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Short-term fleet adaptations and management model

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SUMMARY

The effects of trawling on the benthic ecosystem depends critically on the trawling frequency and location. In turn, the trawling frequency and location depend on the individual skippers in trawling fleet. Those choices result from the adaptive behaviour of fishers operating in a fishery. Hence, in order to understand and predict the effect of fisheries management on the trawling frequency and location we need to understand the adaptive behaviour of fishers. One of the most versatile tools to describe adaptive behaviour is a class of models named "Dynamic State Variable Models". These mechanistic models start from basic assumptions on the utility function of behaviour, and provide forecasts of individual behaviour that depends on the individuals "state". Dynamic state variable models have been applied in a variety of fisheries to analyse vessel fishing behaviour.

A fleet dynamics model with the spatial aspects of size structured fish populations and the price heterogeneity that comes with the size structure was finished and presented at the Benthis meeting in Rome in 2014. In this document we describe the model, describe the implementation of the model in R, and provide three examples of using the implemented model to evaluate fishing effort distribution for simple cases.

An application of this model for the transition of the Dutch beam trawl fleet to pulse fishing was finished, and the manuscript describing the work is in the final stages of being completed (Batsleer et al. subm.). The application studies how the proposed landings obligation affects the spatial distribution of the use of two gear types: traditional beam trawl and pulse trawl, accounting for (1) the differences in costs structures, and (2) the differences in selectivity for the two gear types as estimated in van Marlen et al. (2014). Results suggest that the discards ban will increase the incentive for switching from the traditional beam trawl to the pulse trawl and that the benefits of improved selectivities in the pulse gear may partially be annulled by changes in the spatial and temporal fishing effort allocation that result from switching from traditional beam trawl gear to pulse gear.

TABLE OF CONTENTS

INTRODUCTION

Different species of benthos occur in different areas. Hence, the effects of trawling on the benthic ecosystem depends critically on the trawling frequency and location. In turn, the trawling frequency and location depend on the individual skippers in trawling fleet. Those choices result from the adaptive behaviour of fishers operating in a fishery. Hence, in order to understand and predict the effect of fisheries management on the trawling frequency and location we need to understand the adaptive behaviour of fishers. Each fishery knows many factors that affect this adaptive behaviour. First, biological factors such as the spatial distribution and abundance of target species. Then, economical parameters such as the prices of the different species and size classes of target species, and the price of fuel that is required for the fishing operation. Finally, fisheries management imposes constraints on the fishing operation, such as the setting of quota on fish catches or fishing effort.

One of the most versatile tools to describe adaptive behaviour is a class of models named "Dynamic State Variable Models" (Houston and McNamara 1999; Clark and Mangel 2000). These mechanistic models start from basic assumptions on the utility function of behaviour, and provide forecasts of individual behaviour that depends on the individuals "state". Dynamic state variable models have been applied in a variety of fisheries to analyse vessel fishing behaviour (Gillis *et al*. 1995; Poos *et al.* 2010; Dowling *et al*. 2012; Batsleer *et al*. 2013).

The premise of DSVM is that individuals optimize a utility function. One proxy for the utility function of fishers is the annual net revenue. The state of the individual can be any dynamic trait that potentially changes over time, but the focus is on states that actually affect fishing choices through their effect on the utility function. One example of such a state is the amount of cumulated fishing effort that a fisher has exerted in a fishery with annual fishing effort constraints. Likewise, the cumulated catches of any given target species in a fishery with annual catch quotas can be considered the "state" of an individual that affects the behaviour of individuals. As time progresses the state of individuals changes as a result of past choices. These choices can include the fishing location, or the choice to discards (part of) the catch.

Importantly, dynamic state models allow for making sequences of optimal choices in stochastic environments: the stochasticity will cause the state of individuals to differ, even if they have made the same choices in the past. Once the states of individuals differ, they may make different choices that maximize their respective utilities. Populations of individuals may thus not all make the same choices at the same time, but adapt to the stochastic outcomes of their choices

A fleet dynamics model with the spatial aspects of size structured fish populations and the price heterogeneity that comes with the size structure was finished and presented at the Benthis meeting in Rome in 2014. An application of this model for the transition of the Dutch beam trawl fleet to pulse fishing was finished, and the manuscript describing the work is in the final stages of being completed (Batsleer et al. subm.). The application studies how the proposed landings obligation affects the spatial distribution of the use of two gear types: traditional beam trawl and pulse trawl, accounting for (1) the differences in costs structures, and (2) the differences in selectivity for the two gear types as estimated in van Marlen et al. (2014). Results suggest that the discards ban will increase the incentive for switching from the traditional beam trawl to the pulse trawl and that the benefits of improved selectivities in the pulse gear may partially be annulled by changes in the spatial and temporal fishing effort allocation that result from switching from traditional beam trawl gear to pulse gear.

1 A MODEL FOR A MIXED FISHERY

The model developed for Benthis 1) includes size structured fish catches, and 2) allows for ex-vessel price by size class fluctuate over time. The utility function assumes that fishers are profit maximizers. Although other incentives may play a role in decision making, there is empirical evidence for profit as a useful metric of utility (Robinson and Pascoe 1997).

The model allows for using three size-structured target fish species, the catches of which are size structured, using 3 size classes. The size classes can be based on market categories, or physiological. The size classes have seasonally variable auction prices (Fig. 1). The size structure and species composition of the catch is thus an important determinant for the value of a catch. The expected catch rates of each species/size class combination is defined by probability distributions that are functions of fishing location and season, reflecting spatial and seasonal differences in abundance. Parameters describing the probability distributions can be estimated from historic data.

In the model fishers maximise their annual net revenue by making weekly decisions (i) to go fishing or not; (ii) where to fish; (iii) and how much to discard given their annual landing quota and restrictions on discarding. The model assumes that there are individual quotas restricting a single species. The cumulative landings in weight of species s of the total number of species S and size class n of N size classes is denoted by $L_{s,n}$. The cumulative landings in weight of the quota constrained species, that we define by s=1, represents the state of the individual, denoted by L and equal to $\sum_N L_{1,n}$.

The landings are determined by the discarding decision and the catches which in turn depend on the spatial and temporal distribution of all size classes within the 3 species. Each week t individuals choose to visit fishing area a and to keep or discard any combination of the size classes caught of the different species. This behaviour is defined by a matrix d, having size S,N of which each element $d_{s,n}$ can take the value 0 (discard) or +∞ (keep on board and land) for each combination of species and size class. The catches are modelled as a random variable that can have a negative binomial distribution or a normal distribution. The negative binomial distribution is described by a mean $m_{s,n,a,t}$ per area, week, species and size class, and a dispersion parameter per species r_s. The means and dispersion parameters are estimated from logbook data from the case study fleet. The probability $\lambda_{s,n}(l_{s,n}, d_{s,n}, a, t)$ of making a landings of $l_{s,n}$ are a function of the area choice in a given week, and the discarding decisions such that it has following cumulative distribution function

$$\lambda_{s,n}(l_{s,n} \leq \chi, d_{s,n}, a, t) = f(\chi; d_{s,n}, m_{s,n,a,t}, r_s) =$$

$$\begin{cases} \sum_{l_{s,n}=0}^{\chi} \left(\frac{r_s}{r_s+m_{s,n,a,t}}\right)^{r_s} \frac{\Gamma(r_s+l_{s,n})}{l_{s,n}!\Gamma(l_{s,n})} \left(\frac{m_{s,n,a,t}}{r_s+m_{s,n,a,t}}\right)^{l_{s,n}}, & 0 \leq \chi < d_{s,n}, \\ 1 & , \chi \geq d_{s,n} \end{cases}$$

where $\Gamma(\cdot)$ is the gamma function (Press *et al.* 2002).

In case The catches are modelled using a normal distribution, $\lambda_{s,n}(l_{s,n}, d_{s,n}, a, t)$ has the following cumulative distribution function:

$$\lambda_{s,n}\big(l_{s,n} \leq \chi, d_{s,n}, a, t\big) = f\big(\chi; d_{s,n}, \mu_{s,n,a,t}, \sigma_s\big) =$$

$$\begin{cases} 0 & , \chi < 0 \\ \frac{1}{\sigma_s\sqrt{2\pi}} \int_{-\infty}^{\chi} e^{-(x-\mu_{s,n,a,t})^2/2\sigma_s^2} dx, & 0 \ll \chi < d_{s,n} \\ 1 & , \qquad \chi \geq d_{s,n} \end{cases} \qquad ,$$

The optimal strategy in each week of the year, denoted by t depends on the cumulative landings of the quota species. These landings affect the possibility to continue fishing and land fish without exceeding the annual quota. The expected net revenue at the end of the year is linked to the choices in the preceding weeks by means of a value function between time t and the end of year T. The value function represents the maximum expected net revenue to be made between week t and the end of the year T and depends on the state of the individual L, the amount of quota U for the quota species, the fine per unit weight for exceeding the quota F, and is expressed as $V(L, U, F, t)$. Individuals exceeding their quota get a fine that depends on the quota overshoot. At the end of the year T, after all fishing has been completed, the value function $V(L, U, F, T)$ is defined by the fine of overshooting the quota

$$\Phi(L, U, F) = \begin{cases} 0, & L \leq U \\ -(L - U)F, & L > U \end{cases}$$

For each week before T, the expected net revenue is determined by the value function, the weekly gross revenue and the costs of fishing.

For all times t preceding T we use stochastic dynamic programming to find the optimal solution by backward iteration of the net expected revenue H from t to the end of the year considering the choices a and d and the state L at t and optimal choices in subsequent weeks

$$H(L, U, F, t; a, d) = R(a, d, t) - C(a) + \mathbb{E}_{a,d}[V(L', U, F, t + 1)],$$

where $R(a, d, t)$ is the expected direct contribution of the gross revenue that follows from the sales of fish in a week resulting from choices a and d, and the prices of fish in that week $p_{s,n}(t)$: $R(a, d, t) = \sum_S \sum_N \lambda_{s,n}\big(l_{s,n}, d_{s,n}, a, t\big) * l_{s,n} * p_{s,n}(t)$. The term $C(a)$ represents the variable costs in a week resulting from the choice of fishing area a. The term L' reflects the change of the state L resulting from the weekly landings for the quota species, $\sum_N l_{1,n}$. The term $\mathbb{E}_{a,d}[V(L', U, F, t + 1)]$ denotes the expected future value taken over all possible states resulting from choices a and d. The optimal choice is given by

$$V(L, U, F, t) = \max_{a,d}\{H(L, U, F, t; a, d)\}.$$

Hence, starting with $V(L, U, F, T) = \Phi(L, U, F)$ we can iterate backwards in time and find the optimal choice in terms of location and discarding behaviour for all possible states, combining the net revenue obtained from the sale of fish and costs of a fishing trip and the effect of the annual fines when exceeding annual quota. After the backward iterations, the expected distribution of observed decisions can be determined by the forward iteration. This simulates a number of individuals who choose the optimal path, defined by the optimal strategy, given the stochastic nature of the catches.

2   R IMPLEMENTATION

The model is implemented in R (R Core Team, 2015) in a package named *RDynStateBenthis3.* The package contains a number of classes *DynStateInput*, *DynState.control*, *Sim*, and *DynState*. Below, we describe

how the classes and functions are used to generate input for the model, how to run the model, and how output is provided.

2.1 Input

Data needed to run the model are of several types:

- Means and variances of catch rates per size class for the three species, for each choice[1], in objects of the *DynStateInput* class. One object is used for each species.
- Fishing effort associated to each choice, input as an object of class *numeric* (fishing effort differ between choices because of the distance to harbour)
- Fish prices per market category and period, input as an object of class *array*, one for each species.
- Data on costs structure and fisheries management measures such as individual landings and effort quotas, input in an object of class *DynState.control*
- computational settings of the model, also input in the object of class *DynState.control*

The *DynStateInput* contains the information on the statistical distribution of the catches per size class for each of the species. For each species in the model, one object of class *DynStateInput* is required. The class consists of two arrays, each of which has 3 dimensions. The first array contains μ or m (depending on the assumed distribution of the catches) values. The second array contains the σ or r values. The three dimensions of each of the arrays reflect the size category, season, and option (= area or no fishing). The names of these dimensions have to be equal to "cat", "season", and "option".

Fishing effort per choice, is input as an object of class *numeric,* which has a length that is equal to the number of options (and thus the third dimension of the arrays in the objects of class *DynStateInput.* Fish prices are input as an object of class *array*, one for each species. The arrays should have two dimensions. The first dimension contains the size category "cat", the second dimension contains the time step "season".

The *DynState.control* class contains the variables for the costs structure, the management constraints, and computational settings for the model. Within the *DynState.control* class the costs structure is defined by *fuelUse* (fuel use per unit time), *fuelPrice* (fuel price per unit fuel), and *landingCosts* (landings costs per unit landings). The management constraints are defined by *spp1Quota* (the amount of annual landings quota for species 1), *effortQuota* (the amount of annual effort quota per individual), *spp1QuotaFine* (the fine for exceeding the landings quota per unit landings), and *effortQuotaFine* (the fine for exceeding the effort quota per unit effort).

The computational settings for the model are defined in the *DynState.control* class by *simNumber* (the number of forward simulations, corresponding to the number of vessels in the fleet), *increments* (the number of bins used for describing statistical distributions of catches, e.g. catches can be expressed in 100kg and the distribution would be 100, 200, 300...), *addNoFishing* (logical flag indicating whether to add one option with zero catches and zero effort), *spp1DiscardSteps*, *spp2DiscardSteps*, *spp3DiscardSteps.* The latter contain single values indicating the number of possibilities for discarding to include per size class. In case this value is 0, then no discarding is possible. In case this value is 1, then vessels can either discard no fish of a size class and species, or discard all fish of a given size class and species. In case this value is 2, then vessels can either discard no fish of a size class and species, discard any catches larger than half of the maximum catches of a given size class and species, or discard all fish of a given size class and species. Finally, the *numThreads* value in the *DynState.control* class defines the amount of threads that exist within the computational context of the backward iterations. These threads share the memory needed for the computations, but are able to execute independently. The use of multiple threads allow

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[1] "choice" represents the selection of an area for a given period (here week) or the choice not to go fishing.

parallel execution of the backward iterations in the model on a multiprocessing system.to use when doing the backward iterations.

Objects of the *DynState.control* are most easily created with a call to its creator: *DynState.control*(). This creator takes each of the slots in the class as input. Those slots that are not defined in the call to the creator are set to default values. These default values can be found by making a call to the creator with no arguments, and inspecting the resulting object.

2.2   Running the model

The model itself is invoked by a call to the *DynState*() function. This function takes 7 arguments: *inputSpp1*, *inputSpp2*, *inputSpp3*, *spp1Price*, *spp2Price*, *spp3Price*, *inputEffort*, and *control.*
The *inputSpp1*, *inputSpp2*, and *inputSpp3* inputs are objects of the *DynStateInput* class containing the information describing the statistical distribution of the catches. *Spp1Price, spp2Price, spp3Price* are two-dimensional arrays containing the price for the three species. The first dimension contains the size category "cat", the second dimension contains the time step "season". Then, *inputEffort* is a one dimensional array containing the effort that is required to visit each of the options. Finally, *control* is an object of class *DynState.control* containing the variables for the costs structure, the management constraints, and computational settings for the model.

Internally, the *DynState*() function calls a function in a dynamically loaded library, compiled from c++. The dynamically loaded library does both the backward calculations and the forward simulations. The compiled package is available for windows and linux. In order to speed up calculations, the much of the backward calculation is done using parallel computing, implemented in OpenMP. Once the forward simulations are done, the results are passed into R objects.

2.3   Output

The *Sim* class is nested within the *DynState* class. The *Sim* class contains the results of the forward simulations. The array *choice* contains the area choice per individual and time step. The arrays *spp1Landings*, *spp2Landings*, and *spp3Landings* contain the landings per individual, time step, and size class. The arrays *spp1Hold*, *spp2Hold*, and *spp3Hold* contain the cumulative landings per individual, time step, and size class over the year. The arrays *spp1Discards*, *spp2Discards*, and *spp3Discards* contain the discards per individual, time step, and size class. The array *effort* contains the effort per individual and time.

The *DynState* class is used for object returned by the model. Objects of the *DynState* class contain an object of class *Sim* (see above), an object of class *DynState.control*, containing the information held in the control object used to call the function containing the model such as the costs structure, the management constraints, and computational settings for the model (see above for the full description). Finally it contains three arrays, (*spp1Price*, *spp2Price*, and *spp3Price*) containing the information on prices (per category, species and period).

After the model is run, there are several functions that facilitate inspection of the results: *annualGrossRev* (estimates annual gross revenue per individual), *annualFine* (calculates annual fine from overshooting quotas per individual), *fuelCosts* (calculates annual fuel costs per individual), and *annualNetRev* (calculates annual net revenue per individual).

3   EXAMPLE MODEL RESULTS

3.1 Simple case

3.1.1 Definition

Below, we give a few examples of model results for a simple model, with only two species, and four fishing seasons (instead of the 3 species and 52 weeks that the model is capable of). In this example, there are three different fishing areas (named "a", "b", and "c"). Catches are assumed to be normally distributed. The prices for the two species are different, and there is some difference in the prices for the different size classes (Table 1). The prices for species 2 are higher than for species 1. For simplicity, the prices are assumed to be constant over time.

Table 1: prices for the two species and three size classes in the "simple" case.

	Size class		
Species	1	2	3
1	3.0	4.0	5.0
2	5.0	6.0	7.0

For **species 1**, the mean catches (μ) in area "a", are 10 for all size categories and seasons, in area "b" the mean catches are 12 for all size categories and seasons, and in area "c" the mean catches are 14 for all size categories and seasons. For **species 2**, the mean catches area "a", are 14 for all size categories and seasons, in area "b" the mean catches are 12 for all size categories and seasons, and in area "c" the mean catches are 10 for all size categories and seasons. The σ values are assumed to be equal to 3 for all species, areas, and size classes.

The fishing effort required to fish in any of the three areas is assumed to be 8, and thus equal for each of the possible areas/options. The fuel use per unit effort is assumed to be equal to 1, and the fuel price is equal to 40.

Before running the model with these settings, we use the *addNoFishing* flag to indicating that the model should add one option with zero catches and zero effort, mimicking a fishing season where the vessel stays in port.

The model is run without effort quota, and the quota for the quota species are set to 700 units. This level of quota is higher than can be caught by any individual, even if the environmental stochasticity would result in a sequence of maximum possible catches. Hence the quota is not constraining, and we expect all individuals to make the same choices throughout the year.

3.1.2 Code

```
library(RDynStateBenthis3);

############ INPUT #########################################################
sp1 <- sp2 <- sp3 <- new("DynStateInput")
CMseq <- c(rep(10,12),rep(12,12),rep(14,12))
dmns  <- list(cat=1:3,season= as.character(1:4), option=c("a","b","c"))
catchMean(sp1)  <- array(CMseq,      dim = c(3,4,3), dimnames = dmns)
catchMean(sp2)  <- array(rev(CMseq), dim = c(3,4,3), dimnames = dmns)
catchMean(cp3)  <- array(0,          dim = c(3,4,3), dimnames = dmns)
catchSigma(sp1) <- catchSigma(sp2) <- array(3, dim=c(3,4,3), dimnames = dmns)
catchSigma(sp3) <- array(0.1, dim = c(3,4,3), dimnames = dmns)

effort <- c(8,8,8)
```

```
sp1Price <- array(c(3,4,5),dim = c(3,4), dimnames = dmns[1:2])
sp2Price <- array(c(5,6,7),dim = c(3,4), dimnames = dmns[1:2])
sp3Price <- array(c(0,0,0),dim = c(3,4), dimnames = dmns[1:2])

cntrl <- DynState.control(spp1Quota = 700, effortQuota = NA, fuelUse = 1, fuelPrice = 40,
                          simNumber = 40, numThreads = 40)

############ RUN MODEL #################################################
z <- DynState(sp1, sp2, sp3, sp1Price, sp2Price, sp3Price, effort, cntrl)

############ PLOT OUTPUT ##############################################
par(mfcol = c(3,4))
plotChoice(sp1, z, main = "choices")
hist(annualNetRev(z), xlim = c(0,900), main = "net revenue")
plot(apply(effort(sim(z))[,,],1,cumsum)[,1], type = "s", ylim = c(0,50))
for (ii in 2:dim(effort(sim(z)))[2])
 lines(apply(effort(sim(z))[,,],1,cumsum)[,ii], type = "s", ylim = c(0,50))
hist(apply(spp1Landings(sim(z)),2,sum),20, xlim = c(0,200))
hist(apply(spp2Landings(sim(z)),2,sum),20, xlim = c(0,200))
hist(apply(spp3Landings(sim(z)),2,sum),20, xlim = c(0,200))
#grossRev per spec
LanCost <- control(z)@landingCosts
hist(apply(sweep(spp1Landings(sim(z)),c(1,3),(spp1Price(z)-LanCost),"*"),2,sum),20)
hist(apply(sweep(spp2Landings(sim(z)),c(1,3),(spp2Price(z)-LanCost),"*"),2,sum),20)
hist(apply(sweep(spp3Landings(sim(z)),c(1,3),(spp2Price(z)-LanCost),"*"),2,sum),20)
#discards per spec
hist(apply(spp1Discards(sim(z)),2,sum),20, xlim=c(0,200), main = "discards spp1")
hist(apply(spp2Discards(sim(z)),2,sum),20, xlim=c(0,200), main = "discards spp2")
hist(apply(spp3Discards(sim(z)),2,sum),20, xlim=c(0,200), main = "discards spp3")
```

3.1.3   Results

When the model is run with the settings of the simple case, indeed all individuals choose area "a" for all time steps (Figure 1 top left panel). This choice results in landings of species 2 ranging between 140 and 170 units (Figure 1 2nd column of panels). This is the most expensive species, hence the choice for area "a". The landings for species 1 are lower, between 90 and 140 units. Because we set the landings for species 3 to zero (with a very low sigma) for all areas and time steps, the annual landings for these species are zero for all vessels. The annual landings for the different species and the annual revenues differ among the individuals as a result of the environmental stochasticity in the model.

Because we only model fish larger than the minimum landings size and the quota are not constraining, there is no discarding in the fleet (Figure 1, 4th column of panels). Because all vessels go out fishing in each of the time steps, the fishing effort for all individuals steadily increases over the years (with 8 units of effort per time step) (Figure 1, bottom left panel). The net revenues within the fleet range between 0 and 380 units.
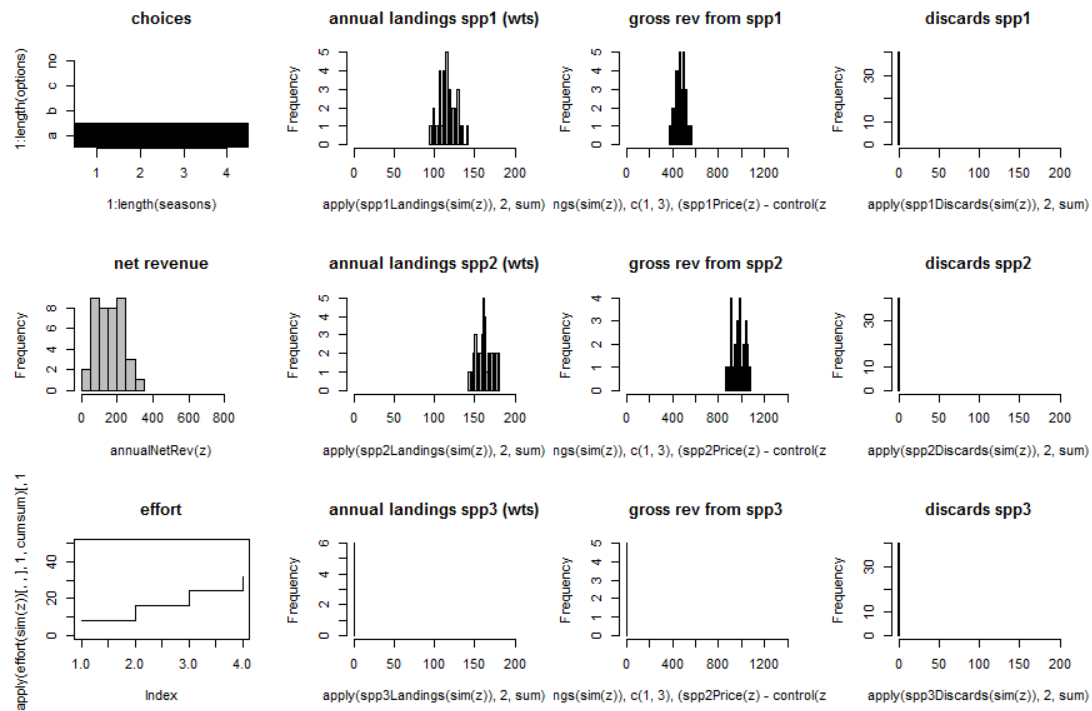
Figure 1. summary of model outputs for the simple case; fraction of population that chooses each option per time step, histogram of net revenues, time series of fishing effort per individual, histogram of annual landings per species, histogram of gross revenue derived from each of the species, histogram of annual discards per species.

3.2   A case with constraining landings quota

Starting from the simple case, we reduce the quota for the first species to 180 units, and we increase the prices for this quota constrained species (Table 2). We do this by simply redefining the *sp1Price* object, and recreating the *cntrl* object, now with *spp1Quota* =180.

```
Sp1Price    <- array( c(6,7,8), dim=c(3,4) , dimnames = dmns[1:2])

cntrl <- DynState.control(spp1Quota=180,  effortQuota=NA, fuelUse=1, fuelPrice =40,
                          addNoFishing=T, simNumber=200,  numThreads=40)
```

After running the model (with a call to the *DynState*() function) we see that while the change in the prices for species 1 create an incentive to visit area "c", the constraining quota prevent vessels from going there in each of the time steps. Instead, vessels will make different choices in time steps 2-4, depending on their catch success in previous time steps (Figure 2, top left panel). Hence, a diffusion of the spatial fishing effort is observed, resulting from the annual quota fpr species 1 combined with the stochasticity in the catches of species 1. The resulting annual landings for species 1 stay within the quota limit for all vessels (Figure 2, 2nd column of panels).

Table 2: prices for the two species and three size classes in the case with constraining landings quota.

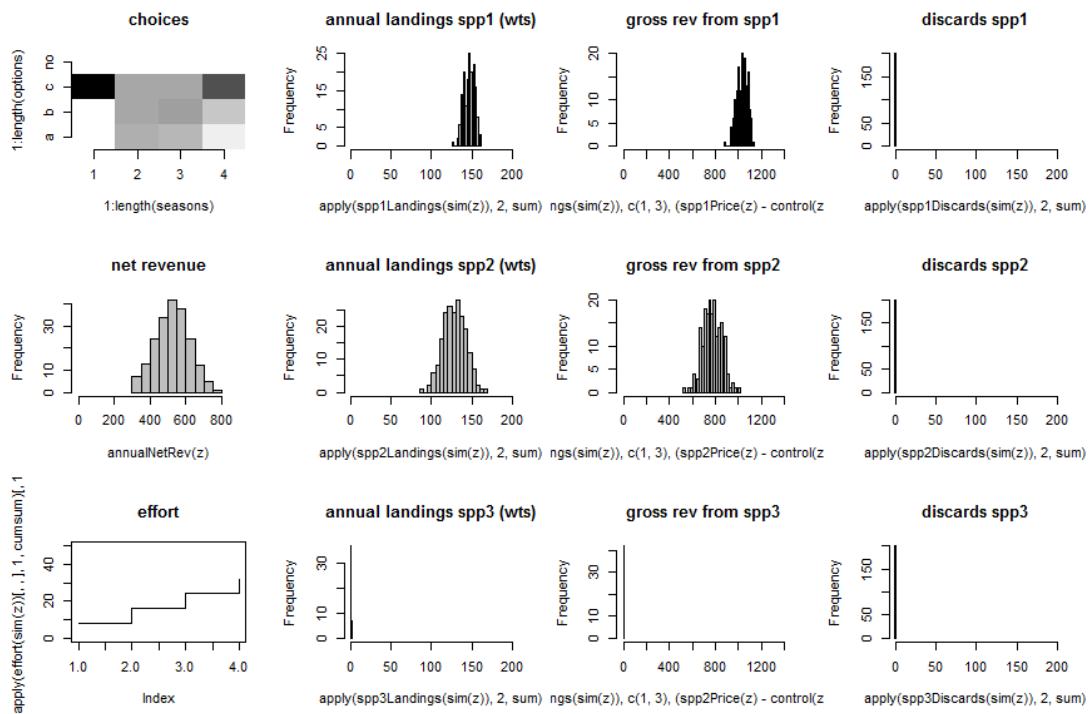| Species	Size class		
	1	2	3
1	6.0	7.0	8.0
2	5.0	6.0	7.0

Figure 2. Summary of model outputs for the quota constrained case; fraction of population that chooses each option per time step, histogram of net revenues, time series of fishing effort per individual, histogram of annual landings per species, histogram of gross revenue derived from each of the species, histogram of annual discards per species.

3.3   A case with constraining landings quota when discarding is allowed

In the previous case, quota for the first species was reduced to 180 units, so that it became a constraining factor for the fishy. As a result, heterogeneity in the spatial distribution emerged from the model. Now, the quota for species 1 are further reduced, and vessels are allowed to discard (part of) their catches that are above the minimum landings size. The prices are the same as in the case with constraining landings quota. In R, we make a new call to the creator function of the *DynState.control* class, setting *spp1DiscardSteps* to 3.

```
cntrl <- DynState.control(spp1Quota=120, effortQuota=NA, fuelUse=1, fuelPrice =40,
                spp1DiscardSteps=3, addNoFishing=T, simNumber=200,
                numThreads=40)
```

The model is then run by making a call to the *DynState()* function, as in

```
z <- DynState(sp1, sp2, sp3, sp1Price, sp2Price, sp3Price, effort, cntrl)
```

As a result of the changes (lower quota for species 1 while discarding marketable fish is allowed) the vessels change spatial and temporal effort allocation so that mainly area "a" is chosen. Only in hte final time step there is heterogeneity in the effort allocation, with some vessels choosing area "b", while others choose area "c". The vessels can fish throughout the year and choose area "a" because they have the behavioural flexibility of discarding parts of their catch (Figure 3). Annual landings for species 1 are less than 120 units, and hence stay within quota. Discarding occurs for species 1, but not for all vessels, and annual discards for species 1 are generally lower than 30 units.

Discarding of marketable fish mainly occurs for size class 1: the fish of this size class is cheaper than the other size classes, and hence discarding these results in a smaller loss of revenue that results from discarding than discarding the other size classes.
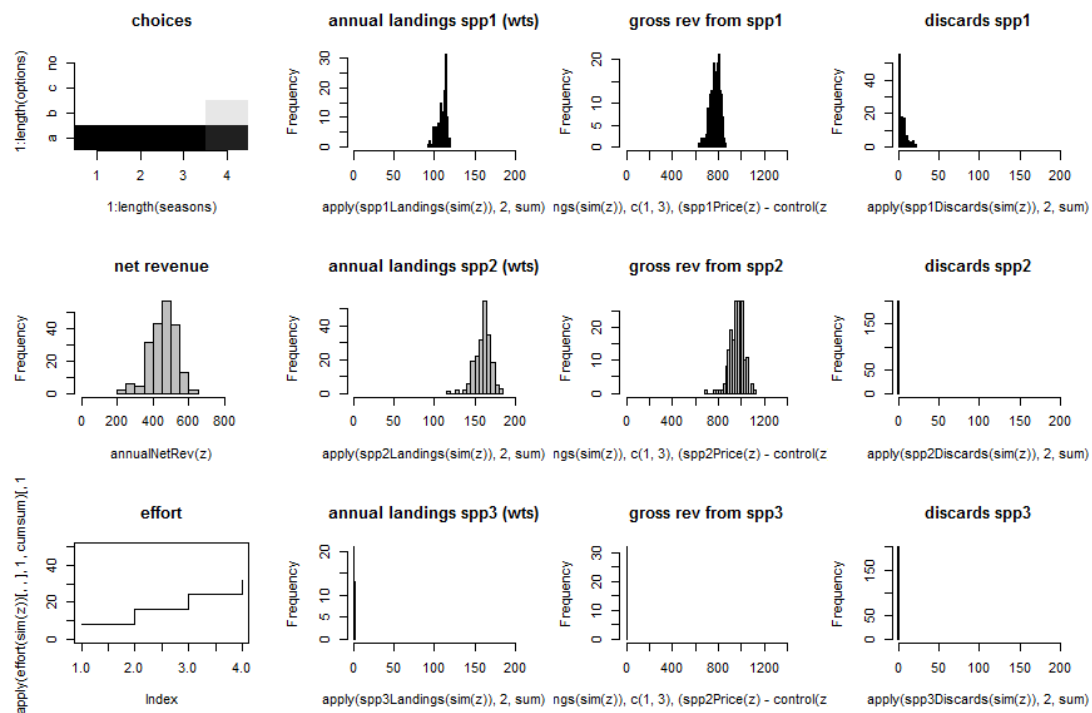

Figure 3. Summary of model outputs for the quota constrained case with discarding marketable species; fraction of population that chooses each option per time step, histogram of net revenues, time series of fishing effort per individual, histogram of annual landings per species, histogram of gross revenue derived from each of the species, histogram of annual discards per species.

3.4   Conclusions from example model results

The examples presented above show how the model can be used to infer spatial and temporal effort distributions for fishing fleets. For reasons of tractability, an extremely simple system is used to show the model results. Real life fisheries can be mimicked in much more detail by including the spatial and temporal heterogeneity in fish abundance and fish prices. In addition, fishing effort quota can imposed, or areas can be closed for fisheries. Below, we describe the use of the model in a number of case studies.

4   MODEL USE IN CASE STUDIES

Batsleer *et al.* (subm.) model the potential effects of a discard ban on the annual fishing strategy of individual fishers in a mixed fishery under quota management using DSVM. The North Sea beam trawl fishery, which catches large amounts of undersized plaice, is used as a model system. Under a discard ban, fishing is restricted to the fishing grounds and weeks where a maximum revenue can be realised with other species while catching the quota of the restricted species with a reduced bycatch of undersized fish. Model results suggest that, if properly enforced, a discard ban provides an incentive to implementation of more selective fishing gears that catch fewer small fish and are more fuel efficient (pulse trawl). If a discard ban is not properly enforced, restrictive quota do not necessarily result in the intended decrease in discarding as the fishery continues to fish while discarding the over-quota catch and least valuable size classes caught.

In Batsleer *et al.* (in prep.) the performance of a combined catch quota and habitat credit system is explored to manage the sustainable exploitation of a mix of demersal fish species and minimise the benthic impacts of bottom trawl fisheries using a dynamic state variable model approach. The model is parameterised for the eastern Channel demersal fishery using otter trawls or dredge and targeting scallops, sole, cod, plaice, sea bass and squid. The target species differ in their association with habitat types. The results suggest that restricting catch quota for sole and cod does not reduce the benthic impact, except when reduced to very low values forcing the vessels to stay in port. Quota management has a minimal influence on fishing behaviour and hence results in a minimal reduction of benthic impact. Habitat credits are required to manage the benthic impact. Indirectly, these restrict the possibilities to exploit the fish species. A management system that combines catch quota and habitat credits is an appropriate tool for ecosystem based management, but requires habitat specific data (e.g. on a haul-by-haul basis or by VMS-location instead of at fishing trip and ICES-rectangle level)

5   DISCUSSION

Dynamic State Variable Models are tools that allow modelling the adaptive behaviour of fishers. The implementation in the Benthis project allows forecasting changes in spatial and temporal effort allocation in fishing fleets that result from changes in fisheries management and economics. Implemented in R, the model allows for three target species, composed of three size classes. Management constraints are either in the form of landings or catch quotas, or effort quotas.

The effects of trawling on the benthic ecosystem depends critically on the trawling frequency and location. In order to get good quantitative predictions about the effects of fisheries, high-resolution results are required. Implementing such high-resolution in DSVM yields thousands of options, and combined with the discard options resulting in unfeasible computation times. In order to combine the ability of modelling adaptive behaviour using DSVM with very high resolution maps that may be required to forecast benthic disturbance. One way to obtain such high resolution maps is to combine the results from the DSVm with existing high-resolution VMS maps. The DSVM then informs about the overall level of fishing effort within fishing areas, and the VMS maps inform about the spatial distribution of the effort within the larger areas.

6   REFERENCES

Batsleer, J., Poos, J.J., Marchal, P., Vermard, Y., Rijnsdorp, A.D., 2013. Mixed fisheries management: protecting the weakest link. Mar. Ecol. Prog. Ser. 479, 177-190.

Batsleer, J., Poos, J.J., Marchal, P., Vaz, S., Vermard, Y., Rijnsdorp, A.D. (in prep.) Exploring habitat credits to manage the benthic impact in a mixed fishery.

Batsleer, J., Rijnsdorp, A.D., Hamon, K., Overzee, H.M.J. Poos, J.J. (subm.) Mixed fisheries management: Can a ban on discarding promote more selective and fuel efficient fishing? Submitted to Fisheries Research

Clark, C.W., Mangel, M., 2000. Dynamic state variable models in ecology: Methods and applications, Oxford University Press, Oxford, UK.

Dowling, N.A., Wilcox, C., Mangel, M., Pascoe, S., 2012. Assessing opportunity and relocation costs of marine protected areas using a behavioural model of longline fleet dynamics. Fish Fish. 13, 139-157.

Gillis, D.M., Pikitch, E.K., Peterman, R.M., 1995. Dynamic discarding decisions - foraging theory for high-grading in a trawl fishery. Behav. Ecol. 6, 146-154.

Houston, A.I., McNamara, J.M., 1999. Models of Adaptive Behaviour, Cambridge University press, Cambridge, UK.

Poos, J.J., Bogaards, J.A., Quirijns, F.J., Gillis, D.M., Rijnsdorp, A.D., 2010. Individual quotas, fishing effort allocation, and over-quota discarding in mixed fisheries. ICES J. Mar. Sci. 67, 323-333.

R Development Core Team, 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing Vienna, Austria. URL http://www.R-project.org/.

Robinson, C. and Pascoe, S. 1997. Fisher behaviour: exploring the validity of the profit maximising assumption. Paper presented at IXth conference of the European Association of Fisheries Economists Quimper, France, 28-30 April 1997.

van Marlen, B., Wiegerinck, J. A. M., van Os-Koomen, E., van Barneveld, E., 2014. Catch comparison of flatfish pulse trawls and a tickler chain beam trawl. Fish. Res. 151, 57-69.