SUPPLEMENTARY MATERIALS FOR:
Exploring balanced harvesting by using an Atlantis ecosystem model for the Nordic and Barents Seas

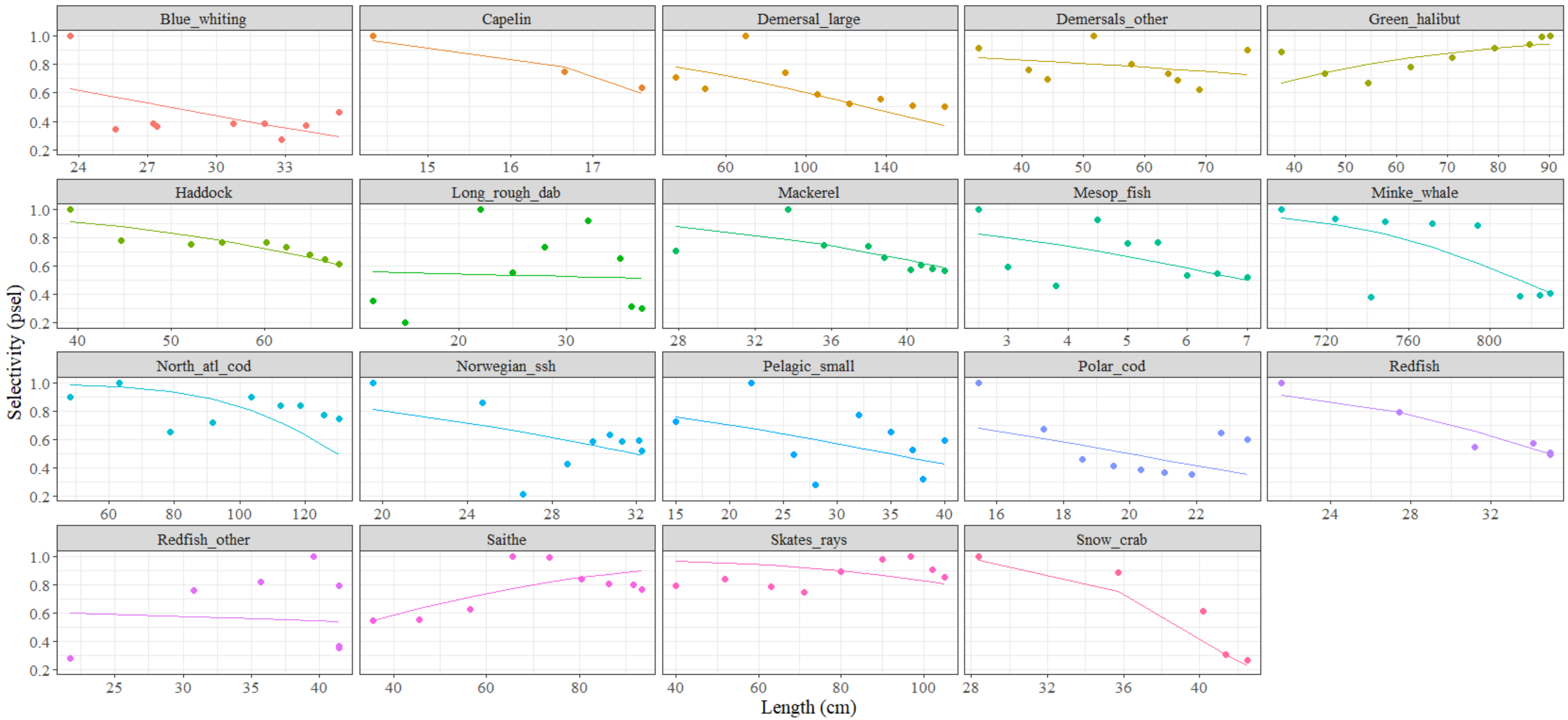
Table S.1

Harvested species connected to model fishing fleets with associated selection curve parameters for all age structured groups.

No	Species	Fishing fleet	*lsm [cm]*	*selb*
1	*Norwegian S.S herring*	pseineSSH	46	-0.0790
2	*Blue whiting*	pseineBWH	28	-0.1476
3	*Mackerel*	pseineMAC	36	-0.1212
4	*Capelin*	pseineCAP	18	-0.9317
5	*Northeast Arctic cod*	dtrawlNCO	157	-0.0489
6	*Haddock*	dtrawlHAD	84	-0.0485
7	*Saithe*	dtrawlSAI	21	0.0282
8	*Greenland halibut*	dtrawlGRH	15	0.0436
9	*Prawns*	dtrawlPWN		
10	*Redfish*	dlineNCO	40	-0.1208
11	*Redfish other*	dlineHAD	39	-0.3187
13	*Zooplankton medium + zooplankton gel*	dlineGRH		
14	*Mesopelagic fish*	dseineNCO	6	-0.4145
15	*Polar cod*	dseineHAD	21	-0.1636
16	*Pelagic small*	dseineSAI	36	-0.0551
17	*Benthic filter feeders*	dseineGRH		
18	*Skates rays*	netNCO	21	0.0364
19	*Long rough dab*	netHAD	77	-0.0053
20	*Demersal large*	netSAI	130	-0.0134
21	*Demersals other*	netGRH	133	-0.0164
26	*Minke whale*	cullMWH	835	-0.0186

Figure S.1

Selectivity curves for all age-structured groups (excluding age class 1). The points represents the mean productivity level at a given size scaled from 0-1, and the line represents the best fitted curve using non-linear square regression.



Individual species responses to BH

Nearly all commercial species are presently fished close to their respective estimated MSY, with the exception of Greenland halibut, golden redfish and capelin (ICES, 2018b, 2018c).

The calculated F_{BH} for Greenland halibut was over 6 times higher than the F_{Histo}, resulting in initially higher yields (Figure 7). However, the high catches were only achieved in the first couple of years and eventually stabilised on a slightly lower level than in the control run. BH also resulted in 80 % reduced stock biomass (Figure 3) which is of concern as Greenland halibut already is below the b_{pa} (Figure 4) There are uncertainties regarding MSY values for Greenland Halibut, as the assessment model is tuned to length data only, which gives indecisive overall biomass levels and hence unsure $F's$ in the stock assessment. It is therefore not clear what the current, or the long term sustainable, fishing mortalities actually are (ICES, 2015b).

Golden redfish has been overfished for years (ICES, 2018b) and was the only species (apart from cod) that had a lower F_{BH} than the current F_{Histo}. Golden redfish represents an interesting case, as the model results indicate that although BH would initially result in lower catches, the stock was projected to recover, and the higher biomass would sustain higher catches without increasing the fishing mortality (Figure 6). The BH catches may eventually have exceeded the control run but since redfish is a slow growing species the simulations ended before this trend could be verified. This represents an example of how BH ca contribute to a stock recovery for an over-fished species. Even if this positive effect could be achieved by lowering the fishing mortality, BH could still be useful as guidance to estimate reasonable fishing mortalities. In ecoregions where more of the stocks are currently overfished one would expect to see more such gains under BH. The results also showed that the positive effect on golden redfish was the same under a full BH regime as when only harvesting golden redfish according to BH. This suggests that BH could have positive effects on individual species without needing to apply a "full" BH regime on all species in the system.

BH on capelin suggested a higher fishing mortality (Table 4) resulting in up to 3 million tonnes extra yield. However, the capelin fishery within Atlantis is modelled as a constant fishing mortality which is known to a be poor fishing strategy for short lived stocks such as capelin and which does not match the actual management of this stock. The capelin has large fluctuations in biomass and using a fixed fishing mortality represents a problematic management strategy for such stocks, especially so for capelin which has a near 100% spawning mortality. In years with large spawning biomass a fixed fishing fraction will result in large amounts of foregone catch, while in low spawning biomass years a fixed F would give a low catch and yet manage to produce a risk of reduced recruitment the following year. The harvest control rule (HCR) of capelin is therefore using a so-called escapement strategy, in which a certain amount is allowed to spawn and only the surplus may be caught. This results in large interannual changes in the TACs, and in some years, the fishery is closed. This dynamic fishing regime is not well replicated in the current Atlantis model, and therefore comparisons to the actual fishery are problematic for this stock. Capelin represents an example of highly variable short-lived species where a fixed fishing pressure is a poor fishing strategy, and therefore an example where a BH strategy would need to be extended to encompass these dynamics, such as the density dependent BH1 (equation 1), which has not been studied in this analysis.

Haddock was the only demersal species that responded strongly to a BH regime even though the calculated F_{BH} was almost similar to F_{Histo} (Figure 3). However, these results should be treated with caution as both the biomass and the catches of haddock were unstable in all the runs. Haddock has highly variable recruitment, so the fluctuations are realistic to some degree, but the model may be exaggerating this instability. The NoBa model has recruitment based on a Beverton-Holt stock-recruitment model (Beverton and Holt, 1957), without stochastic recruitment, but even this deterministic relationship makes it difficult to track the haddock stock.

The calculated F_{BH} for cod was around half of the F_{Histo} applied in the control run, resulting in higher biomass and reduced catches. Cod is another species which is not fished with a constant F, rather the HCR imposes an F close to the single value F_{msy} estimates at SSB sizes between b_{pa} and $2*b_{pa}$ and then increasing to a higher F value at $3*b_{pa}$ (ICES, 2016). This is an attempt to tune fisheries management to increase fishing pressure at high stock sizes where density-dependent effects (both reduced individual growth rates and increased cannibalism) can be expected to reduce stock productivity. This represents another example where traditional fisheries management has progressed beyond a simple time averaged F_{msy}, and where BH1 may be a better choice than BH2 when implementing BH.

Herring and mackerel were both driven to an SSB level below the current b_{pa} suggesting that a BH regime on these two species could result in recruitment overfishing (Figure 4). Mackerel and herring are examples which naturally have extended periods of poor recruitment and can thus be pushed into recruitment overfishing by constant fishing pressure even at moderate levels. In current management the HCRs dictate that F should be reduced at low stock levels (below some trigger level). This issue is reduced under BH, which generally calls for lower fishing mortalities than current management but is not entirely avoided. These species therefore represent examples of stocks where BH, based on productivity (BH2) instead of production (BH1) may need to incorporate additional reductions in fishing pressure at low stock sizes in order to avoid recruitment overfishing.

Beaked redfish was exposed to a F_{BH} almost 7 times higher than F_{Histo} and double as high as F_{MSY}. However, it still had an SSB above b_{pa} and seemed to be relatively robust to the increased F. Beaked redfish has gone through a prolonged period of recruitment failure which has resulted in a low fishing pressure to avoid overfishing. It could therefore be expected that future fishing pressure would be higher than the current pressure. In addition, uncertainties over the SSB in the assessment model have led a fishing regime with a lower fishing mortality than might be expected from the overall estimates of the stock size (ICES, 2018d). This represents an example of the difficulties in translating a target F_{msy} into actual catch quotas which would apply to BH as much as it does to current fisheries management,

BH, with a F_{BH} of 0.25P/B, applied to species categorized as "non-commercial" in the model (either unexploited or lightly exploited in the current fishery) typically resulted in an initial peak in catches followed by a collapse. The almost uniform collapse of these non-commercial species suggested that i) either the methodology used to calculate F_{BH} did not work for these species (although the approach was the same as for the commercial species), or ii) that the NoBa model has been parameterized and tuned for these species in such a way that the model could not tolerate any additional fishing mortality.

The latter explanation seemed the most plausible as the non-commercial species in the model generally have a higher natural mortality (non-predatory) applied in the parameterization compared to those commercially harvested. This is likely a result of the less available amount of information on non-commercial species, and a model development focussing primarily on the dynamics of the commercially important species. The few species that did tolerate the 0.25P/B applied fishing pressure was zooplankton, minke whale and polar cod, which are species that are currently lightly harvested and therefore have more available information. Consequently, to avoid collapse, it was decided to modify the fishing mortality of the remaining non-commercial species to half of the initial calculated F_{BH} corresponding to 12.5% of estimated productivity instead of 25% (Table 2).

After reducing the $BH_{25\%}$ fishing mortalities on the non-commercial species by half, the mesopelagic fish were the only stocks that were driven to near collapse (Figure 5). This reduction had a strong effect on blue whiting as it is highly dependent on mesopelagic fish as a food source. $BH_{25\%}$ on mesozooplankton resulted in a 50 % reduction of biomass (Figure 5) and increased catches of 80 mill tonnes (Figure 7), which is 20 times more than the total Norwegian annual commercial landings. Both mackerel and herring were slightly negatively affected by BH on zooplankton, but not as strong as the reduction of mesopelagic fish affected blue whiting. Large phytoplankton was the functional group that was most affected by harvesting on mesozooplankton (Figure 10), possibly due to increased predation pressure caused by a prey shift by species that would normally feed on mesozooplankton.

In summary, most species in this study experienced a reduced biomass, but higher catches, when subjected to a BH regime (apart from cod, golden redfish and haddock) due to generally higher fishing mortalities (F_{BH}) applied when setting them to 25% of the estimated productivity. A principle of BH is that the fishing mortality (to some degree) substitutes the natural predation mortality, as catch on predators means less predation on prey, which then can be harvested. Still, the recommended "moderate fishing mortality" is not well defined in BH (Garcia et al., 2012), and if the gains from reduced predation are less than the loss from increased F, then the biomass will decrease, although this is not necessarily the same as overfishing. Interestingly, harvesting on non-commercial species had limited effects on the commercial species, although it had a large effect on themselves. The only species that was strongly reduced was blue whiting in response to BH on mesopelagic fish. These findings suggest that the linkages between commercial and non-commercial species in the NoBa model are overall relatively small. In the current model, we suggested to set "moderate fishing mortality" to be 25% of estimated productivity, which is considerably less than the sustainable limit of 40% suggested by Patterson (1992) and Pikitch et al. (2012). It should be noted, however, that the current method of estimating productivities applied within the Atlantis model is novel and has not been fully vetted.