Combined effects of fishing and oil spills on marine fish: Role of stock demographic structure for offspring overlap with oil

Leif Chr. Stige[a,*], Geir Ottersen[a,b], Natalia A. Yaragina[c], Frode B. Vikebø[b], Nils Chr. Stenseth[a,d], Øystein Langangen[a]

[a] Centre for Ecological and Evolutionary Synthesis (CEES), Department of Biosciences, University of Oslo, P.O. Box 1066, Blindern, N-0316 Oslo, Norway
[b] Institute of Marine Research, P.O. Box 1870, N-5817 Bergen, Norway
[c] Polar Research Institute of Marine Fisheries and Oceanography (PINRO), 6 Knipovich Street, Murmansk 183038, Russia
[d] The Centre for Coastal Research, University of Agder, P.O. Box 422, N-4604 Kristiansand, Norway

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ABSTRACT

It has been proposed that the multiple pressures of fishing and petroleum activities impact fish stocks in synergy, as fishing-induced demographic changes in a stock may lead to increased sensitivity to detrimental effects of acute oil spills. High fishing pressure may erode the demographic structure of fish stocks, lead to less diverse spawning strategies, and more concentrated distributions of offspring in space and time. Hence an oil spill may potentially hit a larger fraction of a year-class of offspring. Such a link between demographic structure and egg distribution was recently demonstrated for the Northeast Arctic stock of Atlantic cod for years 1959–1993. We here estimate that this variation translates into a two-fold variation in the maximal proportion of cod eggs potentially exposed to a large oil spill. With this information it is possible to quantitatively account for demographic structure in prospective studies of population effects of possible oil spills.

1. Introduction

Multiple stressors such as over-exploitation and pollution often impact natural systems non-additively, implying a need to study such impacts in concert (Crain et al., 2008). High fishing pressure has led to demographic changes in many fish stocks, towards increased dominance of young and small spawners (Law, 2000; Longhurst, 2002; Berkeley et al., 2004; Ottersen, 2008). It is feared that heavy fishing thereby increases the stocks' sensitivity to environmental influences, including effects of acute oil spills (Hjermann et al., 2007). Specifically, erosion of demographic structure may reduce the diversity of spawning strategies and the spatiotemporal distribution of eggs and larvae (Kjesbu et al., 1992; Opdal, 2010; Opdal and Jørgensen, 2015), which are life-stages thought to be particularly sensitive to toxic oil compounds (e.g., Carls et al., 1999; Sørhus et al., 2015). Hence, the proportional overlap between these sensitive early life-stages and oil in the case of an oil spill may increase. However, quantitative knowledge on how erosion of spawning stock structure influences potential overlap of offspring with oil is scarce.

The Northeast Arctic (NEA) stock of Atlantic cod *Gadus morhua* is currently the world's largest and of high economic and ecological importance (Kjesbu et al., 2014). Spawning occurs along the west and

north coasts of Norway from mid-February to early May (Ottersen et al., 2014) and the eggs and larvae drift pelagically north- and eastwards towards the Barents Sea nursery area (Olsen et al., 2010). The drift path of the eggs and larvae crosses areas with ongoing oil activities as well as areas that are closed for such activities due to concern for fisheries and the environment – a topic of political and scientific debate (Misund and Olsen, 2013; Blanchard et al., 2014).

Statistical analyses of egg survey data for NEA cod for 1959–1993 revealed positive associations of distributional extent of cod eggs with mean weight (and alternatively, age) in the spawning stock, spawning stock biomass and a liver condition index (Stige et al., 2017). We here build on results of Stige et al. (2017) and use the same egg survey data to quantify in more detail how changes in mean weight and total biomass of spawners are likely to influence the egg distribution and thereby the potential overlap between eggs and oil. We first consider a case study where overlap between oil and cod eggs is simulated for a large oil spill near the main spawning grounds of NEA cod for one year, and assess how hypothetical changes in egg distribution associated with demographic variables influences overlap calculations. Subsequently, we construct an index of "worst-case" overlap rate by identifying the areas with highest cod egg concentrations and calculating how large a fraction of a year-class is maximally contained within an area of a given

size. We then assess how this fraction depends on spawning stock biomass and mean weight of spawners. We thus quantify the roles of stock size and demographic structure in influencing potential year-class susceptibility to geographically bounded events such as oil spills. We hypothesize that both low mean weight and low total biomass of spawners lead to increased susceptibility to oil spills.

2. Methods

2.1. Data

Eggs of NEA cod were sampled during dedicated ichthyoplankton surveys by the Polar Research Institute of Marine Fisheries and Oceanography (PINRO), Murmansk (Mukhina et al., 2003). The survey covered main drift areas of eggs and larvae of NEA cod between 67°30′N and 74°30′N from about 7 km (4 nautical miles) to 500 km from the coast. From around 10% to 25% of the landings from the fisheries on spawning fish in years 1959–1969 were from south of the survey area (Opdal, 2010), with the long-term trends in the proportion apparently covarying with the mean age of the spawners [(Opdal and Jørgensen, 2015) but see (Sundby, 2015)]. The survey was conducted in April–May, i.e. 0–2 months after the peak spawning of the cod (Ellertsen et al., 1989), each year from 1959 to 1993, except 1967, when there was no survey. On average 156 stations were sampled each year, but with considerable variability among years in the extent and timing of the survey (Mukhina et al., 2003; Stige et al., 2015). Cod eggs were classified into four developmental stages based on morphology. Stage-1 eggs could not be reliably differentiated from the eggs of haddock. Stage-1 eggs were therefore classified to species according to the fraction of cod compared to haddock eggs of stages 2–4 in the sample. For further details on the ichthyoplankton data we refer the reader to Mukhina et al. (2003) and Stige et al. (2015).

Spawning stock biomass (*SSB*, tonnes) data were obtained from ICES (2009). *SSB* is computed using values for stock number at age from extended survivors analysis (XSA) based mainly on fisheries data, weight-at-age in the stock and maturity-at-age, calculated as weighted averages from Russian and Norwegian surveys during the autumn and winter seasons (Marshall et al., 2006; ICES, 2009). We used log-transformed biomass, $logSSB = \log_e(SSB)$, hence assuming a log-linear relationship with egg abundance in the statistical analysis.

Mean biomass-weighted weight in the spawning stock ($\overline{W}$, kg) was calculated from abundance-at-age estimated by XSA, weight-at-age and maturity-at-age, all from ICES (2009):

$$\overline{W}_j = \frac{\sum_{a=3}^{a=13+} W_{aj}(N_{aj}W_{aj}M_{aj})}{\sum_{a=3}^{a=13+}(N_{aj}W_{aj}M_{aj})} \tag{1}$$

Here, N_{aj}, W_{aj} and M_{aj} are, respectively, number, mean weight (kg) and proportion mature at age a in year j. The product ($N_{aj}W_{aj}M_{aj}$) is thus mature biomass-at-age and the denominator sums up to SSB_j. By weighting by biomass and not abundance of each age class, $\overline{W}$ represents the sizes that dominate the spawning stock in terms of potential egg production. $\overline{W}$ is highly correlated with mean age in the spawning stock (product-moment correlation, $r = 0.92$).

The liver condition index (*COND*, %) is liver wet weight, measured as percentage of total wet weight for cod of lengths 41–70 cm for January–December the year before spawning (Yaragina and Marshall, 2000).

2.2. Statistical analysis of how spawning stock variables influence egg distribution

To quantify the change in spatial distribution of cod eggs under contrasting biomass and size structure in the spawning stock, we fit a spatiotemporal statistical model to the cod egg data. Following results of time-series analyses by Stige et al. (2017) identifying significant

predictors of cod egg distributional extent, we included sampling day-of-year (*Day*), sampling location (*Lon*, °N, and *Lat*, °E), *COND*, $\overline{W}$ and *logSSB* as predictor variables. Following the same results, no abiotic environmental variables were included. The spatiotemporal statistical model was used to estimate the spatial distribution of cod eggs as function of $\overline{W}$ and *logSSB* and mean values of the other predictor variables. Specifically, the expected stage-specific and total egg abundances at different locations in the survey area at a date representing a peak in observed egg abundance halfway through their development (10th April) were calculated by multiplying estimated probabilities from a binomial submodel with estimated conditional abundances from a lognormal submodel. The spatiotemporal statistical model is described in detail in Appendix A.

2.3. Simulation of overlap between oil and fish offspring

To illustrate how spawning stock size and demographic structure can be accounted for in oil spill simulations we used results from Vikebø et al. (2014), who modelled overlap between oil compounds and eggs and larvae of NEA cod for four hypothetical oil spill scenarios, all simulated for the same year (i.e., 1997). The modelling is described in details by Vikebø et al. (2014) and only summarized here. Specifically, 94,500 particles each representing a large number of cod eggs were released at the known spawning grounds and in the spawning period (1 March–30 April) of NEA cod and transported horizontally based on their vertical positioning in the water column and ocean currents. Ocean currents were simulated using a regional ocean model system for the Nordic Seas with resolution 4×4 km (Lien et al., 2014). The transport and fate of oil compounds were simulated based on the same ocean model. We here investigated two oil spill scenarios representing a large oil spill at the peak of the spawning season (i.e., 4,500 tonnes of oil per day for 30 days, 1–30 April) but differing in oil spill location (scenario 1: N 68.67, E 13.92, scenario 2: N 68.83, E 13.45). Two other scenarios with oil spill locations farther south investigated by Vikebø et al. (2014) were not analysed here because the majority of the impacted eggs were outside of the survey area (N 67.5–74.5, E 8–31.5). For each particle we found the maximal concentration of total polycyclic aromatic hydrocarbon (TPAH) along its drift trajectory through the egg and larval stages, here using the highest concentration in the water column (Vikebø et al., 2014, also considered ambient concentrations at the depths of the particles). Overlap was calculated as percentage of individuals having maximal TPAH concentration above thresholds of 0.1 parts per billion (ppb) or 1.0 ppb, representing, respectively, order of magnitude thresholds for sublethal and lethal effects. Note that work is still ongoing to refine these values for different stages and species.

The simulation results of Vikebø et al. (2014) represent a historical average situation in terms of spawning stock size and –structure. To assess the effect of altering $\overline{W}$ or *logSSB* we weighted the particles, i.e. the number of individuals each particle represented, based on the results of the statistical analysis of how spawning stock variables influence egg distribution. The weighting was based on the location of the particles half-way through the egg development, i.e., around the transition from the second to the third egg stage. To simulate the egg distribution expected under high $\overline{W}$ each particle was weighted by the predicted egg abundance for that location for the 90th percentile of $\overline{W}$ divided on the prediction for the same location for mean $\overline{W}$. The predictions were for total numbers of stage-2 and stage-3 eggs at April 10, which was between the peaks of abundance for these two stages. Note that effects of $\overline{W}$ and *logSSB* on egg distribution in the statistical model were assumed to be independent of day-of-year and egg stage (at the linear scales of the predictors in the binomial and lognormal submodels); hence the application of these weights based on locations at a single developmental stage independent of when that stage is reached is consistent with the statistical model. Particles outside of the survey area (representing 20% of the individuals) were excluded from the analysis