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Electronic Supplementary Material

The good, the bad and the ugly of Marine Reserves for fishery yields

Giulio De Leo and Fiorenza Micheli

Table of contents

Appendix S1: The simulation model

Let $n_{j,i,t}$ be the number of individuals in size class j (j=1,2,3), patch i (i=1..S) at time t and ϕ_j their fertility. The first size class consists of pre-reproductive individuals (fertility $\phi_1 = 0$), while the third one represents old, large spawners, for whom per capita fertility is assumed to be much larger than that of reproductive individuals in the second size class ($\phi_3 >> \phi_2$). Let σ_j be the annual survival in size cass j, and γ_j the fraction of individuals that move from size class j to the next one every year.

The total number of eggs $L_{i,t}$ produced in patch i at year t is computed as follows:

$$L_{i,t} = \sum_{j=1}^{3} \phi_j n_{j,i,t} \tag{S1}$$

Before settlement, a fraction of larvae produced in patch i disperses to contiguous patches k with probability $mpL_{i,k}$. The migration kernel $mk(x)$ has been defined by assuming that the dispersal probability to a distance x [km] has a normal shape centred on the area of origin, that is:

$$mk(x) = \frac{1}{\sqrt{2\pi}\Sigma} \exp\left(-\frac{x^2}{2\Sigma^2} \right)$$

Given the mean range of dispersal (d_L) of 90% of the larvae, the corresponding standard deviation Σ_L can been computed so as:

$$\int_{-\frac{1}{2}d_L}^{+\frac{1}{2}d_L} \frac{1}{\sqrt{2\pi}\Sigma_L} \exp\left(-\frac{x^2}{2\Sigma_L^2} \right) dx = 0.9$$

As each patch is 1 km long, by centring the migration kernel in the middle of the patch i (that therefore stretches from i-0.5 to i+0.5), the retention rate α_L (that is the fraction of individuals that remain in the same patch) can been computed as follows:

$$\alpha_L = \int_{-0.5}^{+0.5} \frac{1}{\sqrt{2\pi}\Sigma_L} \exp\left(-\frac{x^2}{2\Sigma_L^2} \right) dx$$

while the fraction $mpL_{i,k}$ of larvae produced in patch i and drifted to patch k ($k \neq i$):

$$mpL_{i,k} = \int_{|i-k|-0.5}^{|i-k|+0.5} \frac{1}{\sqrt{2\pi}\Sigma_L} \exp\left(-\frac{x^2}{2\Sigma_L^2} \right) dx \tag{S2}$$

The total number of eggs in patch *i* after dispersal is computed as follows:

$$L'_{i,t} = \sum_{k=1}^{S} L_{k,t}\, mpL_{k,i} \tag{S3}$$

If boundaries (at *i=1* and *i=S*) are permeable, a fraction of the larval recruitment is lost at the edges because of passive dispersal outside the suitable habitat.

The fraction of Larvae that successfully settle down and recruit to the first size class is assumed to be density dependent of the Beverton-Holt type, that is:

$$\sigma_0(L'_{i,t}) = \frac{\sigma_{0Max}}{1+\delta L'_{i,t}} \tag{S4}$$

where σ_{0Max} is survival at low larval density and δ a saturation constant proportional to the strength of the density dependency. The maximum number of recruits in the first size class (for $L'\rightarrow\infty$) is thus equal to σ_{0Min}/δ.

Parameters σ_{0Max} and δ of the recruitment function were computed as follows [1]:

$\sigma_{0Max} = C\, R_{\mathrm{eq}}/L_{eq}$

$\delta = (C-1)/\, L_{eq}$

where L_{eq} is the local larval abundance and R_{eq} the recruitment at the un-fished equilibrium. Although varying *C* does not change population density and structure at equilibrium, the smaller the value of *C* the lower the effect of density on larval settlement and the slower the population dynamics when perturbed (e.g., recovery towards the unfished carrying capacity after decline)

Even though the oceanographic and ecological processes driving passive larval dispersal are obviously different from those related to active fish movement, for the purpose of the present analysis we used a similar mathematical formulation to describe the movement kernel $mp_{j,i,k}$ ($k=1,..,S;\ j=1,2,3$) of juvenile (first size class) and adult (size classes 2 and 3) individuals, namely:

$$n'_{j,i,t} = \sum_{k=1}^{S} n_{j,k,t} \cdot mp_{j,k,i}$$

where $n'_{j,i,t}$ is the number of individuals in stage *j* in patch *i* after dispersal,

$$mp_{j,i,k} = \int_{|i-k|-0.5}^{|i-k|+0.5} \frac{1}{\sqrt{2\pi}\Sigma_j} \exp\left(-\frac{x^2}{2\Sigma_j^2}\right) dx$$

and the standard deviation Σ_j of the dispersal kernel in stage j is computed from the mean range of dispersal (d_j) of 90% of the individual in stage j so that:

$$\int_{-\frac{1}{2}d_L}^{+\frac{1}{2}d_L} \frac{1}{\sqrt{2\pi}\Sigma_j} \exp\left(-\frac{x^2}{2\Sigma_j^2}\right) dx = 0.9$$

Timing of the events simulated by the model is as follows: reproduction, dispersal, growth and fishing.

Fishing effort

We assume that the fishing effort $E_{i,t}$ is not uniformly distributed along the fishable area because fishermen concentrate their effort where the catch is expected to be larger, that is where biomass is more abundant. Let total effort (TE) be:

$$TE = \sum_{i=1}^{S} E_{i,t} = const. = \text{total number of boats} \qquad \text{(S5)}$$

and

$$TFB_t = \sum_{i=1}^{S} \sum_{j=2}^{3} w_j n_{j,i,t} = \text{total fishable biomass,} \qquad \text{(S6)}$$

w_i being the mean weight of organisms in size class j (if a size class/stage j is not fished, w_j was set to zero).

The number of fishing boats in patch i at time t can be thus computed as follows:

$$E_{i,t} = TE \frac{\omega_{i,t}}{\sum_{i=1}^{S} \omega_{i,t}} \qquad \text{(S7)}$$

where

$$\omega_{i,t} = \exp\left[-\varphi\left(1 - \frac{\sum_{j=2}^{3} w_j n_{j,i,t}}{\max_i\left(\sum_{j=2}^{3} w_j n_{j,i,t}\right)}\right)\right] \qquad \text{if patch } i \text{ is not in a reserve} \qquad \text{(S8)}$$

, $\omega_{i,t} = 0$ if patch i is in a reserve

and $\varphi > 0$ is a scaling parameter - the larger φ, the more clumped boat distribution is in areas with highest biomass.

Total Allowable Catch (*TAC*)

The *TAC* is computed as follows:

$$TAC_t(f_i) = \sum_{j=2}^{3}\sum_{i=1}^{S} w_j\left(1-\exp(-f_j)\right)n'_{j,i,t} \tag{S9}$$

Where $n'_{j,i,t}$ is the number of individuals in stage j in patch i after dispersal and f_j are the stage specific fishing mortalities (if a stage j is not fished, w_j is set to zero). Here we have assumed that fish in the first stage are not harvested (f_1=0) either because enforced regulations do not allows small fish harvesting or because their body size is smaller than the mesh size and thus cannot be caught in the fishing gear. As we assume that the catchability of large spawners q_3 is larger than that of individuals in stage 2 (i.e., $q_3 = k\, q_2$ with $k \geq 1$), fishing mortality f_3 suffered by big spawners at a given level of fishing effort is also larger than that in stage 2 (i.e, $f_3 = k\, f_2$). The value of fishing effort E^{MSY} and the corresponding values of mortalities f_2^{MSY} and f_3^{MSY} (= $k\, f_2^{MSY}$) that allow for the maximum sustainable yield (MSY) under traditional management were derived through numerical simulations.

The potential catch at time t (PC_t) is then equal to:

$$PC_t = \sum_{j=2}^{3}\sum_{i=1}^{S} w_j\left(1-\exp(-q_j E_{i,t})\right)n'_{j,i,t} \tag{S10}$$

If PC_t is larger than TAC_t, the length of the fishing season is reduced to a fraction z_t ($0 < z_t \leq 1$) so that the actual catch (AC_t):

$$AC_t = \sum_{j=2}^{3}\sum_{i=1}^{S} w_j\left(1-\exp(-z_t q_j E_{i,t})\right)n'_{j,i,t} = TAC_t \tag{S11}$$

where z_t can be computed numerically starting from the initial value:

$$z_t = \frac{TAC_t}{PC_t}$$

Otherwise, if $PC_t \leq TAC_t$, then $z_t=1$ and $AC_t = PC_t$.

If parameter w_j, besides differences in weight, accounts also for differences in price between size classes, then AC_t values can be interpreted as revenues.

Fish abundance $n_{j,i,t+1}$ at the end of the fishing season can be computed as follows:

$$n_{j,i,t+1} = \exp\left(-z_t q_j E_{i,t}\right) n'_{j,i,t} \quad \text{(S12)}$$

Reserve Implementation

When a reserve is implemented, fishing boats are excluded from the protected patches and thus fishing effort is set to zero within the no-take zones and fishing boats are redistributed in the fishable ground according to eqs. S7 and S8 Following on Hilborn et al.'s [2] result that in order to maintain population abundances *TAC* may need to be recalculated based only on the fraction of the population that can be fished, instead of the total population inside and outside the marine reserve, we calculate *TAC* in two alternative ways. In the first case, *TAC* is computed with eq. S9 as a fraction of the total biomass inside and outside reserves. In the second case, eq. S9 is modified so that *TAC* is computed only on the biomass outside reserves.

Environmental Stochasticity.

Environmental variability and uncertainty in parameter estimation were explicitly accounted for in the model. We simulated environmental stochasticity with two alternative assumptions on the probability distribution function used to draw values of model parameters at each time step:

1) following Stefansson and Rosemberg [3], we used a bias-corrected longnormal multiplicative error for the model parameter *mp* reported in Table 1 – including fishery parameters - namely $mp_s = mp_m \cdot \exp(\varepsilon_{mp} - \sigma^2_{mp}/2)$ where mp_m the mean expected value, ε_{mp} is a normal deviate with mean zero and standard deviation σ_{mp} and the parameters bounded between 0 and 1 (such as annual survival and transition probabilities) log transformed to compute instantaneous rates before multiplying them with the lognormal multiplicative error, and then back transformed in their natural scale. σ_{mp} was calibrated so that model parameters were characterized by 30% coefficient of variation.
2) In the alternative, we run simulations by using a truncated beta distribution with mean corresponding to the value of model parameters reported in Table 1, minimum and maximum value equal to ±50% of the mean value and coefficient of variation set to 30% for all model parameters (unless reported otherwise in Table 1). The minimum and

maximum range of variation for survival in size classes 1, 2 and 3 were identified by log transforming survivals so as to guarantee that random deviates were bounded between 0 and 1. To simulate uncertainty in stock assessment and year-to-year variability in fishery operations, we used a truncated beta distribution also to draw annual values of: the catchability coefficients q_j, the degree of effort aggregation φ, and the fishable biomass in size classes 2 and 3 used to derived the TAC (coefficient of variation set to 30% for all these parameters).

While the actual value of the metrics used to assess fishery performance under different management regimes obviously changed depending upon the approach used to simulate environmental stochasticity (namely, a bias-corrected longnormal multiplicative error vs a truncated beta distribution), the trends in fishery performance as a function of protection level of the fishing ground, number and size of MRs, dispersal distance in the larval or juvenile/adult phase, incremental gain in reproductive output of large spawners, fishing mortality used to compute the TAC, Goodyear compensation ratio, etc. were not affected by the choice of the distribution function used to draw values of model parameters for the stochastic simulations. Therefore, we reported the results obtained by using a truncated beta distribution.

Values of model parameters were drawn each year from their respective probability distribution function and the same sequence of year-to-year environmental variability in the demographic parameters was used to simulate population dynamics under conventional quota management and MR implementation.

For each management scenario, we set the initial population density to the value corresponding to a population managed with a conventional TAC-regulated fishery (no MPA) at MSY. As in this specific study we were interested in assessing long term fishery performances and contrasting them with that of Hilborn et al. (2006) and other theoretical studies, after MRs were implementated we run the model for additional 70 year burn-in period and then assessed population performance over a 10 year period replicated 500 times. Because high year to year variability may mask differences in fishery performance (see Table S2, Fig. S4-5), we computed the mean catch and stock biomass over a 10 year period for each management scheme and then computed the fraction of time, over 500 replicates, in which catch (stock biomass) under MRs implementation was larger or smaller than MSY (stock biomass at MSY) under conventional quota management. Results for the MRs fishery management regimes were reported, unless stated otherwise, as relative increase (when positive) or decrease (when negative) of mean catch and mean stock biomass over the 10 year interval with respect to the same metrics for a conventional TAC-regulated fishery (with no MRs).

Simulation results were used also to compute quasi-extinction probabilities and, specifically, the probability that the population drops below 10% or 20 % the unfished carrying capacity (here taken as thresholds for population collapse and decline respectively, the latter coinciding with the limit reference point for most fisheries under management in the developed world) in a 10 year period.

Appendix S2: Derivation of the stock-recruitment parameters of larval survival as a function of population carrying capacity and the Goodyear compensation ratio

Here we show how the parameters σ_{0Max} and δ of the stock-recruitment relationship $\sigma_L(L)$ describing larval survival, settlement and recruitment in stage n_1 can be derived for any assigned value of population carrying capacity K at the unfished equilibrium and the Goodyear compensation ratio GCR. The general model describing the dynamics of an unfished population is the follows:

$$\begin{aligned}
n_{1,t+1} &= \sigma_L(L_t)L_t + (1-\gamma_1)\sigma_1 n_{1,t} \\
n_{2,t+1} &= \gamma_1\sigma_1 n_{1,t} + (1-\gamma_2)\sigma_2 n_{2,t} \\
n_{3,t+1} &= \gamma_2\sigma_2 n_{2,t} + \sigma_3 n_{3,t} \\
L_t &= \phi_1 n_{1,t} + \phi_2 n_{3,t} + \phi_3 n_{3,t}
\end{aligned}$$

At the long-term equilibrium, $n_{j,t+1} = n_{j,t} = n_j$ (j=1,2,3) and the population reaches a stable stage distribution with:

$$\begin{aligned}
n_2 &= \frac{\gamma_1\sigma_1}{1-(1-\gamma_2)\sigma_2} n_1 \\
n_3 &= \frac{\gamma_2\sigma_2}{1-\sigma_3} n_2 = \frac{\gamma_2\sigma_2}{1-\sigma_3} \frac{\gamma_1\sigma_1}{1-(1-\gamma_2)\sigma_2} n_1
\end{aligned}$$

In addition, at the long term equilibrium $n_1 + n_2 + n_3 = K$, where K is the unfished carrying capacity. Therefore, given K, we can derive n_1 as follows:

$$n_1 = \frac{K}{1 + \frac{\gamma_1\sigma_1}{1-(1-\gamma_2)\sigma_2} + \frac{\gamma_2\sigma_2}{1-\sigma_3} \cdot \frac{\gamma_1\sigma_1}{1-(1-\gamma_2)\sigma_2}}$$

and, then, compute n_2 and n_3 accordingly.

We can now compute the abundance of larvae L_{eq} at the long term equilibrium, namely:

$$L_{eq} = \phi_1 n_1 + \phi_2 n_3 + \phi_3 n_3$$

The value of larval survival at the long term equilibrium is computed from the equation describing the dynamics of the first size class n_1, namely:

$$\sigma_L(L_{eq}) = \frac{[1-(1-\gamma_1)\sigma_1]n_1}{L_{eq}} \ .$$

According to Walters et al. (2007), the Goodyear compensation ratio is the ratio of maximum larval survival at low density (σ_{0Max}) to survival at un-fished natural abundance, i.e. $\sigma_L(L_{eq})$. As larval survival is describe by the Beverton-Holt function, it follows that:

$$GCR = \frac{\sigma_{0Max}}{\sigma_L(L_{eq})} = 1 + \delta L_{eq} \ .$$

Therefore, given the values of GCC and K, we can derive δ as follow:

$$\delta = \frac{GCR - 1}{L_{eq}} \ .$$

Finally, as:

$$\frac{\sigma_{0Max}}{1 + \delta L_{eq}} = \sigma_L(L_{eq})$$

we can solve this equation for σ_{0Max}, namely:

$$\sigma_{0Max} = (1 + \delta L_{eq}) \cdot \sigma_L(L_{eq}) = GCR \cdot \sigma_L(L_{eq}) \ .$$

Appendix S3: Size-fecundity relationship

According to Fishbase (www.fishbase.org), the ratio between maximum length and length at sexual maturity for several rockfish species (such as Canary, Bocaccio, Cowcod fish, Darkblotched rockfish, Pacific Ocean Perch) as well invertebrates (such as the abalone spp.), typically ranges between 1.5 and 2.5 with a mean around 2. For some species, such as the California spiny lobster, this ratio can be substantially larger, as maximum length (about 30 cm) is five times the size at sexual maturity (between 60-80mm). Assuming that fecundity (that is usually proportional to body mass) scales allomerically with body length to the power 3 (and in some cases substantially more, for instance: 5.68-6.24 for haddock *Melanogrammus aeglefinus* [4]; 5.28 for spanish flag snapper *Lutjanus carponotatus* [5]; 4.37 for the Atlantic cod *Gadus morhua* [6], 3.16 for southern rock lobster *Jasus edwardsii* [7]), the fecundity of an old, larger individual can be from 5 to 60 times larger than the individual of the same species at size of sexual maturity. For green and pick abalone, for instance, fecundity increases linearly with body mass [8,9] and body mass increases with $L^{3.36}$ for *Haliotis fulgens* and $L^{3.50}$ for *Haliotis corrugata* [10]: therefore, doubling abalone length from size at sexual maturity to that of a large spawner implies a ten-fold increase in per-capita fecundity from ca. 800 thousand to ca. 8.2 million eggs [11].

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Table S1

Coefficient of variation of the long term population and catch measured in biomass (unless stated otherwise). Model parameterized as in Table 1 with 50 km larval dispersal (retention rate 3%) and 1 km juvenile/adult dispersal (retention rate 90%), fishing effort $TE = 3 \cdot TE^{MSY}$ and fishing mortality $f = f^{MSY} = qE^{MSY}$; in the MR regime, 36% of habitat is protected and divided in 4 marine reserves of 9 km each.

	Year to year coefficient of variation	Coefficient of variation of cumulated catch and mean biomass over a 10 year period replicated 500 times
Long term unfished population		
Biomass	25%	19%
Abundance	28%	21%
Yield		
Conventional quota management (MSY)	52%	30%
TAC computed on the whole stock	46%	25%
TAC computed only on the stock outside MRs	48%	25%
Stock [Biomass] for a harvested population		
Conventional quota management	33%	25%
TAC computed on the whole stock	28%	19%
TAC computed only on the stock outside MRs	26%	18%

Table S2

Results of sensitivity analyses investigating effects of different assumptions on the fish mortality used to set the TAC, the range of fish dispersal (*rd*) and the number/size of MRs and level of protection in the case of adult dispersal. Results are reported as % increase of decrease with respect to conventional quota management. The reference case (RC) corresponds to the model parameterized as in Table 1, with 50 km larval dispersal (retention rate 3%), all the other parameters as in Table 1. In the reference case, fishing mortality $f = f^{MSY} = qE^{MSY}$; 36% of habitat is protected and divided in 4 marine reserves of 9 km each, adult dispersal rate is 1km (90% retention). The outcome corresponding to the reference case is reported in *Italic*.

a) Sensitivity analysis on fishing mortality

	TAC computed on the whole stock		TAC computed only on stock outside MRs	
	ΔBiomass (%) ± S.D.	**ΔCatch (%) ± S.D.**	**ΔBiomass (%) ± S.D.**	**ΔCatch (%) ± S.D.**
$f = 0.8 \cdot f^{msy}$	17.96 ± 6.40**	15.67 ± 7.29**	47.81 ± 9.36**	-18.34 ± 5.26 *
$f = f^{msy}$	*33.94 ± 11.40***	*19.71 ± 11.37***	*65.83 ± 15.06***	*-10.00 ± 8.45 n.s.*
$f = 1.25 \cdot f^{msy}$	63.73 ± 23.04**	31.62 ± 18.79**	97.58 ± 28.45**	5.59 ± 15.52 n.s.
$f = 1.50 \cdot f^{msy}$	100.5 ± 38.89**	48.61 ± 30.39**	135.6 ± 46.47**	25.07 ± 25.66 n.s.

b) Sensitivity analysis on fish movement, i.e. the range of dispersal rd of 90% of the larvae

	TAC computed on the whole stock		TAC computed only on stock outside MRs	
	ΔBiomass (%) ± S.D.	**ΔCatch (%) ± S.D.**	**ΔBiomass (%) ± S.D.**	**ΔCatch (%) ± S.D.**
rd = 1 km	*33.94 ± 11.4***	*19.7 ± 11.37***	*65.83 ± 15.06***	*-10.0 ± 8.45 n.s.*
rd = 5 km	14.40 ± 5.69**	11.8 ± 5.59**	54.37 ± 12.13**	- 7.75 ± 7.43 n.s
rd = 10 km	6.38 ± 2.76**	6.13 ± 2.70**	47.86 ±10.61**	- 6.26 ± 6.91 n.s.
rd = 15 km	4.14 ± 1.80**	4.29 ± 1.79**	45.45 ± 10.18**	- 5.28 ± 6.7 n.s.
rd = 20 km	3.29 ± 1.50**	3.50 ± 1.47**	44.81 ± 10.36**	- 4.41 ± 7.03 n.s.
rd = 25 km	1.86 ± 0.77 **	2.18 ± 0.84**	34.65 ± 7.021**	-11.18 ± 4.83*
rd = 50 km	2.14 ± 0.90**	2.41 ± 0.93**	40.98 ±10.83**	- 6.61 ± 7.26 n.s.
rd =100km	4.14 ± 2.38**	4.29 ± 2.34**	78.32 ±52.78**	15.9 ±34.23 n.s.

c) Sensitivity analysis on number of marine reserves and level of protection in the case of fish movement (rd=25 km), in addition to larval dispersal (50km). Reference case has 4 marine reserves

	TAC computed on the whole stock		TAC computed only on stock outside MRs	
	ΔBiomass (%) ± S.D.	**ΔCatch (%) ± S.D.**	**ΔBiomass (%) ± S.D.**	**ΔCatch (%) ± S.D.**
4 MPA 36%	*1.86 ± 0.77 ***	*2.19 ± 0.84***	*34.65 ± 7.02***	*-11.18 ± 4.83**
3 MPA 36%	2.91 ± 1.12**	3.45 ± 1.20**	36.80 ± 7.51**	-11.78 ± 5.03*
2 MPA 36%	5.13 ± 1.96**	6.03 ± 2.05**	40.95 ± 8.47**	-12.96 ± 5.38*
1 MPA 36%	8.74 ± 4.91**	7.05 ± 5.15ns	49.28 ±10.6**	-17.81 ± 5.59**
1 MPA 30%	4.53 ± 3.18*	5.94 ± 3.28*	40.63 ± 8.85**	-11.74 ± 5.35*
3 MPA 42%	3.95 ± 1.56**	4.31 ± 1.64**	43.23 ± 8.77**	-16.53 ± 5.34**

d) Sensitivity analysis with respect to different assumptions on the error in stock assessment and estimation of the TAC

cv(TAC)=15 %	*29.62± 9.893*	*20.01 ± 10.69*	*63.58 ±13.37*	*-11.18 ± 7.699*
cv(TAC)=30%	*33.94 ± 11.40***	*19.71 ± 11.37***	*65.83 ± 15.06***	*-10.00 ± 8.45 n.s.*
cv(TAC)=40%	*34.77 ± 13.95*	*18.9 ± 13.5*	*64.98 ± 17.38*	*-10.19± 9.592*

Fig. S1

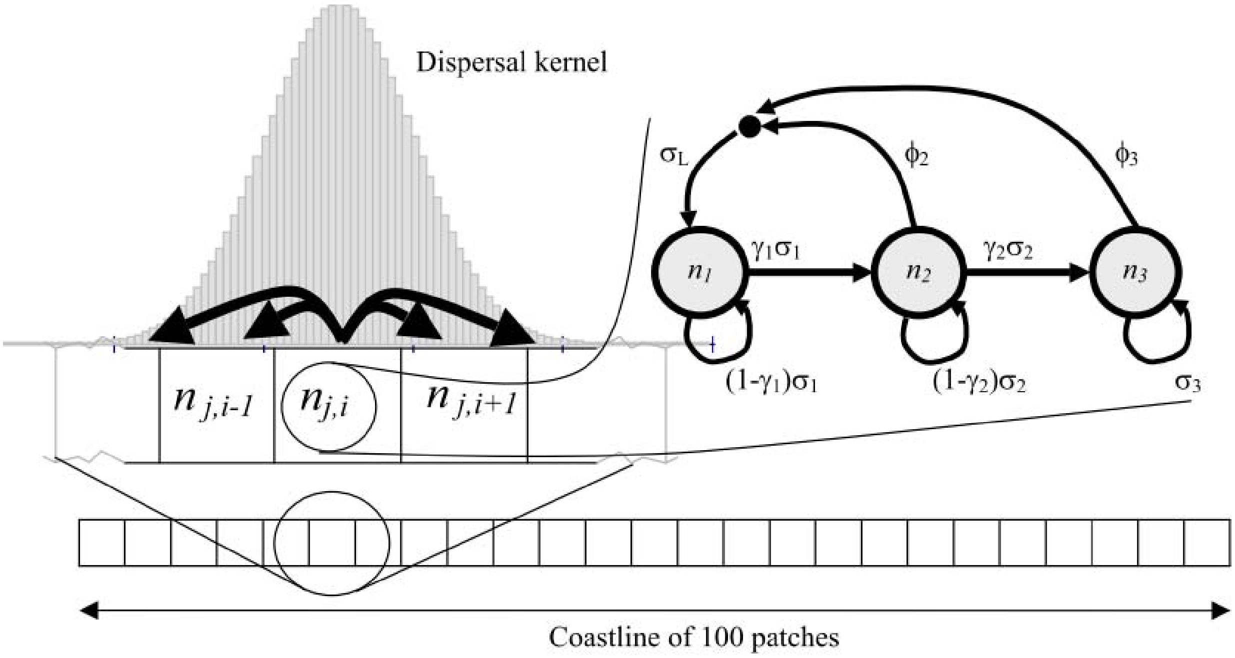

Fig. S1 - A schematic representation of the stage structured, spatially explicit demographic model.

Fig. S2

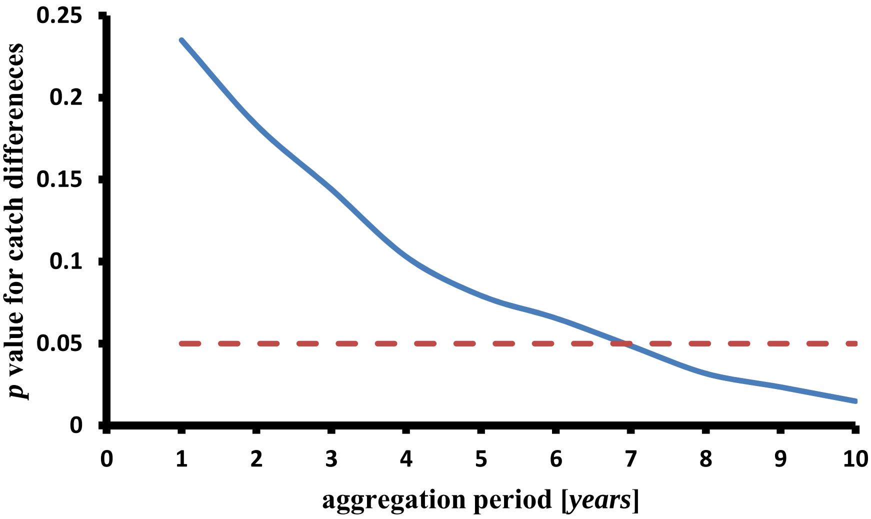

Fig. S2 – Level of significance of the difference between catch with a network of marine reserves in a TAC overcapitalized fishery and catch at MSY under conventional management as a function of the period of aggregation, significance level of the difference in cumulated catch over 1, 2… 10 years. The red dashed line corresponds to the canonical significance level at p=0.05. For values of p larger than 0.05 the null hypothesis cannot be rejected. Model parameters set as in Table 1; larval dispersal range: 50km; adult dispersal range: 1km; fishing mortality to compute the quota equal to f_{msy} ; total effort TE= $3E_{msy}$; TAC computed over the whole stock inside and outside MRs. Significance calculated as the fraction of times, over 500 replicates, in which the n-year average catch (n=1..10) with MR implementation was larger than the catch averaged on the same period for a conventional fishery at MSY. Figure shows that year to year environmental variability masks differences in fishery performances between alternative fishery schemes. When catches are averaged out over a sufficient number of years, yield of a fishery management scheme that includes also MRs is significantly larger than that of a conventional fishery at MSY.

Fig. S3

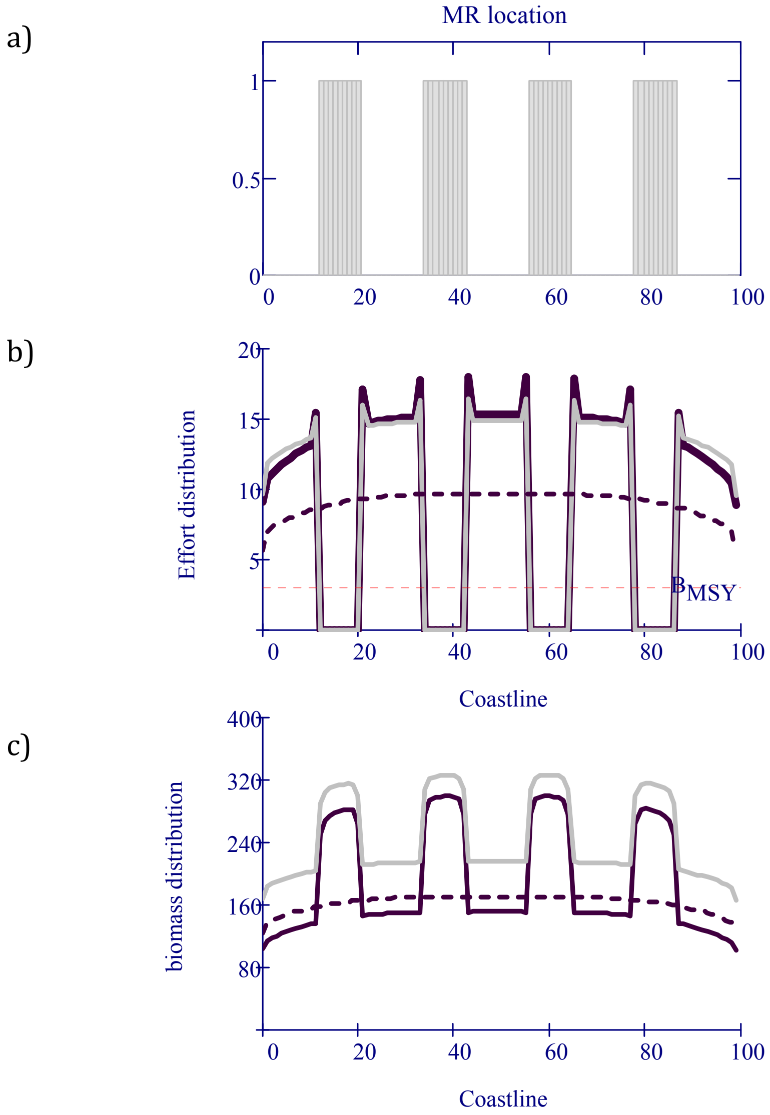

Fig. S3 – a) Distribution of 4 MRs of 9 km each along a 100km coastline (36% protection level). b) Spatial distribution of fishing effort along the coastline and c) the distribution of fish stock: the dashed line represents case of conventional quota management for an overcapitalized fishery where $TE=3E_{msy}$; the black line the case of a TAC-regulated fishery where the TAC is computed on the whole stock inside and outside MRs; the grey line the case of a TAC-regulated fishery where the TAC is computed only on the stock outside MRs. The red dotted horizontal line in panel (b) represents the level of effort sufficient to guarantee the maximum sustainable yield. Model parameters as in Table 1 for a population with a 50km average larval dispersal and sedentary adults. Fig. S2b clearly shows the "fishing the line" phenomenon [12], i.e. effort aggregation at the MR boundaries

Fig. S4

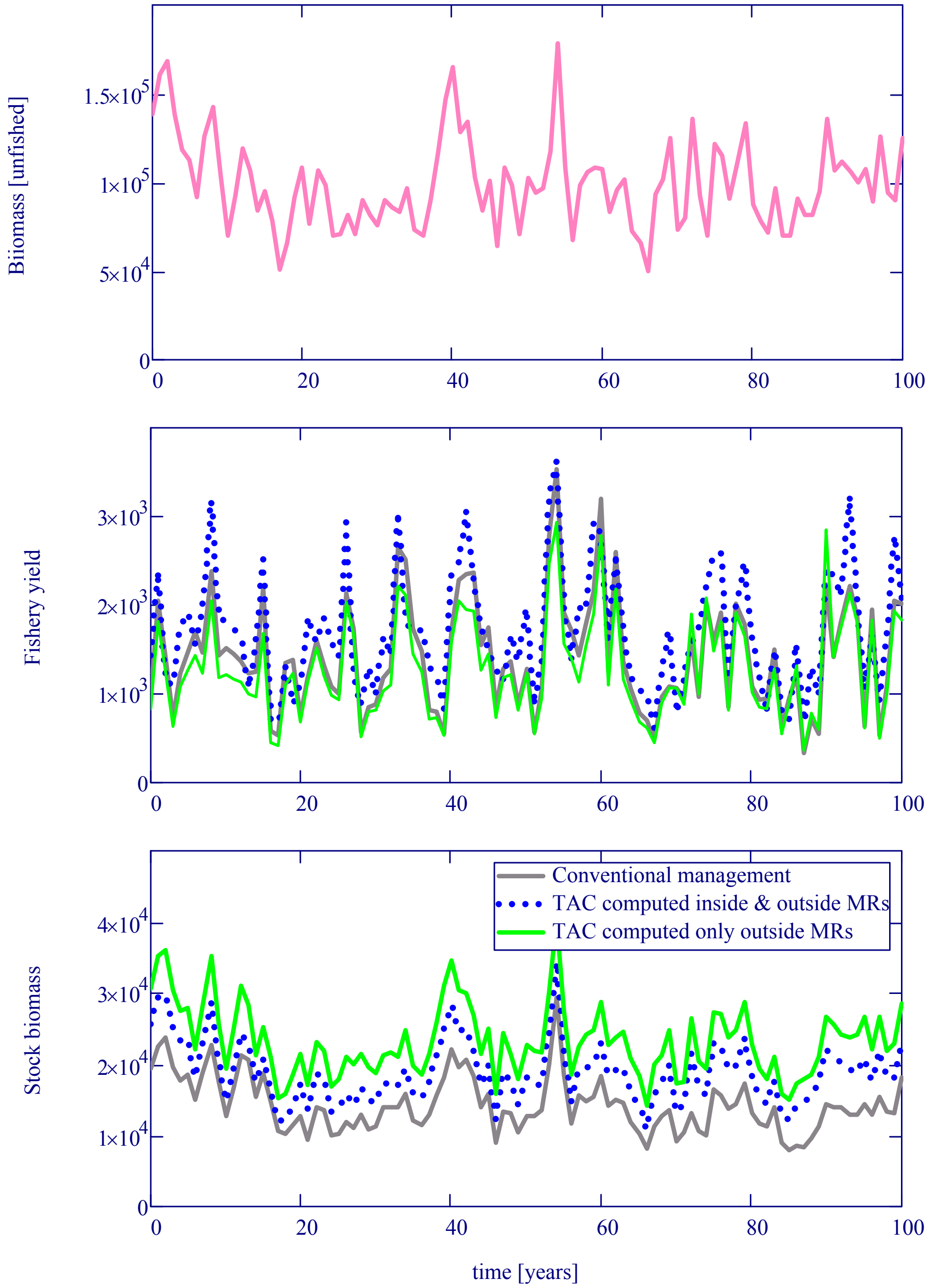

Fig. S4 – A stochastic realization of population dynamics of the unfished population (panel a, pink line) and of catch (panel b) and biomass (panel c). The grey line corresponds to the case of a TAC regulated fishery with conventional quota management, the blue dotted line of a TAC regulated fishery with a network of 4 MRs on 9 km each where the TAC in computed over the whole stock inside and outside MRs; the green line as the previous case but the TAC is computed only on the catch outside MRs. Model parameters as in Table 1 for a population with a 50km average larval dispersal, sedentary adults and 4 MRs of 9 km each (for a total of 36% of the fishing ground set aside in MRs).

Fig. S5

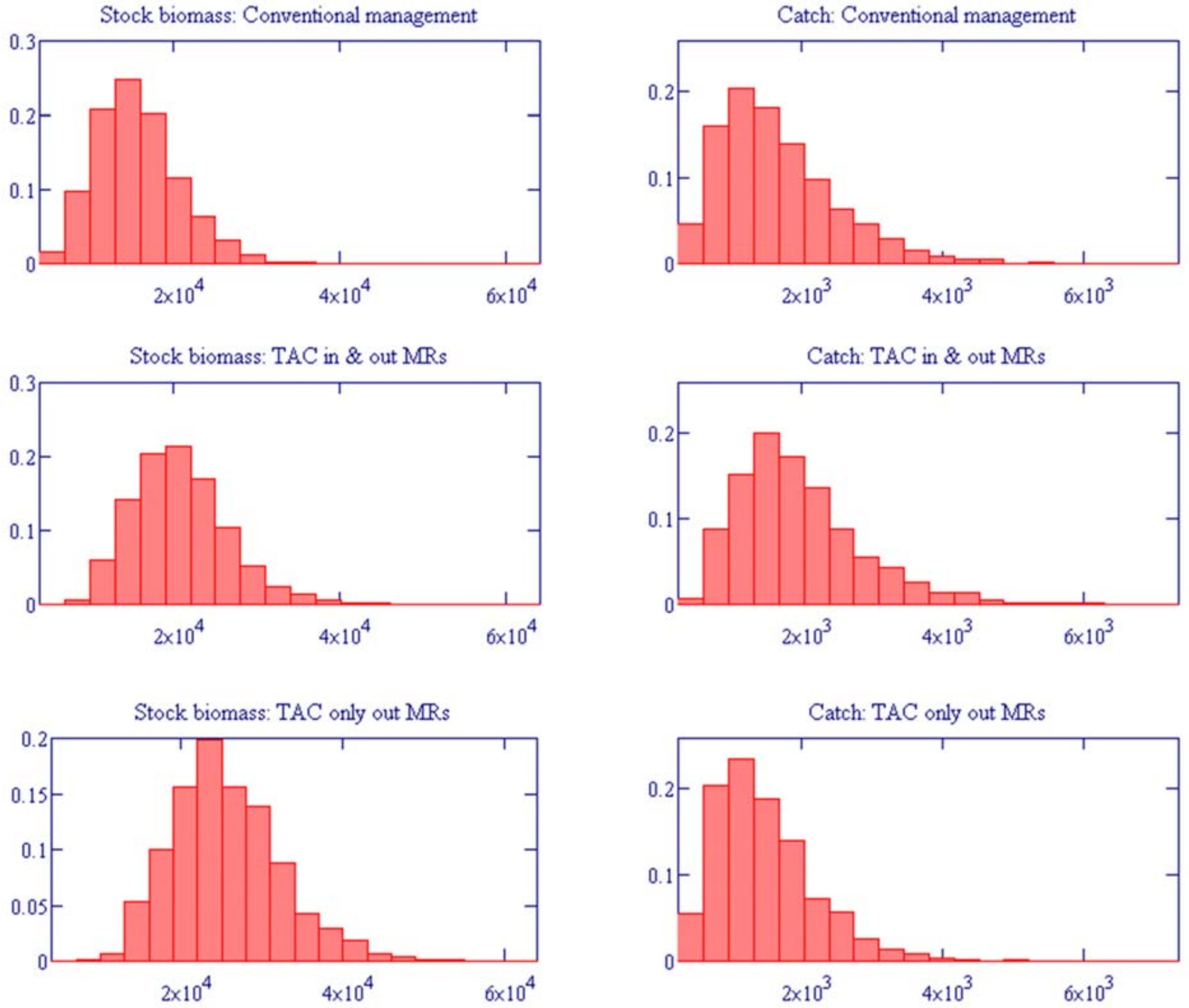

Fig. S5 – Probability density distribution of biomass and catch as derived through stochastic simulations corresponding to a model parameterized as in Table 1, 50km larval dispersal distance and 4 MRs of 9 km each (for a total of 36% of the fishing ground set aside in MRs).

Fig. S6

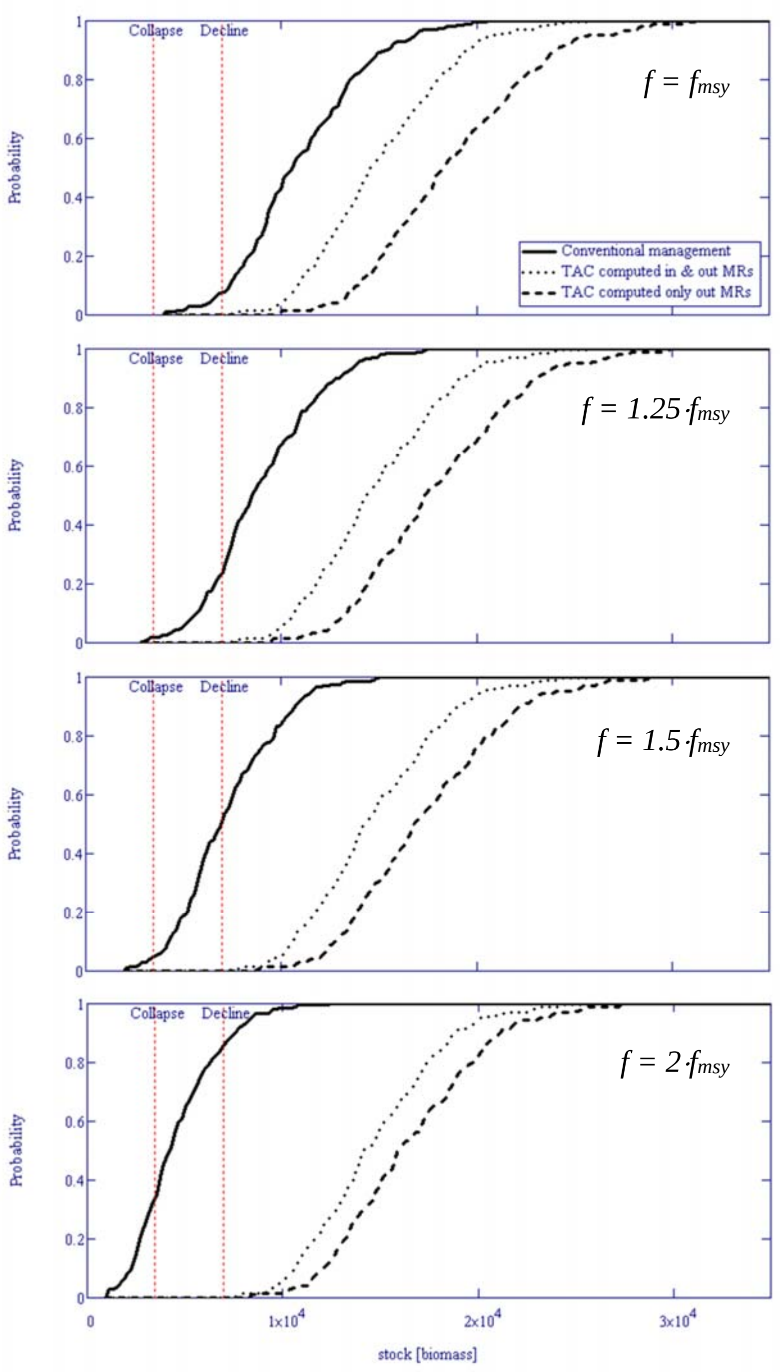

Fig. S6 – Quasi-extinction threshold, i.e. probability (vertical axis) that the population drops below a given density threshold (horizontal axis) in a 10 year period. Panels report the results of stochastic simulations for increasing levels of fishing mortality. Continuous line: conventional TAC regulated fishery(no MRs); dotted line: TAC regulated fishery where the TAC is computed on the whole stock inside and outside MRs; dashed line: TAC regulated fishery where the TAC is computed only on the stock outside MRs. The two vertical red dotted lines identify threshold density for population collapse (10% of the mean unfished carrying capacity) and decline (20% of the mean unfished carrying capacity). Model parameterized as in Table 1, 50km larval dispersal distance and 4 MRs of 9 km each (for a total of 36% of the fishing ground set aside in MRs)