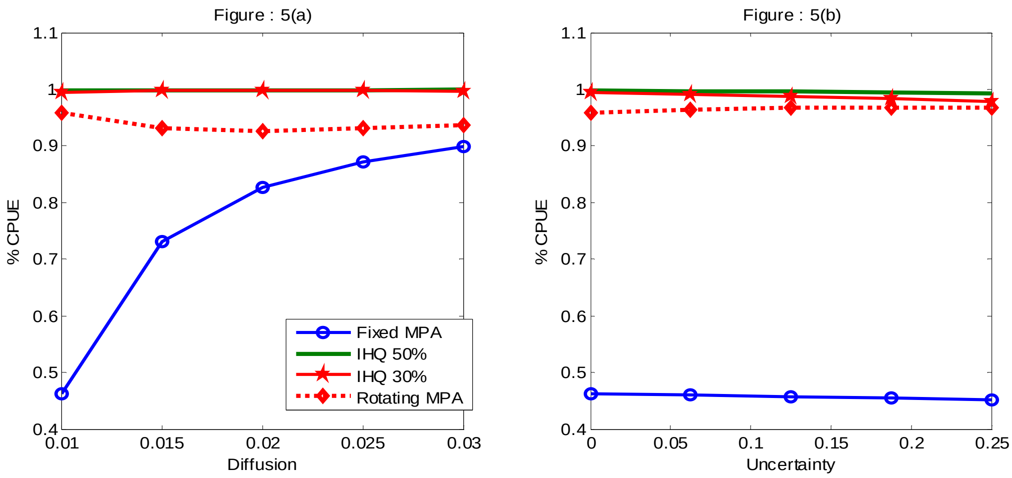


**Figure 6:** Average habitat quota price for the IHQ policy assuming a 30% habitat target and various rates of diffusion and uncertainty.

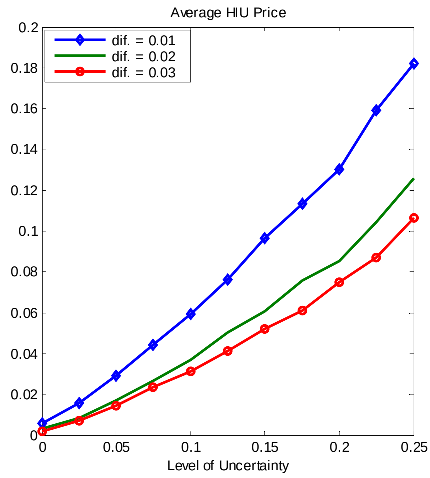


**Figure 7:** Pre-policy mean non-target species population in year 20 expressed as a fraction of the species carrying capacity. Because the pre-policy population levels of SESS 1 and SESS 2 are graphically indistinguishable only SESS 1 is shown.

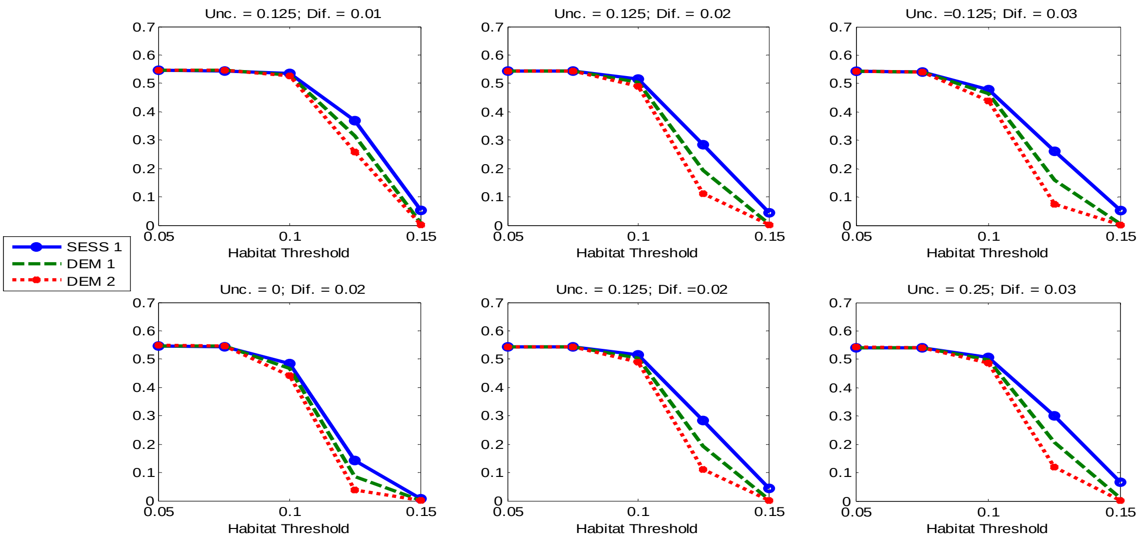


**Figure 8:** Mean SESS1 population over the duration of the policy as a percentage of the carrying capacity.

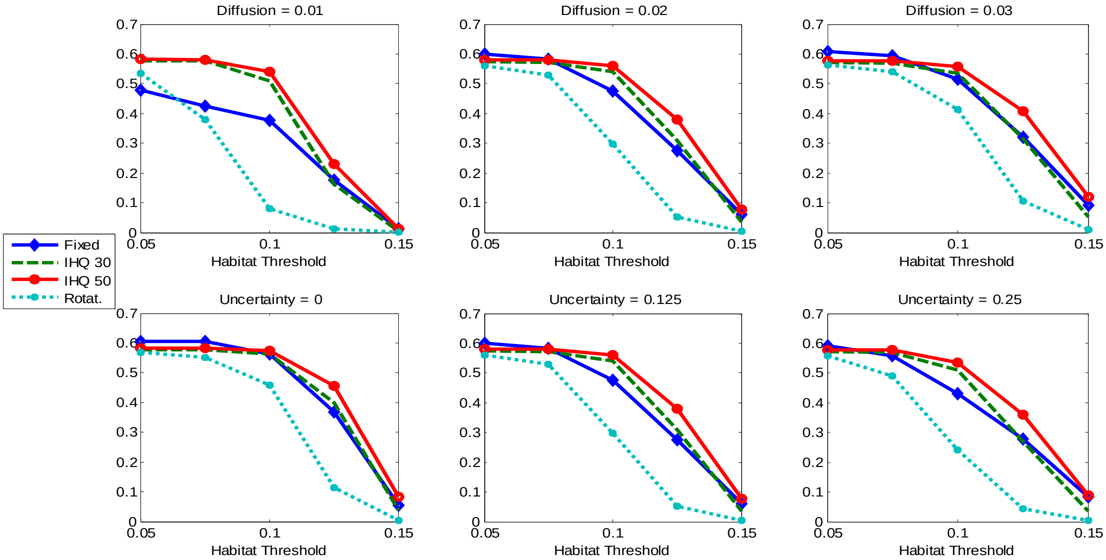


**Figure 9:** Mean SESS2 population over the duration of the policy as a fraction of the carrying capacity.

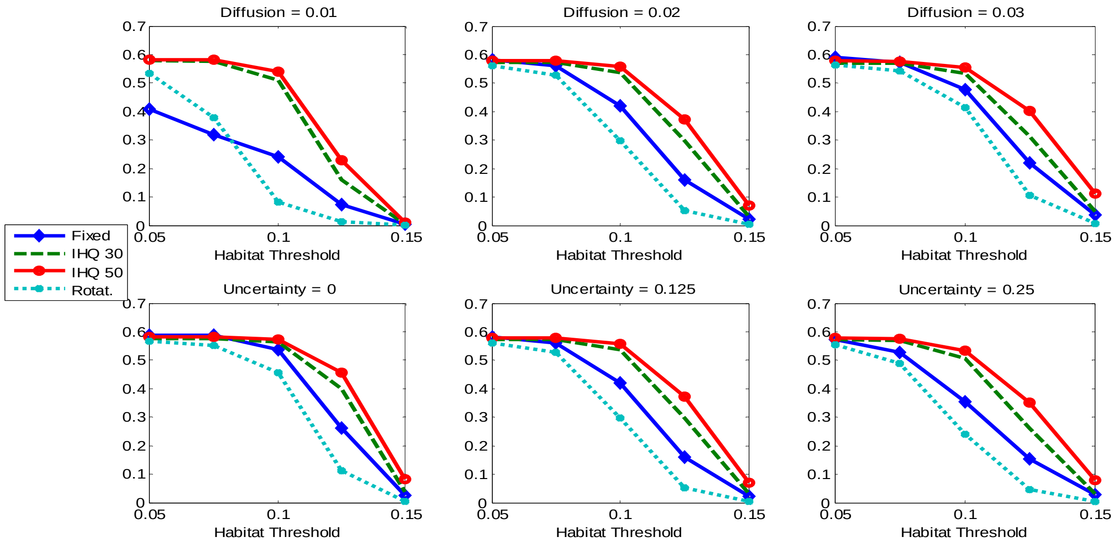


**Figure 10:** Mean DEM1 population over the duration of the policy as a fraction of the carrying capacity.

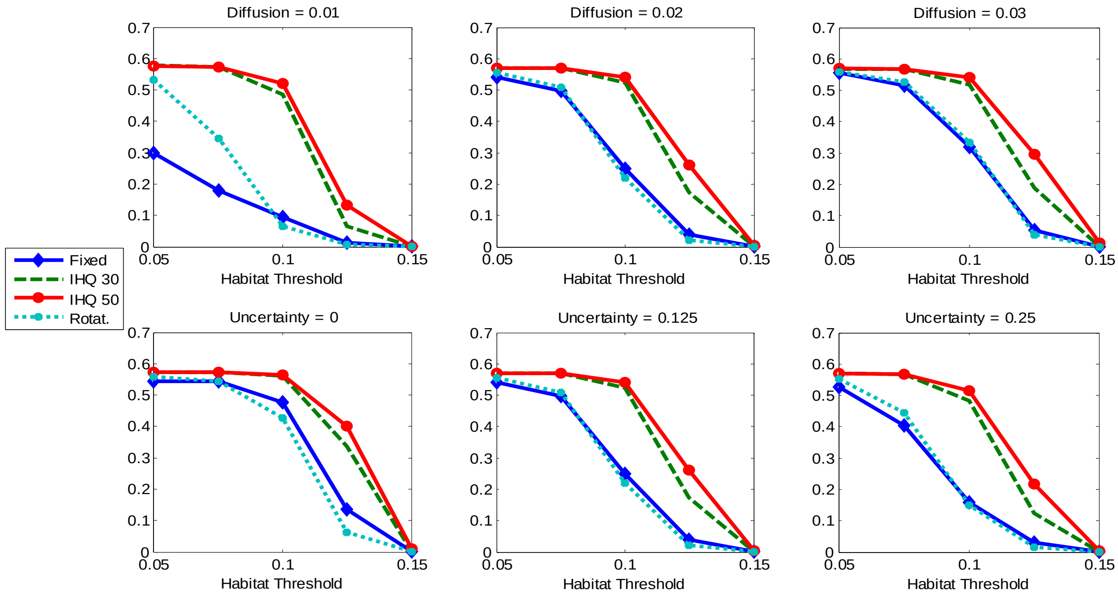


**Figure 11:** Mean DEM2 population over duration of each policy as a fraction of the carrying capacity.

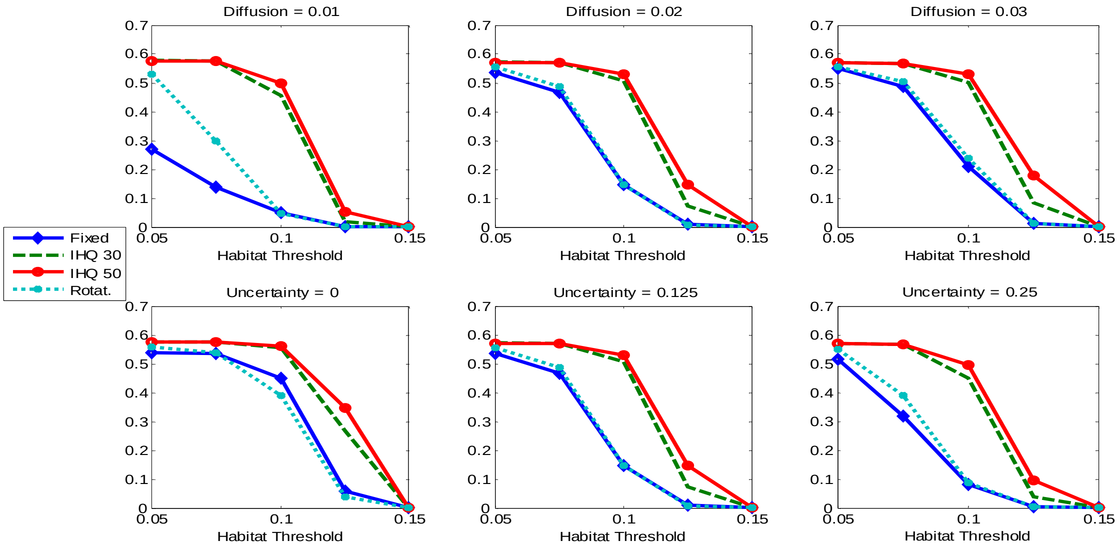
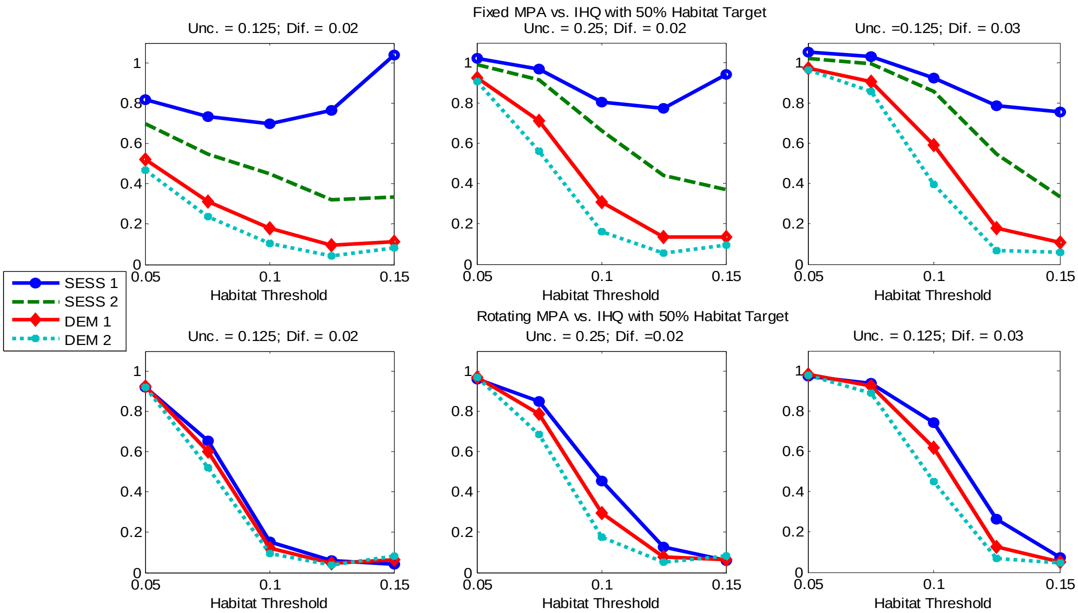


**Figure 12:** Plot of mean non-target population maintained under a fixed or rotating MPA policy as a percentage of the mean population maintained under the IHQ_50 policy.



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(lxviii) This paper was presented at the ENGIME Workshop on “Governance and Policies in Multicultural Cities”, Rome, June 5-6, 2003

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(lxxiv) This paper was presented at the ENGIME Workshop on “Trust and social capital in multicultural cities” Athens, January 19-20, 2004

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