The economic value of environmental data: A notional insurance scheme for the European anchovy

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Abstract

Anchovy population dynamics in the Gulf of Cádiz are governed by environmental processes. Sea surface temperature, intense easterly winds and discharges from the Guadalquivir River have been identified as key factors determining early life stage mortality in this anchovy stock. We have constructed an environment-based recruitment model that simulates the abundance of juveniles under alternative parameters representing plausible biological hypotheses. We are able to evaluate how modelling environment-based recruitment can affect stock assessment and how responding to environmental information can benefit fishery management to allow greater average catch levels through the application of harvest control rules based on environmental conditions. While the environment-based rules generally increase allowable catch levels the variance in catch levels also increases, detracting from the improved value based only on average yield. In addition to changes in revenue, the probability of stock collapse is also reduced by using environmental factors in harvest control rules. To assess the value of these management systems we simulate a notional insurance scheme, which applies a value to both average yields and uncertainty. The value of the

information-driven rules can be determined by comparing the relevant premiums payable for equal levels of insurance cover on revenue within each specific management regime. We demonstrate the net value of incorporating environmental factors in the management of anchovies in the Gulf of Cádiz despite the increased variability in revenue. This could be an effective method to describe outcomes for both commercial fisheries and ecosystem management policies, and as a guide to management of other species whose dynamics are predictable based on in-season observations.

Introduction

The state of European anchovy (*Engraulis encrasicolus*) in the Gulf of Cádiz is described by ICES (2012) as "not known precisely because of the inadequacy of the available information to evaluate the spawning stock or fishing mortality relative to risk" of overfishing. Data limitations are compounded by large inter-annual fluctuations in abundance and the high dependence upon recruitment which is unpredictable using traditional stock-recruitment relationships that do not account for variability in environmental factors (Ricker or Beverton-Holt models).

The great variability of the stock has led to several attempts to understand the mechanisms that govern anchovy population dynamics. Important results were presented by Ruiz et al. (2006) reiterating the importance of environmental forcing when modelling small pelagic fisheries dynamics (Fréon et al., 2005) and identifying the sea surface temperature (SST), intense easterly winds and discharges from the Guadalquivir River as the main influences on early life stage mortality for the Gulf of Cádiz anchovy stock.

Ruiz et al. (2009) describe a Bayesian population model that links environmental covariates to anchovy recruitment dynamics. Using that population dynamics structure it is possible to evaluate different harvest control rules by simulating long series of catches under diverse environmental scenarios. This approach is a form of management strategy evaluation (MSE), pioneered by the International Whaling Commission (Kirkwood, 1997; Butterworth and Punt, 1999; Kell et al., 1999, 2005), which has been used widely in fisheries (Kell et al., 2007). The complexity of the modelling frameworks for MSE varies from simple single species production models to models that encompass entire ecosystems, such as the Atlantis platform (Fulton et al., 2011; Kaplan et al., 2012; Smith et al., 2014). The model employed in this study fits within a class of Minimum Realistic Models (Plaganyi and Butterworth, 2012; Plaganyi et al. 2012) because it includes only a few environmental processes and their effect on a single species. The economic part of the model is also simple, presuming a homogeneous fleet with constant prices independent of the local catch. The focus of the study is on issues pertaining to an unusually dynamic species and the advantages that can be gained from modelling and understanding dynamics on a fine (in this case, weekly) timescale. This paper shows how knowledge of environmental conditions could be used to improve in-season management in stocks that are highly dependent on easily monitored environmental variables and how the resulting uncertainties could be accounted for in valuing improved management.

An Environmental Harvest Control Rule (EHCR), using scientific knowledge of environmental parameters to estimate the likely occurrence of unusually large year classes of anchovy, can be simulated to demonstrate how catch levels could change compared to fixed catch rules. An EHCR would respond to unfavourable conditions by reducing fishing pressure on the affected year class. This is a novel approach, that differs from the management strategy applied to anchovy in the Gulf of Cádiz over the last ten years, which sets an annual threshold for catches (TAC) based on surveys and 17-year averages of the recorded landings (ICES, 2012). A more variable harvest control rule, compared with a relatively fixed allowable catch level, is likely to result in more variable returns to fishermen, which should be accounted for along with the value of additional catch potential in evaluating the overall impact of a new regime.

Insurance policies have been widely used in agriculture to reduce risk to farmers, but the cost of insurance is also an effective measure of the value of risk. In fisheries, insurance policies are very hard to implement with current regulations (Greenberg et al., 2004) but they could be used as a theoretical tool to measure the efficiency with which different harvest control rules (HCR) deal with economic uncertainty. A comparison of the economic value of both approaches to the Gulf of Cádiz anchovy management, those that use the knowledge of the dependencies between environment and recruitment and management rules that do not, is complicated by the difference in uncertainty on revenues that goes with changes in the mean yield. The overall value, including the implied costs of uncertainty, can be compared using a simulated insurance scheme following Mumford et al. (2009). This concept of notional insurance pricing has also been used to value uncertainty in relation to climate change measures (Marland et al., 2014). Calculating the difference in required premiums under the hypothetical insurance scheme allows the value of using environmental information to be calculated.

Material and Methods

The main step of the MSE process is to construct a simulation model that captures the most relevant features of population dynamics and management. In this section we present a general description of the population dynamics, the model assumptions and sources of data upon which it was conditioned, and finally we give definitions of the scenarios and criteria to evaluate relative performance of the harvest control rule that takes advantage of the environmental information (EHCR). A more complete description of the model is found in the appendix.

Environmentally-forced population dynamics

To simulate anchovy dynamics, it is necessary to understand the environmental processes behind early-stages anchovy survival in the Gulf of Cádiz (Figure 1). Before recruitment, stock dynamics are mainly driven by the variable environment, and after that it is mainly determined by fishing mortality (Ruiz et al., 2006, 2009).

Pre-recruit survival is highly affected by the wind and the discharges from the Guadalquivir River (Ruiz et al., 2006) while spawning depends mainly on SST (Motos et al., 1996; García and Palomera, 1996). Spawning can be assumed to follow a weekly time scale taking place when a minimum of 16°C SST is reached and an increase of at least a quarter of a degree occurs from one week to another, consistent with the increase of a degree per month considered by Ruiz et al. (2009). These conditions hold with higher probability from May to September when individuals from nine to twenty-four months old could spawn up to four times per month.

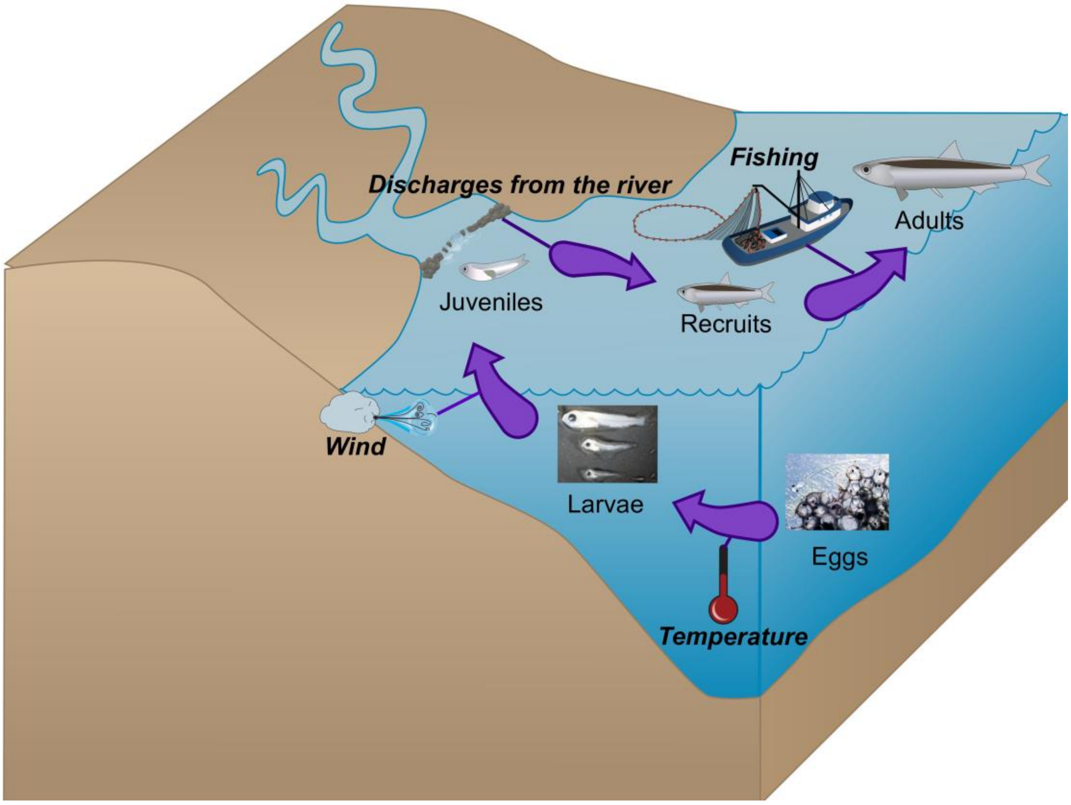

Figure 1: Diagram of anchovy life-cycle in the Gulf of Cádiz including environmental factors affecting different life stages. Courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

When spawning occurs the eggs and larvae can be advected by the effect of easterly winds on currents, which have a negative impact on survival (Ruiz et al., 2006). The effect of advection is considered negligible on juveniles more than three months of age, when the first juveniles are able to swim and better control their position. These first juveniles are affected by freshwater regulation in the Alcalá del Río reservoir during the following two months of development, with a positive effect on survival when discharges are close to an optimum value of 100 hm^3 per month, major deviations in either direction affect survival negatively (Ruiz et al., 2009).

This response to river discharges and wind is a consequence of the different habitats the anchovy occupy during their life cycle. In the egg and larval stages individuals are very vulnerable to currents that advect them from the favorable conditions of the shelf towards offshore waters where survival is poor. In the northern shelf of the Gulf of Cádiz these strong currents are the result of intense easterly events (Ruiz et al., 2006). With further development, juvenile stages of anchovy are able move towards the estuary or its influence area at the inner shelf. Discharges have a dual effect on these stages depending on the level of fresh water being introduced in the estuary. Low levels of fresh water discharges constrain primary productivity of the shelf limiting the food supply for juveniles (Prieto et al. 2009), while Ruiz et al. (2009) pointed out that very high discharges cause low salinities in the estuary. Anchovy juveniles cannot survive these low salinities and must leave the protective environment of the estuary, thus reducing recruitment. However, discharges in periods significant for recruitment success have historically been relatively stable and thus had little influence over recruitment variability.

Individuals that have survived for five months are considered recruits and are included in the stock because of their availability to the fishery. The Gulf of Cádiz anchovy fishery corresponds to the ICES Sub-division IXa South and it is mainly exploited by single purpose purse seiners. Since 1999 the number of Gulf of Cádiz purse seiners has oscillated between 145 (in 2004) and 82 (in 2014) vessels (ICES, 2012, 2014). Fishing for anchovy usually begins in March and ends in November with the majority of the catch taken in spring (about 80% of the annual catch, Uriarte et al. 1996).

Assumptions for environmentally-sensitive Harvest Control Rule

Anchovy recruitment has been shown to be affected by the environment, and this knowledge is used here to test a harvest control rule. Based on literature review and discussions with experts we simulated dynamics that are largely dependent on strong easterly winds. Survival of juveniles is highly sensitive to the number of windy days at the lower end of the scale, hence seasons with few windy days coincide with exceptionally high survival resulting in larger cohorts (Figure 2, left panel). The modelled impact of discharges on survival is substantial, but more constant from season to season with less impact on variability of cohort sizes than the wind (Figure 2, right panel). These features suggest the use of harvest control rules in which allowable fishing mortality can be modified by taking into account wind conditions in the months preceding anchovy recruitment, but ignore the effects of discharges.

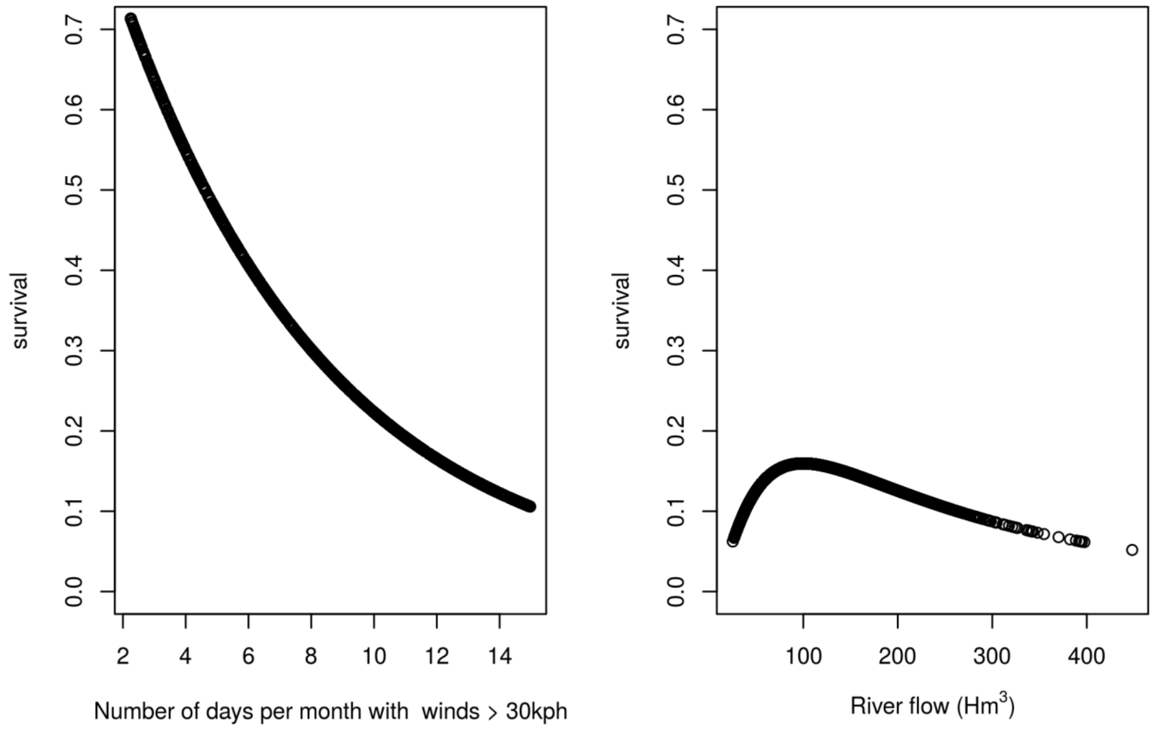

Figure 2: Left: Effect of strong easterly winds on survival after one month for 1000 values of simulated wind values. Right: Effect of discharges on survival after 1 month for 1000 values of simulated discharges.

For the environmental harvest control rule, a default monthly fishing mortality $F* = 0.04$ is modified once each year according to the number of days strong easterly winds blow (> 30 kph) from May to September in the previous year. The modified fishing mortality is applied each month from March to October.

The rule to modify F^* is that the fishing pressure is reduced linearly from $2F^*$ to $F^*/2$, the default value F^* is reached when the number of windy days over five months is average (that is five times monthly wind average $\mu W = 8.62$ based on a uniform distribution derived from ranges in historical observations, see appendix for more explanation) (Figure 3).

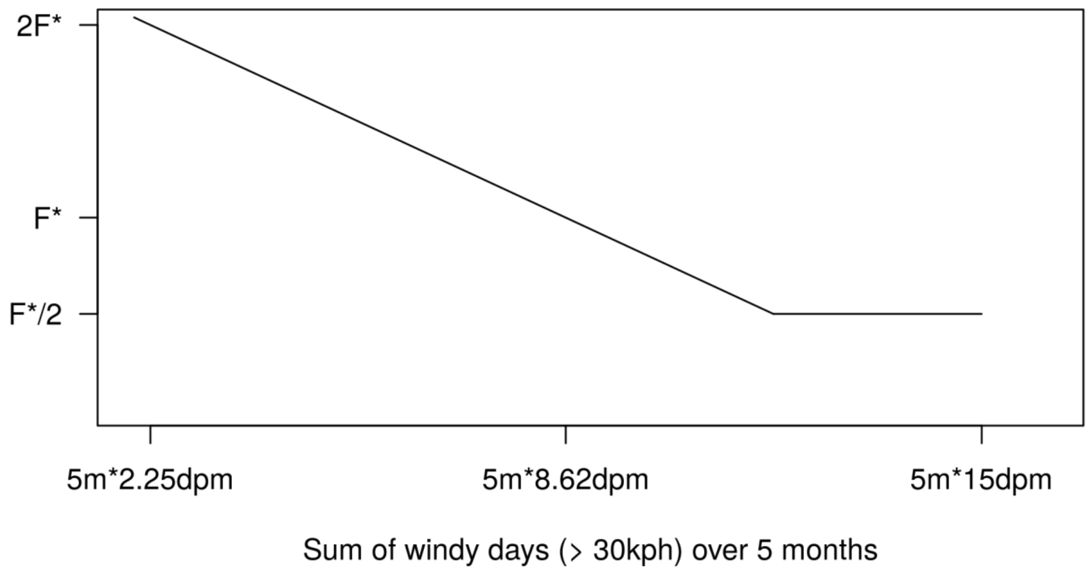

Figure 3: Fishing pressure of the EHCR as a function of the number of windy days during the five months (May to September) with highest proportion of juveniles younger than 3 months. The number of easterly windy days per month (dpm) is uniformly distributed on the interval [2.25,15]. The average number of windy days per month is 8.62, the average number of the easterly windy days for the entire period is 5 m*8.62 dpm.

Insurance scheme

An effective environmentally-based harvest control rule may increase the mean catch, but with greater variability than under a fixed rule. Insurance pricing is a mechanism to demonstrate the value of the increased mean while accounting for the possible added risk of more variable catches.

The values for insurance compensations and premiums are calculated from the simulations of the population dynamics model as depicted in Figure 4. The insurance scheme is used only as a means to demonstrate the value of information used in the harvest rules, it is not a proposal for actual insurance in the anchovy fishery. See Mumford et al, 2009 for a more detailed description of insurance calculations.

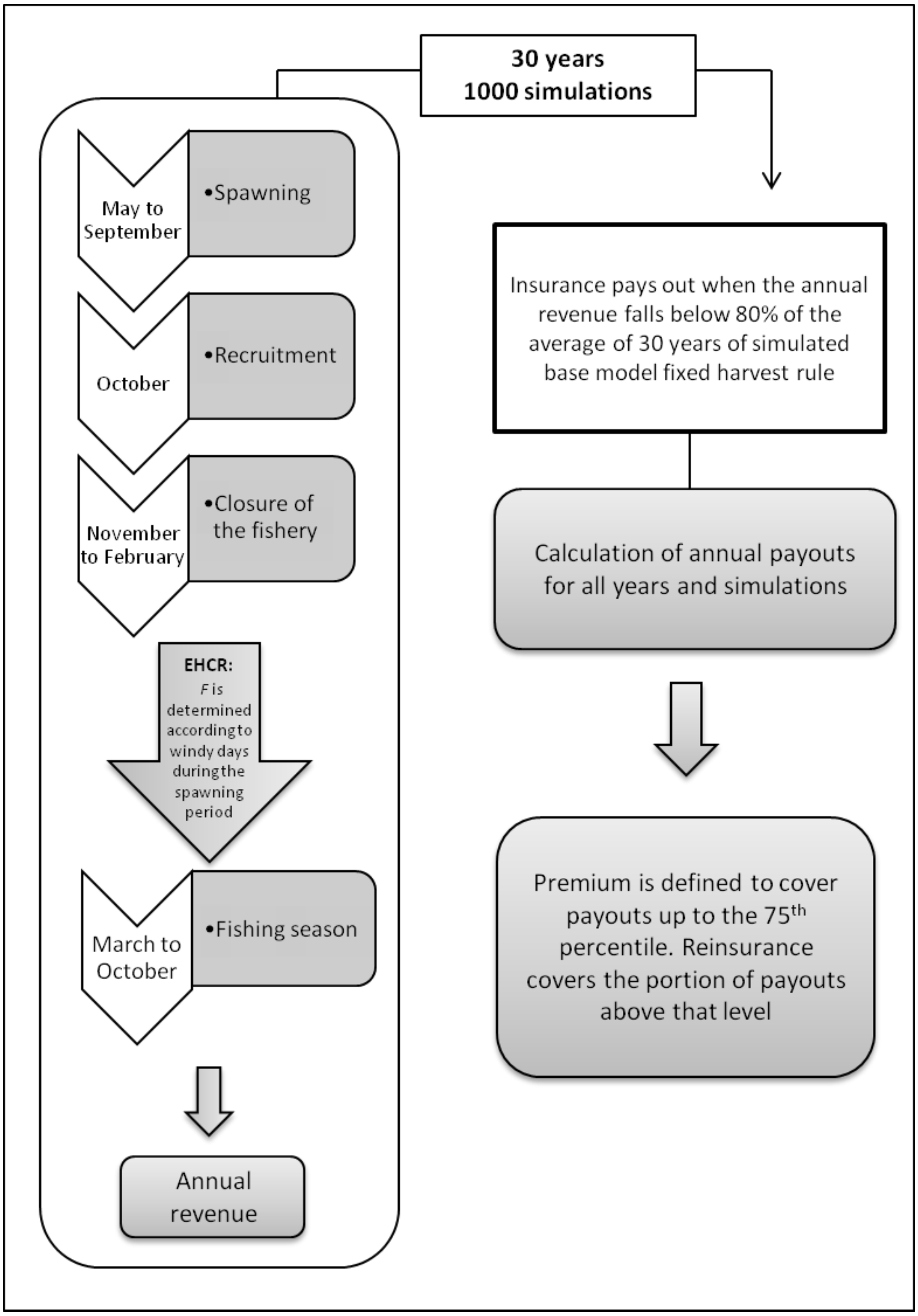

Figure 4: Model diagram

Compensation in the year y and simulation s, $IP_{y,s}$, (Insurance Payout), is paid if the simulated annual revenue falls below a pre-set coverage level ($Trigger$) and it is calculated as the difference between the simulated catch value and the coverage value:

$$IP_{y,s} = \begin{cases} Trigger - Rev_{y,s} & if \quad Trigger > Rev_{y,s} \\ 0 & if \quad Trigger < Rev_{y,s} \end{cases}$$

where $Trigger$ is set at 80% of the average of a simulated 30 year run of catches using a fixed effort regime. This level is similar to the upper end of common crop insurance coverage (Shields, 2013). The annual revenue (in millions of euros) in the simulation is calculated by multiplying the modelled annual catch in numbers (millions of individual fish) by a fixed price (p).

Annual premiums paid by the policy holders include two parts. The first is calculated as the expected value of annual payouts from a mutual fund designed to cover up to the 75th percentile of potential compensation payments. Insurance funds typically "reinsure" the upper tail of the distribution of potential payouts by placing that portion of the risk with a wider pool of insurers. This additional reinsurance premium is calculated as the expected value of all annual reinsurance payouts plus an arbitrary additional charge of 25% of that value paid as a risk margin to cover administration and profit for the reinsurance plan, about double the current rate allowed in heavily regulated US crop insurance (Shields, 2013).

Data

Annual catch data from 1988 to 2013 were extracted from ICES reports (ICES, 2006, 2014). Deterministic values of the model were taken from the literature and two experts were consulted for their knowledge, following the assumption that if data were not available from the same stock, they should be taken from the closest (genetically and geographically) stock under a similar exploitation pattern. Constant monthly fishing mortality was approximated as 0.075 using the annual natural mortality for anchovy in the Northern Alborán Sea (GFCM, 2014), M = 0.92. From Millán (1999), we extracted constant parameter values including a 1:1 sex-ratio (sexr = 0.5), an average length at maturity equal to 11.2 cm (for females) corresponding to 11 months old individuals, and a = 0.0029 and b = 3.3438 for the power length-weight relationship. The number of eggs spawned per gram fec = 500 eggs g^{-1} was approximated from a review on spawning traits of 22 anchovy stocks in European waters (Somarakis et al., 2004).

The price for an individual anchovy p = 0.023 euro was approximated using the mean price per kilogram in 2012 for Andalucía, extracted from the last national anchovy market report (Secretaría General de Pesca, 2013).

Historical records from 1996 to 2004 used to simulate environmental covariates (SST, discharges from the Alcalá del Río reservoir and wind) were obtained as follows: SST was extracted from the Advanced Very High Resolution Radiometer (AVHRR) sensor data; SST data was used to obtain a distribution for the number of spawning events per month; discharges were provided by Confederación Hidrográfica del Guadalquivir and corresponded to the monthly accumulated cubic hectometers that were discharged from the reservoir each month. The wind data, relevant to the pre-recruitment survival of anchovies, were presented as accumulated fractional days measured hourly in which easterly winds are greater than 30 kph. These data were recorded at the meteorological station of Cádiz.

Scenarios and comparison criteria

Population and insurance models were implemented in R (R Development Core Team, 2011) to simulate 1000 iterations. The model was initialised with values taken from a run long enough to stabilise the model values around a sustainably fished equilibrium, and the results for a period of a further thirty simulated years were analysed in this paper.

Simulations were implemented for the two harvest control rules and five different scenarios listed below:

1. Base model: Standard deviation of discharges equal to 0.4, reference monthly fishing mortality equal to 0.04, and environmental parameters, λ for wind and ρ for discharges, equal to 0.15 and 0.4, respectively.
2. Extreme discharge variability: Standard deviation of discharges equal to 0.6, reference monthly fishing mortality equal to 0.04, and environmental parameters, λ for wind and ρ for discharges, equal to 0.15 and 0.4, respectively.

3. Higher F: Standard deviation of discharges equal to 0.4, reference monthly fishing mortality equal to 0.045, and environmental parameters, λ for wind and ρ for discharges, equal to 0.15 and 0.4, respectively.

4. Sensitivity to λ: Standard deviation of discharges equal to 0.4, reference monthly fishing mortality equal to 0.04, and environmental parameters, λ for wind and ρ for discharges, equal to 0.13 and 0.4, respectively. Because λ is a multiplier of wind induced instantaneous mortality rate, lower λ corresponds to better average juvenile survival and lesser impact of wind variability.

5. Sensitivity to ρ: Standard deviation of discharges equal to 0.4, reference monthly fishing mortality equal to 0.04, and environmental parameters, λ for wind and ρ for discharges, equal to 0.15 and 0.45, respectively. Because ρ is the multiplier of the effect of discharges on survival of juveniles, higher ρ values correspond to better average survival but greater influence of discharge variability.

Reference parameters λ = 0.15 and ρ = 0.4 were found to simulate a stable long-term population dynamics within the biomass range that was historically observed. The target monthly fishing mortality (0.04) was chosen to lie below F_{MSY}. This value was identified by performing simulations in the base model with different fishing mortalities to find the one that gave the highest average yield in stochastic simulations over the 30-year period. The base case was arbitrarily chosen as a default for comparison of scenarios. Other combinations of parameters might be plausible, see appendix for further details. A web application designed using the *shiny* R package (Chang et al., 2015) was developed to enable testing of a wider combination of parameters. We present two versions: a faster one with 200 simulations, at http://161.111.144.195:3838/VoI_anchovy_200/ and a more precise versión with 1000 runs, at http://161.111.144.195:3838/VoI_anchovy_1000/ .

We present here some combinations that exemplify the trends. Several alternatives were considered, in particular with respect to early survival. The combined effects of the λ and ρ parameters define juvenile survival, which must be high enough to prevent population collapse.

To measure the value of environmental information, average annual yield, coefficient of variation for annual yield, average combined insurance+reinsurance premium and probability of stock collapse were calculated for both approaches in all the scenarios. The average combined insurance premium was calculated as the sum of the annual mutual fund premium and reinsurance premium, and probability of stock collapse as the probability of having a spawning season with a number of eggs less than 10% of the maximum number of eggs.

In order to test the significance of differences between EHCR and HCR, a Mann-Whitney-Wilcoxon test (Mann and Whitney, 1947) was calculated for simulated annual yields for all the scenarios. This test was chosen in order to avoid normality assumptions.

Results

As an example of simulated annual catches, Figure 5 shows some random trajectories of simulated catches under the two management regimes in the base model (solid lines for HCR and dotted for EHCR). In most cases the annual catches are greater under the EHCR (see mean values in Table 2), but the variability of yields increases, with both the upper and lower ranges extended.

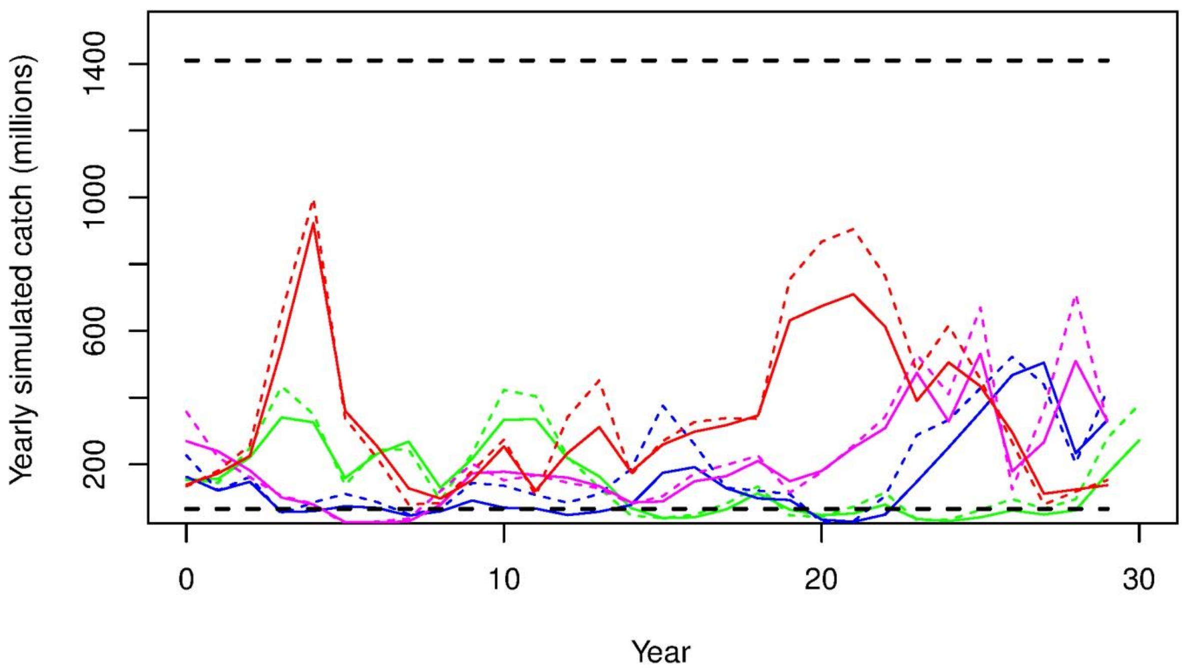

Figure 5: Four samples of simulated catches under two regimes in the base model, with the fixed HCR (solid lines) and with the EHCR (dotted lines). The black dashed lines represent minimum and maximum of annual catches in millions of individual fish registered by ICES for the years 1988 to 2013.

Table 2: Comparison between fixed and variable environmental-based HCRs. The first two columns are for the base model, the other columns are for tests of values for standard deviation of simulated discharges, reference F, λ and ρ, respectively. Annual revenue and the combined annual insurance+reinsurance premiums are in millions of euros while coefficient of variation (CV) and probability of annual stock crash are in percentages.

	Base model		Extreme Disch. sd=0.6		Higher F=0.045		Lower λ =0.13		Higher ρ =0.45	
Annual values	HCR	EHCR	HCR	EHCR	HCR	EHCR	HCR	EHCR	HCR	EHCR
Avg. revenue (€ mn)	5.2	5.8	1.7	1.9	5.4	6.1	11	12	9.9	11
CV %	75	84	140	150	80	89	48	60	58	70
Premiums (€ mn)	0.73	0.71	0.69	0.83	0.83	0.78	0.80	1.0	0.91	1.1
Prob. stock crash %	4.1	2.7	43	41	6.5	4.6	0.0	0.0	0.1	0.0
Avg. revenue net of premiums (€ mn)	4.5	5.1	1.0	1.1	4.6	5.3	10	11	9.0	9.9

Average revenues are higher in EHCRs in each paired scenario because a variable harvest rule allows more flexible exploitation in years with very high yield potential, which exceeds the harvest restrictions in low potential years. A Mann-Whitney-Wilcoxon test indicates that the differences in revenues under the two rules are statistically highly significant in all scenarios. Annual insurance premiums (including reinsurance) are calculated for each scenario. In each of these paired scenarios there is a higher net value (average revenue minus insurance) using the EHCR. Insurance premiums are higher relative to average revenues in scenarios with higher variability, such as the case in which higher discharge variability is simulated that also corresponds to a higher probability of the stock collapsing. Premiums are higher in scenarios with higher average revenues (although premiums are lower as a proportion of those higher revenues), despite lower variability, because the revenue differences covered by insurance are greater. Insurance is slightly cheaper in the base model EHCR than in the fixed HCR, and in the higher F case, because the average revenue increases with EHCR outweigh the increased variability in the model.

Discussion

The management scenarios compared in this paper all have a target fishing mortality that is below F_{MSY}. This is a more precautionary value than in the current management regime, but the notion of F_{MSY} may not be truly applicable in highly dynamic fisheries such as anchovies. In our model, we assumed that greatest mortality is a result of low river discharges since historical records show stock collapse during periods of catastrophic droughts. However, during more normal years, the variability in mortality from cohort to cohort is mainly driven by the frequency of strong easterly winds. Given such sources of environmentally driven variability, a constant fishing mortality regime will either over-exploit a given cohort or under-exploit it. We attempted to introduce more flexible management by varying exploitation based on environmental factors that strongly influence cohort strength. Unlike other attempts to include ecosystem concepts in fisheries management (Fulton et al., 2011; Pikitch et al., 2012; Kaplan et al., 2012; Smith et al., 2014), we have not considered ecological interactions arising from the need to account also for predator conservation. Instead our criteria for management involved only economic criteria and a desire to avoid stock collapse. In this paper we attempt to use a notional insurance scheme coupled to the stock simulations in order to measure the value of using environmental information that can predict recruitment strength. Lower insurance premiums would indicate a lower economic risk, while higher insurance premiums indicate a cost due to greater uncertainty in a management regime. The preliminary results indicate that making the HCR responsive to a critical environmental factor increases both the average revenue and the uncertainty of catch levels. Mean revenue increases sufficiently to allow insurance to compensate for the increased volatility using the EHCR. Adapting to environmental conditions appears to benefit biological sustainability as measured by lower risk of recruitment failure. These findings seem to be robust to alternative scenarios regarding environment and fishing. The main conclusion from the modelling is that adapting management to environmentally driven stock dynamics increases both revenues and revenue volatility while lowering the risk of stock collapse.

The robustness of this conclusion was investigated through various scenarios, several of which were presented in the results section. When there is greater discharge variability, the advantage of using the EHCR almost disappears because the relative importance of wind on stock dynamics (the only environmental information that the EHCR uses) declines as other sources of variability (discharges) are amplified. In addition, the collapse probability and coefficient of variation are the highest compared with the other scenarios. These results suggest that if discharge variability increases, it might be necessary to consider a harvest control rule that responds to changes in discharges as well as to information about the number of easterly windy days.

The impact of assuming that dynamics are less dependent on wind is assessed in the scenario where λ value is reduced (guaranteeing better juvenile survival), both profits and premiums increase in absolute terms. As expected, this scenario shows a lower coefficient of variation and substantially reduces the stock collapse probability. A similar impact is observed when juvenile survival is improved relative to the base case because of a higher ρ value.

The relevance of this analysis to actual management practice depends strongly on the plausibility of assumptions in the operating model. We have tried to develop a model that describes anchovy dynamics in accordance with expert beliefs and consistent with available data, but there remains a possibility that the model differs from reality in ways crucial to the inferences made from the analysis. Many assumptions in the model are oversimplifications of reality. For example, we made a decision not to focus on price volatility as a source of stochasticity because historically prices showed no elasticity to landings in the Gulf of Cádiz (MAGRAMA, 2013). However, anchovy prices could be influential in the dynamics of the fishery in the future.

The trade-offs revealed in this modelling exercise should be discussed with both managers and fishermen. Higher profits and lower risk of stock collapse could be attractive prospects. Given the short life cycle of anchovy, it might be possible to experimentally determine if varying fishing pressure based on the wind information is beneficial.

The particular drivers of stock dynamics, such as the number of easterly windy days and the volume of freshwater outflow into the estuary, are specific to this fishery, but the idea of using information that can predict in-season variability is generic. The method to evaluate trade-offs that arise from implementing environmentally sensitive harvest control rules that we outline in our paper, particularly the use of a notional insurance scheme to measure economic value, is transferable to other case studies. Although, we have not been able to engage stakeholders in this study, we recommend that the trade-offs that are modelled and the uncertainties, with respect to which the sensitivity of management procedures are evaluated, should be elicited from stakeholders prior to establishing the model framework so that it is able to accommodate stakeholder knowledge, interests and concerns (Leach et al., 2014).

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Appendix I

Modelling details

Table 1. List of symbols used in the model specification.

Indices	
a	Monthly age, a = 1, . . . , 23
y	Year, y = 1, . . . , 30
k	Month, k = 1, . . . , 12
s	Simulation number, s = 1, . . . , 1000
Simulated Variables	
$C_{y,s}$	Annual catches in numbers at year y
$Eggs_{y,k,s}$	Number of eggs spawned in month k
$F_{y,k,s}$	Monthly fishing mortality
$N_{a,y,k,s}$	Population in the stock
$S_{y,k,s}$	Number of spawns in a month
$W_{y,k,s}$	Number of days that strong easterlies have blown during month k
$D_{y,k,s}$	Discharges from Alcalá del Río dam (Hm^3)
$Rev_{y,s}$	Revenue
$IP_{y,s}$	Annual insurance payouts
Parameters	
λ	Parameter for the effect of easterlies
ρ	Parameter for the effect of discharges
F^*	Reference fishing mortality
Fixed Values	
ME	Maximum number of eggs
M	Monthly natural mortality M = 0.075
w_a	Weight at age
fec	Number of eggs per gram spawned by a female fec = 500 eggs g−1
sexr	Proportion of females in the population, 50%
p	Fixed assumed price for individual anchovy = 0.023 Euros

Population simulation model

We used four-dimensional arrays storing the number of individuals by age (a), year (y), month (k) and simulation (s), where every year starts in May (k = 1) and a goes from 0 to 24 because negligible numbers of anchovies survive beyond this age in this stock (Ruiz et al., 2009).

The initial state of the fishery is simulated assuming unfished conditions and the carrying capacity is expressed as a number of eggs, *ME* = 286 × 10^{10}. The following general equation determines adult survival:

$$N_{a+1,y,k+1,s} = N_{a,y,k,s}e^{(-M-F_{y,k,s})}$$

Where $N_{a,y,k,s}$ is the number of individuals of age at month k of year y, M represents the natural mortality and $F_{y,k,s}$, the fishing mortality. Maximum number of eggs, *ME*, corresponds to 1000 times the stock abundance estimate provided by an acoustic survey in 2007 (ICES, 2012), which is the highest of the values recorded. The resulting value is also consistent with historical catch records (Figure 5 below).

The number of eggs produced by mature females (i.e. older than 11 months) from May to September is calculated as follows:

$$Eggs_{y,k,s} = fec * sexr * S_{y,k,s} * \sum_{a=11,k=1}^{a=24,k=5} N_{a,y,k,s} * w_a$$

Where fec is the number of eggs that a female could spawn per gram, $sexr$ is the proportion of sexually mature anchovy and, $s_{y,k,s}$ and w_a corresponds to the number of spawning events in a month and the weight at age, respectively.

We calculate the probability of spawning events that occur once, twice, three or four times in a month from a SST time series available from 1996 to 2004. They were respectively, 0.37, 0.37, 0.22 and 0.04 during the spawning season from May to September. Then, to calculate $s_{y,k,s}$ at each month, during the spawning season, we sampled randomly from {1, 2, 3, 4} with the corresponding probability.

Weight at age, w_a, for mature anchovies is calculated using a linear regression from the seasonal von Bertalanffy growth model (Bellido et al., 2000) to transform age to length, and then the weight at length relationship $w = aL^b$.

The $Eggs_{y,k,s}$ are vulnerable to wind in the first three months and to the discharges from the Guadalquivir River during the following three months, accordingly the number of recruits age 6 months is given by:

$$N_{6,y,k+5,s} = Eggs_{y,k,s} \prod_{m=0}^{2} e^{(-\lambda W_{y,k+m,s})} * \prod_{m=3}^{5} \rho\varphi\big(\ln(D_{y,k+m,s}) - \ln(100)\big)$$

Where φ is the normal density function, $W_{y,k,s}$ is the number of days that strong winds blow, and $D_{y,k,s}$ (hm^3) represents the monthly discharges from the Guadalquivir River. Number of windy days and discharges are randomly sampled from uniform and lognormal distributions, W ~ Unif (2.25, 15) and D ~ LN (4.6, 0.4) so that Median (D) = 100 (hm^3), respectively. These distributions were chosen based on ranges from historical records of wind and discharges from 1996 to 2004. Considering the seasonal pattern of discharges and the period when the juveniles occupy the estuary, mean and standard deviation of the logarithm were calculated using only the discharges from March to October of each year.

Annual catches are calculated from a Baranov equation where a proportion of dead fish in the catch is given by a fraction of fishing mortality to total mortality, in general:

$$C_{a,y,k,s} = N_{a,y,k,s}(1 - e^{-(M+F_{y,k,s})}) * \frac{F_{y,k,s}}{F_{y,k,s} + M}$$

Environmentally-sensitive Harvest Control Rule

This control rule modifies a reference monthly fishing mortality *F** once each year as a function of the wind from May to September ($W_{y,k,s}$, k = 1, . . . , 5), as depicted in Figure 3. The corresponding equation is:

$$F_{y,k,s} = max\left(\left[\alpha * \sum_{k=1}^{k=5} W_{y,k,s} + \beta\right], 0.5F^*\right)$$

Where the parameters $\alpha = -0.0314F^*$ and $\beta = 2.35F^*$ of the linear equation are calculated from requiring the line to pass through two points: when the number of windy days are at a minimum, the fishing mortality must be twice the fixed rate $F_{y,k,s} = 2F^*$; and when the number of windy days is average, then the fishing mortality must equal the fixed rate $F_{y,k,s} = F^*$. The line is truncated at half the fixed rate, $0.5F^*$.