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A MODEL FOR THE BIOECONOMIC EVALUATION OF MARINE PROTECTED AREA SIZE AND PLACEMENT IN THE NORTH SEA

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ABSTRACT. The use of marine protected areas (MPAs) as a basic management tool to limit exploitation rates in marine fisheries has been widely suggested. Models are important in predicting the consequences of management decisions and the design of monitoring programs in terms of policy goals. However, few tools are available that consider both multiple fleets and ecosystem scale dynamics. We use a new applied game theory tool, Ecoseed, that operates within a temporally and spatially explicit biomass dynamics model, Ecopath with Ecosim, to evaluate the efficacy of marine protected areas in the North Sea in both ecological and economic terms. The Ecoseed model builds MPAs based on the change in values of predicted economic rents of fisheries and the existence value of biomass pools in the ecosystem. We consider the market values of four fisheries operating in the North Sea: a trawl fishery, a gill net fishery, a seine fishery, and an industrial (reduction) fishery. We apply existence values, scaled such that their aggregate is similar to the total fishery value, to six biomass pools of concern: juvenile cod, haddock, whiting, saithe, seals, and the collective pool 'Other predators' that include marine mammals. Four policy options were considered: to maximize the rent only; to maximize the existence values only; to maximize the sum of the rent and existence values; and, finally, to maximize the sum of the rent and the existence values, but excluding only the trawl fleet from the MPA. The Ecoseed model suggests that policy goals that do not include ecological considerations can negatively impact the rents obtained by the different fishing sectors. The existence values will also be negatively impacted unless the MPA is very large. The Ecoseed model also suggests that policy goals based solely on existence values will negatively impact most fisheries. Under policy options that included ecological considerations, maximum benefits were derived from an MPA that covered 25–40% of the North Sea, placed along the southern and eastern coasts. Finally, the Ecoseed model suggests that an exclusion of the trawl fishery only from the MPA can provide small-to-substantial positive impacts to most species and fleets; this relative impact depends on level of interaction between the trawl fleet and the other fleets target species (e.g., through bycatch).

1. Introduction. Modern fisheries management has concentrated on the use of output controls, primarily limiting catches through the establishment of quotas, in order to achieve policy objectives. The large uncertainty in such methods (Walters [2000], Botsford et al. [1997]) has led to the increasing advocacy of input controls, or directly limiting exploitation rate, as necessary to the process of rebuilding or sustaining fisheries (Walters [2000]). The direct limitation of exploitation rates can be accomplished through various methods, such as the establishment of marine protected areas (MPAs) that physically limit the percentage of the population vulnerable to exploitation (Bohnsack [1990], Walters [2000]).

Though MPAs in various forms already exist (Farrow [1996], Sumaila et al. [2000]), two concerns have so far prevented their widespread use. The first of these concerns is ecological. At present, the impacts of MPAs are not well understood (Holland [2000]), in part because they were implemented in an ad hoc fashion, inherently reducing the likelihood of attaining any conservation objectives (Allison et al. [1998]). The second concern is of an economic nature. Specifically, it is feared that MPAs would reduce yields substantially (Hastings and Botsford [1999]). In order to address these concerns, modeling becomes an important first step in the design and implementation of MPAs.

An evaluation of MPAs, however, will require new and more comprehensive models than those presently used in fisheries management (Walters [2000]). Several models have already been proposed to evaluate and predict the impacts of MPAs (Table 1). The majority of these models lack explicit spatial components (including fish and effort redistribution) and have focused instead on comparing populations within and without an MPA. The populations are usually connected through a dispersal process, during juvenile or larval stages. Adults are generally assumed not to move at all. Thus, the fisheries are supported only through recruitment from within the MPA, that is, the 'seed' effect of MPAs. The population model is generally deterministic, either a logistic growth or an age-structured model. Fishing mortality, and the effect of the MPA, are modeled through varying the exploitation rate. The 'size' of the MPA increases as the exploitation rate decreases. In general, the models are limited to single species and single fishing fleets. The conclusions of such models are similar: the stock is enhanced, but fishery yields either decline or may increase at high diffusion rates. In one case (Mangel [2000]), the model suggested that yields may be 'stabilized,' an economic benefit in terms of avoiding boom and bust cycles, but not increased.

Models described above are essentially simple traditional stock assessments, with the addition of a theoretical 'protected area' that is used to limit exploitation rates. These models are limited as a tool for policy exploration, because they allow at most two variables: juvenile diffusion rates across MPA boundaries and exploitation rate (MPA size). MPAs, however, protect more than a single targeted species, and can impact large portions of entire ecosystems. Where an MPA is placed, moreover, may have more impact than its size. Further, the behavior of fishers, in terms of their ability to exploit resources adaptively, should not be ignored, as it is well known that fishers rarely operate on a random search basis (Walters and Martell [2001]). At its very simplest then, modeling MPAs must include the explicit ability to account for the movement of both species and fishers in time and space as a consequence of both location and size of an MPA.

Models must also consider the further ecological consequences of protecting portions of ecosystems. The most obvious is that more than one species will be afforded refuge within the MPA. The MPA, thus,

TABLE 1. A list of some of the models used to evaluate marine protected areas. Indicated is the type of population model and whether the model used contains features similar to those in the model developed for this study.

Citation	Population model	Multiple		Economic component	Spatially explicit	Movement		Trophic interactions	Suggested size (% total area)	MPA effect	
		Species	Fleets			Species	Fishing			Species	Fishing
Hastings & Botsford [1999]	equilibrium	no	no	no	no	yes, larval dispersal	no	no	not specified	equilibrium	identical to traditional management methods
Holland [2000]	age-structured	yes	yes	yes	yes	yes, random diffusion	yes, gravity model	no	25–50%	varied by species	positive at high diffusion rates
Lauck et al. [1998]	logistic growth	no	no	no	no	stock fills entire fishing ground each year	no	no	50–99%	positive	positive
Mangel [2000]	logistic growth	no	no	no	no	a proportion of adults, all juveniles	no	no	not specified	positive	stabilized catches
Meester [2000]	length based delay-difference	yes	no	no	yes	yes	yes, random distribution	no	5–25%	positive, if placed correctly	negative
Sladek & Robts. [1999]	age-structured	no	no	no	no	larval dispersal	no	no	40%	positive	positive
Sumaila [1998]	age-structured	no	no	yes	no	yes, transfer rates in/out of reserve	no	no	10–70%	positive	negative
Walters [2000]	biomass dynamics, delay difference	yes	yes	no	yes	yes, random diffusion	yes, gravity model	yes	large	positive	not stated
Walters & Bonfil [1999]	biomass dynamics, delay difference	yes	yes	no	yes	yes, random diffusion	yes, gravity model	no	5–15%	varied by species	not stated
Watson et al. [2000]	biomass dynamics, delay difference	yes	yes	no	no	no	no	yes	20%	varied by species	positive

will have its own food web structure that in turn depends on rates of exchange across the reserve boundary. Furthermore, more than one of the species within the reserve may be a target of a fishery or fisheries; therefore it is necessary that the model have the ability to consider the impact to and from more than one fleet. Therefore, in order to provide useful insights, a model describing the impact of MPAs should have at least the ability to define an MPA in terms of: juvenile and adult dispersal rates, its effects on trophic interactions and the behavior of fishers (Walters [2000]). Of the four examples in Table 1 that include spatially explicit movement of fishers and species in the model, all allow for multiple species, three allow for multiple fleets, and only one allows for trophic interactions to be included. Of the three that allow multiple fleets, only one accounts for trophic interactions.

A final criterion that we add here to those of Walters [2000] is that to be useful in the evaluation of management policies, a model must be both adaptable as well as allow a clearly defined set of possibly conflicting goals to be optimized. Of the four models above, all involve selecting a percentage of the fishing ground or the habitat to be protected, running the model and then evaluating the outcome. The selections of the size, configuration and placement of the MPA are arbitrary. While the optimal setting for each of those three may be discovered after some number—possibly a great number—of simulations, it is unlikely to be arrived at quickly. This is not unlike the concept of a 'blundering forager' (Adler and Kotar [1999]), which must guess when the optimal time to move to a new patch of food will occur, in the face of not knowing where the new patch is. It must get 'lost' to find new food, always a risky policy for any forager. An unconstrained optimal forager, by contrast, always knows the optimal time to leave a patch (when the density of food falls below some critical point) because it knows where the next patch of food is. The blundering forager, needless to say, always has a lower average payoff than the optimal forager since the next patch it encounters while lost may have a lower food density than the one it left (Adler and Kotar [1999]).

We have built on the work of Walters et al. [1999] and Walters [2000] to combine applied game theory, a useful tool in the economic analysis of fisheries (Sumaila [1999]), with a multi-species, multi-fishery, temporally and spatially dynamic ecological model, Ecopath with Ecosim (EwE), to create a new model. The objective of the new model is to evaluate the optimal size and placement of an MPA in an exploited ecosystem while exploring various policy objectives quickly and easily. We then apply an Ecoseed model to an EwE model of the North Sea.

The North Sea has a history of fishing dating back centuries and presents a good test case for evaluating the impact of MPAs. Most stocks today in the North Sea are considered either fully exploited, as, for example, the haddock and sole fisheries, or overexploited, most notably the herring and more recently the cod stocks. This has resulted in a call to implement or study a number of possible conservation measures, including reductions in fleet sizes and area closures. The Sea Around Us Project (for more information see `http://www.fisheries.ubc.ca`) recently updated an EwE model of the North Sea ecosystem, tuned with Multispecies Virtual Population Analysis (MSVPA) data. Using this model we conducted a preliminary evaluation of the size and placement of potential MPAs in the North Sea. Specifically, we evaluate the impact to the rents obtained by four representative fishing fleets (trawl, seine, gill net and a reduction fishery) and the existence value of six component groups of the ecosystem (juvenile cod, whiting, saithe and haddock; seals and a collective group described as 'other predators'). We consider four differing management policies: to maximize the rent only; to maximize the existence values only; to maximize the combined rent and existence values; and finally, to maximize the rent and the existence values, with the trawl fleet excluded from the MPA.

2. Methods.

2.1 The Ecopath with Ecosim model. The foundation of the EwE suite is an Ecopath model (Christensen and Pauly [1992], Pauly et al. [2000]), which creates a static mass-balanced snapshot of the state of an ecosystem represented by trophically-linked biomass 'pools'. The biomass pools consist of species, or species groups. The Ecopath model's data requirements are relatively simple and generally already available in the literature: biomass estimates, total mortality estimates, consumption estimates, diet composition, and fishery landings and values from the ecosystem. The core routine of Ecopath is derived from the Ecopath program of Polovina [1984] modified to render superfluous its original assumption of steady state. Ecopath no longer assumes steady state, but instead bases the parameterization on an assumption of mass balance over an arbitrary period, usually a year. In its present implementation, Ecopath parameterizes models based on two master equations, one to describe the production term and one for the energy balance of each group. The Ecopath master equation is as follows:

$$(1)\quad B_i \cdot (P/B)_i \cdot EE_i - \sum_{j=1}^{n} B_j \cdot (Q/B)_j \cdot DC_{ji} - Y_i - E_i - BA_i = 0$$

where (i) is the prey of predator (j), B is the biomass, P/B is the production-to-biomass ratio, Q/B is the consumption-to-biomass ratio, DC is the fraction of (i) in the average diet of (j), Y is the total fisheries catch rate, E is the net migration rate, and BA is the biomass accumulation rate.

The Ecosim model puts the Ecopath model in a temporally dynamic setting, using a system of differential equations that expresses changes in the biomass of pools as a function of time-varying biomass and harvest rates (Walters et al. [1997]). Thus, while the initial state of the Ecosim model is identical to the Ecopath model, the state of the system at the end of the simulations, including pool biomasses and fishery harvests, can be very different. The basics of Ecosim consist of biomass dynamics expressed in form of coupled differential equations derived from the Ecopath master equation (Equation 1 above), of the form:

$$(2)\qquad dB_i/dt = g_i \sum_j C_{ji} - \sum_j C_{ij} + I_i - (M_i + F_i + e_i)B_i$$

where (i) and (j) are again prey and predator respectively. The left side gives the growth rate of (i) in terms of its biomass (B), g is growth efficiency, F is fishing mortality rate, e is emigration rate, I is immigration rate, and the C_{ij} are consumption rates of type (i) biomass by type (j) organisms. The C_{ij} are calculated by assuming that:

a) the B_i are divided into vulnerable and invulnerable components (Walters et al. [1997]), and it is the transfer rate (V_{ij}) between these two components (adjustable by the user) which determines if control is top-down (i.e., Lotka-Volterra), bottom-up (i.e., donor-driven) or intermediate (see below);

b) in case of split pools (juveniles vs. adults of the same species), account is kept of the numbers that recruit from the juvenile to the adult stages (using the Deriso-Schnute delay-difference model), which allow the inclusion of stock-recruitment relationships (not discussed here) as part of the Ecosim outputs.

These assumptions lead to the rate equation:

$$C = v_{ij} \cdot a_{ij} \cdot B_j \cdot B_j / (v_{ij} + v'_{ij} + a + ij \cdot B_j) \tag{3}$$

where the v and v' parameters represent rates of behavioral exchange between invulnerable and vulnerable states and a_{ij} represents rate of effective search by predator (j) for prey type (i). The Ecosim model has been applied in the study of the role of top predators in ecosystems and the impacts of fishing (reviewed in Pauly et al. [2000]), but until the addition of Ecospace (Walters et al. [1999]), it lacked any explicit spatial component system (for more information on the EwE model, see `http://www.ecopath.org`).

The Ecospace model allows the evaluation of spatially explicit policies, such as the implementation of MPAs on both large and relatively small scales. An Ecospace model is essentially a grid or two-dimensional matrix of 'cells' in which each cell consists of a single Ecosim model (initially identical, as the Ecosim model inherits its parameters from the Ecopath model). This matrix of cells is then expressed at the user interface level as a map. Each cell in the map, excluding land cells, is linked through two processes: dispersal of organisms and the redistribution of effort due to changing cell-specific profitabilities and/or the creation of areas closed to fishing (Walters et al. [1999], Walters [2000]).

The user defines the base map by sketching it on the interface with the computer mouse. Over the top of the base map can be sketched: patterns of relative fishing cost (effort 'avoids' cells associated with a relatively high fishing cost; for example, cells far from their home port that require high fuel costs to reach); patterns of relative primary production; and patterns of habitat to which biomass pools and fishing fleets can be assigned (Walters et al. [1999], Walters [2000]). Recent modifications to the Ecospace model allow the estimation and comparison of the 'value' obtained from MPAs, either as a function of the monetary value of fisheries or the change in biomass of pools. It was recognized that the information included in these routines could be adapted to evaluate the size and placement of MPAs, thus leading to the development of the model presented herein called Ecoseed.

2.2 The Ecoseed model. In game theory, one is concerned with the actions of decision makers who have an awareness both of the other decision maker's actions, and the impact of their own actions upon the others (Rasmusen [1995], Sumaila [1999]). A fully described game would include players, strategies and payoffs; all together, these comprise the rules of the game. Games can be cooperative (players work together to maximize joint benefits) or noncooperative (players seek to maximize only their own benefits), with or without conflict (Rasmusen [1995]).

The Ecoseed model is a simple multi-player, cooperative or non-cooperative model. The players in the model are the fishery managers or other interested parties (the regulator), and the fishing fleets (the fleet[s]). The game is modeled in two stages. In stage 1 the regulator decides what broad policy objective it wants to pursue. In stage 2 the fleets decide where and how to fish within the constraints set forth by the regulator, in order to maximize their own private rents through the redistribution of their effort within the unprotected area. The regulator can explore several strategies (policy objectives): either to maximize the fleet rent or to maximize the benefit to a species, or group of species (or increased habitat leading to an increased species biomass may be a surrogate). In this paper, we view the regulator as playing a 'cooperative' game with the fleets if the former objective is chosen. This is because we assume rent maximization to be the objective of the fleet owners. On the other hand, the regulator plays a non-cooperative game if the regulator chooses to maximize ecological benefits only. The final strategy available to the regulator is to find a compromise that maximizes the benefits to both the fleets and the biomass pools through some form of tradeoffs. The regulator initiates the game by choosing a strategy, then the Ecoseed model is used to select an area to place an MPA, then the fleets respond by redistributing their effort, and the Ecoseed model responds by either increasing the size, or changing the placement, of the MPA until the outcome that best meets the stated objectives is calculated. The primary goal of an Ecoseed model game is to allow the regulator to evaluate as many differing policy scenarios as possible. The outcomes resulting from different strategies collected and tested during gaming can then be used for informed policy analysis and implementation. It should be stressed that, as for any model, the Ecoseed model does not provide the 'right' numbers. It can only shed light on the expected direction and magnitude of change resulting from strategies undertaken, given the set of input parameters. As such, an Ecoseed model should also assist in the design of monitoring programs that should be part of the establishment of any MPAs.

The selection of the 'best' cell from a single or set of seed cells is guided by the primary Ecoseed model objective function, which is expressed simply as:

$$\begin{aligned}\text{Best cell} = \text{Max } (&\text{Sum of surplus production from fisheries} \\ &+ \text{Sum of existence value of species})\end{aligned} \tag{4}$$

where the values of surplus production and existence are summed over all water cells, all fleets, and all species for each seed cell considered. Equation (4) can be formalized as follows:

$$O_{i,j} = \text{Max}\left[\sum_{i,j,k}(R_{i,j,k} - FC_k - EC_{i,j,k} - SC_{i,j,k}) + \sum_{i,j,s}(B_{i,j,s} \cdot V_s)\right] \tag{5}$$

where (i) is the number of rows in the grid map, (j) is the number of columns, R is the total revenue in cell (i,j) for fleet (k), FC is the fixed cost for fleet (k), and EC is the cost associated with effort expended in cell (i,j) by fleet (k). Note here that since effort is presently constant in the simulations, the value of EC is fixed. SC is the spatial cost of fishing in cell (i,j) for fleet (k), B is the biomass in cell (i,j) of species (s) and V is the existence value per unit of species (s). R is calculated as follows:

$$R_{i,j,k} = \sum_{i,j,k,s}(Y_{i,j,k,s} \cdot P_{k,s}) \tag{6}$$

where Y is the catch of species (s) in cell (i,j) for fleet (k) and P is the ex-vessel price of species (s) for fleet (k). Note that the Y for any cell is a function of B for that cell. (For a detailed description on the estimation of biomass, catch and effort for cells in Ecospace, see Walters et al. [1999]).

The procedure followed during an Ecoseed game is as follows. The user defines either a single seed cell, or block of seed cells (block sizes presently available are 4, 9, 16 and 25 cells since these provide a square MPA block), many seed cells or blocks of seed cells, or all cells can be considered as seed cells initially. In the case of the single seed cell or a set of single seed cells, the Ecoseed model evaluates the seed cell that is then accepted as the initial MPA. In the case of multiple seed cells, the best cell as defined above is selected. Next, the four adjacent cells (above, below, left, right) are set as seed cells and evaluated, the best is selected and the process repeats. Note that once they are selected as seed cells, the cells remain as such. If all cells are selected as seed cells initially, then the user can either direct the Ecoseed model to select the best cell and then remove all other seed cells (the user assumes this is the optimal initial area to place an MPA) or retain all seed cells (the addition of an MPA and the resulting redistribution of effort may change where the optimal MPA is sited). The procedure is the same when blocks of seed cells are used. The ability to select blocks of many cells was added in order to speed up the simulations when very large maps are used. Note that with blocks of seed cells, land cells may in some cases be included in the blocks. They are not actually considered as an MPA; however, this was merely a programming convention that was found to be necessary in order to be able to consider multiple cells at once.

Depending on the objective set forth by the regulator, the objective function O is then maximized when the sum of the rent from fisheries and the existence values is maximized, given the relevant constraints. Further, setting the rent to zero causes O to be a function of existence value only, and conversely. Finally, note that the sum of EC over all cells is constant in the model as long as total effort remains constant. This constant-effort assumption is a shortcoming of the present approach and the ability to include variable effort as a policy option is in development. It should, however, be noted that this assumption can be justified in the short run because fishing vessel capital is generally non-malleable under short time periods (see Sumaila [1995] and Clarke et al. [1979]).

2.3 The North Sea model.

2.3.1 *The Ecopath model setup.* An Ecopath model of the North Sea was constructed as an updated version of the model presented by Christensen [1995]. The model was updated to include data on biomasses, production and consumption from the key-run of the most recent version of the ICES Multispecies Virtual Population Assessment (MSVPA, Vinter, pers. comm., Danish Institute for Fisheries Research). The base period represented is changed to the year 1970 in order to take advantage of information from time series data. Further, catches have been added for the groups not included in the MSVPA, based on the STATLANT database as available from ICES (`www.ices.dk`). The model consists of 31 biomass pools, from detritus and primary production to top predator fish and seabirds (see `www.Ecopath.org` for details of the model parameterization).

Four fisheries are included in the model: a trawl fleet, a gill net fleet, a seine fleet, and an industrial (reduction) fishery. These fleets were chosen to represent the majority of fishing activity in the North Sea. The initial catch distribution of species or groups among fleets in the underlying Ecopath model is assumed. Discarding is not explicit; however, no commercial value is applied to the trawl fleet's catches of juvenile biomass pools. Table 2 shows the values by species and fleet used in estimating the rents and the existence values. Ex-vessel prices were obtained from `http://www.fis.com/fis/marketprices/` and were current as of July 2000. The existence values of the six groups were assumed to be similar and set so as to sum to a value similar to the value of the fisheries at the start of the Ecoseed model run.

2.3.2 *Ecosim, Ecospace and Ecoseed model setup.* For simulation purposes, the Ecosim model was set to run for 50 years. The first 21 years were fit to time-series data. All Ecoseed model runs were set to begin the year following the end of the time-series data.

Five habitat types were defined according to bathymetric contours. Table 3 shows the habitat types, habitats assigned to biomass pools, and dispersal rates of the biomass pools. Biomass pools were assigned to habitats based on described distributions within the system, if

TABLE 2. Values applied to the individual fisheries by biomass pools of interest, and total values, costs and profits by fishery estimated by Ecopath.

			Fishery value ($\$\mathrm{kg}^{-1}$)			Existence value	Total value
Group	Trawlers	Gill Net	Seiners	Industrial	Total	($\$\mathrm{kg}^{-1}$)	($\$\mathrm{kg}^{-1}$)
Cod	0.59	0.25			0.85		0.85
Haddock	0.46	0.20			0.65		0.65
Herring	0.30		0.12		0.14		0.14
Mackerel	0.12		0.47		0.59		0.59
Norway pout				0.19	0.19		0.19
Plaice	0.22	0.10			0.32		0.32
Saithe	1.47				1.47		1.47
Sandeel				0.90	0.90		0.90
Sole	0.13	0.60			0.19		0.19
Whiting	0.13	0.60			0.19		0.19
Gurnards	0.19				0.19		0.19
Horsemackerel				0.10	0.10		0.10
Other predators						0.27	0.27
Seals						< 0.01	< 0.01
West mackerel	0.20		0.10		0.12		0.12
Juvenile cod						0.50	0.50
Juvenile haddock						1.25	1.25
Juvenile saithe						0.30	0.30
Juvenile whiting						0.77	0.77
Sprat				0.90	0.90		0.90
Dab	0.20				0.20		0.20
Total value	3.39	0.66	0.69	0.38	5.12	2.38	7.50
Total cost	2.88	0.53	0.55	0.32	4.29		
Total profit	0.51	0.13	0.14	0.60	0.84		

known. If descriptions were not available, the group was assigned to all habitats. Their distribution developed only as a result of trophic interactions and tradeoffs between the need for food and predation risk. Penalties for dispersal into non-optimal habitats were left at the Ecospace model default values (5 times movement rate, 2 times the vulnerability for predation, and 1% of feeding success) for all groups

TABLE 3. Individual group assignments to habitat types, base dispersal rates and penalties for not being within a preferred habitat type. A '+' sign indicates that the habitat is preferred by the biomass pool, a '-' sign indicates habitat not preferred.

			Depth (m)				
Group	0-30	30-50	50-200	200-400	>400	All depths	Base dispersal rate (km·year^{-1})
Cod	-	+	+	-	-	-	150
Haddock	+	+	+	-	-	-	10
Herring	-	-	-	-	-	+	100
Mackerel	-	-	-	-	-	+	10
Norway pout	-	-	+	+	+	-	100
Plaice	+	+	+	-	-	-	10
Saithe	-	-	+	+	+	-	10
Sandeel	+	+	+	-	-	-	10
Sole	+	+	-	-	-	-	10
Whiting	-	+	+	-	-	-	100
Birds	-	-	-	-	-	+	300
Gurnards	+	+	+	-	-	-	10
Horsemackerel	-	+	+	-	-	-	10
Other predators	-	-	-	-	-	-	10
Raja	+	+	+	+	-	-	10
Seals	+	+	-	-	-	-	300
West mackerel	-	-	-	+	+	-	100
Other invertebrates	-	-	-	-	-	+	5
Juvenile cod	+	+	-	-	-	-	10
Juvenile haddock	+	+	+	-	-	-	10
Juvenile saithe	-	-	+	+	-	-	10
Juvenile whiting	+	+	-	-	-	-	10
Sprat	+	+	-	-	-	-	10
Dab	+	+	+	-	-	-	10
Copepods	-	-	-	-	-	+	300
Euphausiids	-	+	+	+	+	-	300
Other crustaceans	-	-	-	-	-	+	10
Echinoderms	-	-	-	-	-	+	10
Polychaetes	-	-	-	-	-	+	10
Other macrobenthos	-	-	-	-	-	+	10
Phytoplankton	-	-	-	-	-	+	300
Detritus	-	-	-	-	-	+	5
Proportion total area	0.26	0.15	0.29	0.20	0.10	1.00	

except juvenile cod. For this group the penalties were reduced (10 times the movement rate, same vulnerability, 90% feeding success) in order to prevent cod groups from going extinct in the simulation. Note that through considerable simulation, these default values have been found to be realistic, both in biological terms and in terms of the model behavior they generate. Thus, while considerable uncertainty remains associated with the defaults which have not as yet been rigorously tested, they appear to be a reasonable starting value, particularly in the absence of data to the contrary.

Figure 1A shows the base map of the North Sea used in the Ecoseed model runs. Note that each cell is 5 km in length. Shown on the base map here is the habitat types, or depth zones. The spatial cost of fishing was set so that cells greater than 3 from the coastlines were considered to be 20% more costly to fish as a result of increased fuel costs. We also assume that fuel costs represent the greatest factor in the spatial component of the cost of fishing.

3. Results and discussion. Maximum and minimum values of the predicted rent, existence value and objective function are summarized in Table 4, including the percent change relative to the value just prior to the addition of MPA cells, for all policy scenarios. Results obtained under each policy are described individually below.

3.1 Policy A: Maximizing economic rent only from all fleets. This policy resulted in the only predicted decline in existence value, and rent under this policy declined to less than zero with the least total MPA coverage (Table 4). Figure 2A shows the predicted impacts as a function of increasing MPA size. The predicted rent never increased under this policy, but declined less than 5% until 40% MPA coverage. No positive benefit to the existence value is predicted until greater than 70% of the area was MPA. Figure 1B shows the proposed MPA for 40% (dark grey cells) coverage and 70% (light and dark grey cells) coverage. The fishery does not lose more than 5% of its initial rent until areas to the south and east are selected. The initial cells selected are along the Eastern coast of Britain and tend to be mostly land.

FIGURE 1. **A.** Basemap used for all Ecospace model and Ecoseed model simulations, showing the different habitat types. **B-E.** MPA size and placement predicted by Ecoseed model under differing policy scenarios. The dark grey areas are MPAs, the black areas are land. **B.** Maximizing the rent from all fisheries only. Light grey cells indicate 40% coverage. The predicted rent declined by less than 5% until this point. An increase in the existence value is not predicted until greater than 70% coverage. **C.** Maximizing for existence value only. The predicted existence value increased by 50% at 36% coverage, shown here. Note that the cells selected are almost all different from those shown in light grey in B. **D.** Maximizing for the combined rent and existence values. The maximum predicted increase in existence value in this game, 42%, at a coverage of 27%. At this point the rent showed a 22% predicted decrease. Total coverage required is 27%. Note that the cells selected are very similar to those for C. **E.** As for D, but excluding only the trawl fishery from the MPA. Total coverage by MPA is 41%, the existence value predicted is 37% increase, and there was an 18% predicted decrease in total rent. Rent for fisheries other than trawl, however, increased by 21% at this point.

TABLE 4. Minimum and maximum values of the rent, existence value and objective function and the percent MPA coverage at which they were observed under the four different policy scenarios. The percent change from the initial value is shown in brackets.

Policy		Maximum value ($\$km^{-2}$)	MPA coverage (%)	Minimum value ($\$km^{-2}$)	MPA coverage (%)
A	Rent[a]	4.78	2	1.52	91
		(+1)		(-68)	
	Existence value	7.10	100	4.27	45
		(+26)		(-24)	
	Objective function	1.01	2	0.32	91
B	Rent[a]	4.74	0	0.30	87
		(-)		(-93)	
	Existence value	8.47	37	5.62	0
		(+50)		(-)	
	Objective function	1.51	37	1.00	0
C	Rent	4.74	0	0.00	100
		(-)		(-100)	
	Existence value	5.91	28	4.16	0
		(+42)		(-)	
	Objective function	1.08	23	0.60	100
D	Rent	4.74	0	0.41	96
		(-)		(-91)	
	Rent (trawl excluded)	2.04	46	1.69	0
		(+20)		(-)	
	Existence value	5.70	41	4.16	0
		(+37)		(-)	
	Objective function	1.08	37	0.59	96

[a] Point of last positive value

Our simulation suggests that placing an MPA based on a policy goal of minimizing the economic impact to commercial fisheries, while ignoring ecological considerations, can have a strong negative impact on both the fisheries and the ecosystem. The explanation for this is straightforward. Cells were placed first in areas where there was relatively little effort being expended to start with, either because the expected yields were low or because the cost to fish there was high relative to the expected yields. Cell blocks were also selected such that a minimal area was closed off initially. The first ten blocks added accounted for only 28% of the total area, with 39% of this being land cells. Further, the rent obtained by the trawl fleet accounted for more than half of the rent from all fisheries. In effect then, the selection of cells was primarily driven by the impact to the trawl rent. The effort from all the other fisheries was displaced then into open areas where the trawl fleet 'preferred' to fish. This can have two consequences which are not mutually exclusive.

First, all fleet effort is redistributed and concentrated onto the same grounds preferred by juveniles of several of the commercially fished species, notably cod, haddock and saithe. The juveniles, bycatch species in the trawl fishery, were subjected to increased fishing mortality, and their existence value declined as a result. Second, the areas closed represented much of the available relatively low-cost areas open to the gill net and the seine fleets. This negatively impacted their rents. Similar negative impacts of the redistribution of effort due to closing grounds have been pointed out for other fisheries that target multiple species and stocks (Walters and Bónfil [1999]). Here we add that in a multi-fleet setting, the economic impacts to different fleets need consideration. Overall, the model predicts that this management policy can lead to results that provide neither ecological nor economic benefits in the long run.

3.2 Policy B: Maximizing existence value only, and Policy C: Maximizing combined rent to all fisheries and existence values. Policy B resulted in the largest predicted increase in existence value (Table 4). The impact to the rent and the existence value here are both more dramatic (Figure 2B). The predicted rent declined linearly with increasing MPA size. The small increase in rent observed in the very last cell is a result of a zero value returned when no fishing can take place, thus the rent 'increases' from a negative number to zero. Note here that the seine fleet benefited from an MPA, with a maximum increase of more than 5% at between 20 and 25% MPA coverage. Figure 1C shows the proposed MPA for this game to 50% coverage. Cells selected here are mainly in the southeast section of the North Sea. Cells selected in this area under Policy A precipitated the greatest declines in rent.

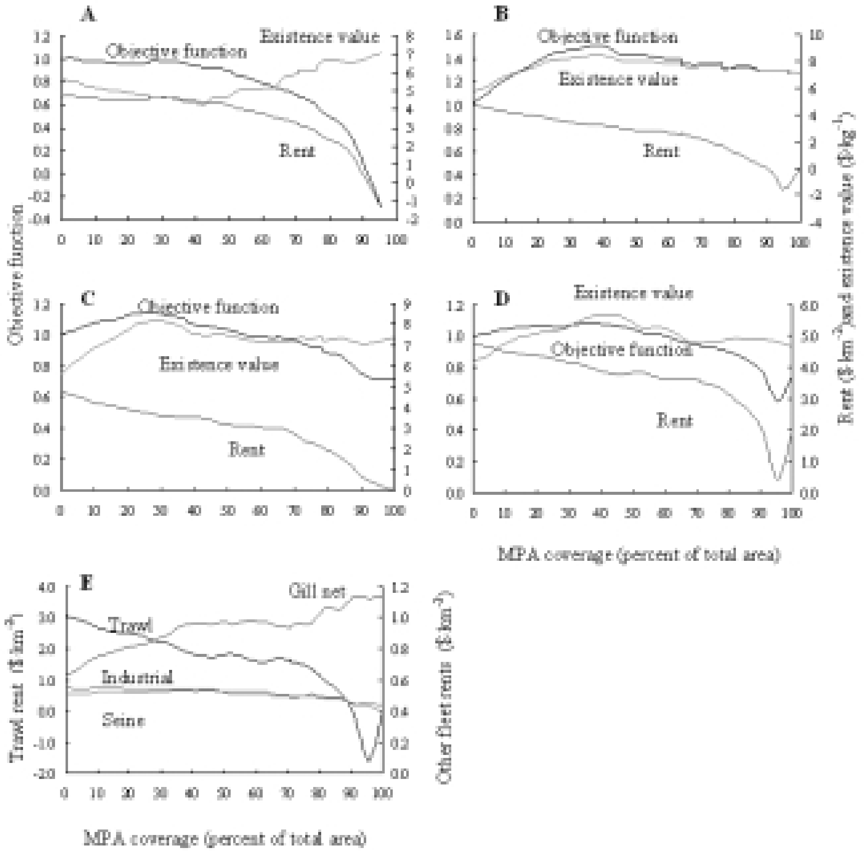

FIGURE 2. Values of the objective function, rent and existence value obtained under the different policies as a function of increasing MPA size, expressed as percent of the total area. **A.** Maximizing the objective function in terms of rent only. Fishery values decline by less than 5% until greater than 40% coverage. No increased benefit to the existence value is predicted until greater than 65% coverage is achieved. **B.** Maximizing the objective function in terms of the existence value only. The largest increase in existence value was predicted in this game, however, a peak is still predicted at 40% coverage. **C.** Maximizing the objective function in terms of the combined rent and existence value. The peak existence value occurs at 30% coverage, and the loss in rent is less than that predicted in B. **D.** As in C, but excluding only the trawl fishery from fishing in the MPA. The peak for the existence value is predicted at 50% coverage. The decline in predicted total rent is less than that for C. **E.** As in D, but showing the rents predicted for individual fleets. Note that only the trawl fleet has a predicted loss. For other fleets the predicted impacts are negligible (Seine, Industrial) to large increases (Gill net).

The predicted rent and existence values for Policy C were similar (Table 4). Here, the predicted rent declined at a slower rate, and was not less than zero (Figure 2C). As for Policy B, the seine fleet showed a predicted increase in rent, with a maximum increase of more than 5% at 36% coverage. Also similar to Policy B, the predicted existence value peaked, though at a lower value and at less total MPA coverage. Figure 1D shows the cells proposed as an MPA as a result of this game. The cells selected in this game are very similar to those for the previous game.

The results from management policies B and C differed dramatically from results obtained under policy A, but were similar to each other. In both cases, cells added to the MPAs first were cells to the south and east of the North Sea, primarily habitat for juveniles of major commercial species such as cod and saithe. The existence values were predicted to increase in both cases, and in both cases the increases began with the addition of only one block of cells. Further, the model indicates maximum benefits to the existence value would be obtained at between 25-40% MPA coverage and that the addition of MPAs that protect the juveniles of commercially important species would provide the maximum ecological benefit. At levels greater than this coverage, changes in relative predation rates negatively impact species of concern, in this case primarily due to cannibalism. At this level of coverage, however, only the seine fleet is predicted to have positive gains in rent (as much as 5%), while the trawl and gill net fleets have predicted losses greater than 10%. Holland [2000] found that the impacts of MPAs on yield to fisheries varied with species. Here, the seine fleet benefits, in part because it targets primarily herring and mackerel that are not targeted heavily by other fleets. The seine fleet does not have to cope with the increased effort by other fleets in a smaller area, and thus receives all the benefits in terms of yield of these species that the MPA has created. If all fisheries are considered equally important, however, then in neither scenario did the Ecoseed model increase in economic rents.

3.3 Policy D: Maximizing the rent and existence values, excluding only trawl from the MPA. This policy resulted in positive predicted values to both the rent (for fleets other than trawl) and the existence values (Table 4). The total rent declined at slower rate than in the previous game, and at 80% coverage showed a loss of 58% (Figure 2D). The losses here were less than in previous scenarios as fleets other than the trawl fishery continued to be allowed to fish everywhere they could expect a reasonable profitability (Figure 2E). The apparent increase in trawl rent after 95% coverage is due to the rent 'increasing' to zero from negative values as the entire area available was closed and the fishery is shut down. Similar to the previous two policies, the predicted existence value peaked, and at a similar percent total MPA coverage (Figure 2D). Figure 1E shows the cells selected for this game that provided the largest increase in existence value. While more cells were needed for a slightly smaller gain than for the previous two policies, otherwise excluding only the trawl fleet from the MPA resulted in the identical cells being selected.

Note here that the inherent complexity of ecosystem management is vividly illustrated by Figure 2E. One might predict that the exclusion of the trawl fleet would benefit all other fleets, since the trawl fleet was responsible for the vast majority of catches in the North Sea. Only the gill fleet benefits to any great degree, however, while the other fleets are little affected. The gill net fleet targeted cod, much the same as the trawl fleet, so this result is expected. The industrial and seine fleets targeted other species, however, and were not in direct competition with the trawl fleet. Over time, sustained exploitation rates along with changes in the trophic structure of the system (Section 3.2) combine to the detriment of both fleets as the MPA grows very large, and the impact of the trawl fleet thus very small.

This management option was explored as it became apparent that the trawl fleet had the greatest influence on the outcome of the simulations. This is primarily because the fleet's predicted rent was more than all other fleets combined. In this scenario, the existence value showed a predicted maximum at just over 40% coverage, similar to the latter two policy options. Dispersal rates for species here were set to 2–30 times the cells size, and MPAs were added in blocks of a maximum 16 times the cells size. Walters [2000] found that movement rates of 1–2 cells per year had considerable impacts, thus our dispersal rates here can be considered high.

The most striking difference from the previous policies observed here was the large scale increases in rent predicted for the gill net fleet. The predicted seine fleet rent increased as well, similar to the percent increase predicted under policy scenarios A and B, while the industrial fleet showed a predicted loss of less than 3% at the optimal coverage in relation to the existence value. With direct spatial competition for fish with the trawl fleet removed, we would predict small to substantial benefits would accrue to other fleets operating in the North Sea, and increased existence values. Thus, if a policy option is to control the exploitation rate of the trawl fishery, the Ecoseed model indicates that MPAs may provide both ecological and economical benefits.

4.0 Conclusions. We have explored several different policy options in terms of size and placement of MPAs in the North Sea, using a bioeconomic tool in combination with an ecosystem model recently constructed and tuned with MSVPA data. The size and placement of the MPA was determined according to its impacts to the rent obtained by the fleets, the existence value of species, or by a combination of the both. Several key points revealed through this exercise are as follows. First, careful evaluation of the possible consequences of policy decisions should be made before they are implemented. Assumptions that MPAs will provide benefits to species of concern no matter where they are placed may not be valid. Implementing an MPA based solely on ecological concerns would negatively impact all fisheries operating in the North Sea. Second, for policy options that considered either just the ecological or the ecological and economic impacts combined, the maximum size of an MPA necessary to benefit species of concern in the ecosystem is in the range of 25-40% of the total North Sea area. The Ecoseed model further indicates that the MPA should be along the southern and eastern coasts of the North Sea. Though a 40% closure may seem large, recently about 40% of the North Sea was temporarily closed to fishing as an emergency response to protect spawning cod stocks (Anon. [2001]). Third, among policy options that consider all fleets equally, it was predicted that most fleets would be negatively impacted by the implementation of an MPA of any size in any area, but some would be positively impacted. Finally, if the exclusion of the trawl fleet only from the MPA were a policy option, the Ecoseed model indicates small to large positive impacts to both the economic rents for other fleets and the existence value of species.

While we feel that the Ecoseed model presented here is a useful tool in the design of MPAs, room for improvement exists in several key areas. First, note that all these simulations were essentially predictions into the future of an MPA imposed upon a relatively heavily exploited system. While the first 21 years were validated to best time series data available, no such constraints are in place once the Ecoseed model begins. Thus, there was no attempt to model, for example, whether any quotas for the trawl fleet in scenarios D and E (where the trawl fleet is the only fleet excluded) could still be met while the MPA is enforced. The trawl fleet is slowly excluded from the MPA, while attempting to catch as much as possible with the only constraint being a reduced area within which to fish. The ability to do such exploration is, however, included within the software, one need simply lengthen the time series data to include future quotas. Including such a factor in the calculation of the Ecoseed model objective function might improve its utility. Second, perhaps as a further extension to the above, the ability to weight the components of the objective function could improve its utility by allowing the varying relative importance of each in, and evaluating the subsequent impact to, the achievement of policy goals. This would add some realism relative to the simple on/off mechanism used here. Third, the components of the objective function as stated here are limited in scope and do not include such potentially crucial considerations such as social consequences of imposed MPAs. The Ecosim component of the software recently has been modified to include a search routine that maximizes an objective function based on four components: fishery economics, ecosystem structure, judicial mandates and a social impact component. We expect in the future that Ecoseed model will be modified to closely mirror the more complex Ecosim function, allowing a far wider scope of policy goals to be explored. Finally, Ecospace itself is limited in its ability to expressly model the movements of species within the system, primarily by computational complications, and as yet cannot include such factors as migration. The development of routines that allow such movements to be modeled is proceeding however. Nevertheless, the Ecoseed model at present is capable of providing useful, though broad, insights.

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