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The effects of oil spills on marine fish: Implications of spatial variation in natural mortality

Ø. Langangen [a,*], E. Olsen [b], L.C. Stige [a], J. Ohlberger [a,c], N.A. Yaragina [d], F.B. Vikebø [b], B. Bogstad [b], N.C. Stenseth [a,e,f], D.Ø. Hjermann [a,g]

[a] Centre for Ecological and Evolutionary Synthesis (CEES), Department of Biosciences, University of Oslo, PO Box 1066, Blindern, N-0316 Oslo, Norway
[b] Institute of Marine Research, PO Box 1870, Nordnes, N-5817 Bergen, Norway
[c] School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195, USA
[d] Polar Research Institute of Marine Fisheries and Oceanography, 6 Knipovich St., Murmansk 183038, Russia
[e] Institute of Marine Research, Flødevigen, Nye Flødevigveien 20, 4817 His, Norway
[f] Centre for Coastal Research (CCR), Department of Natural Sciences, University of Agder, PO Box 422, N-4604 Kristiansand, Norway
[g] Norwegian Institute for Water Research, Gaustadalléen 21, N-0349 Oslo, Norway

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ABSTRACT

The effects of oil spills on marine biological systems are of great concern, especially in regions with high biological production of harvested resources such as in the Northeastern Atlantic. The scientific studies of the impact of oil spills on fish stocks tend to ignore that spatial patterns of natural mortality may influence the magnitude of the impact over time. Here, we first illustrate how spatial variation in natural mortality may affect the population impact by considering a thought experiment. Second, we consider an empirically based example of Northeast Arctic cod to extend the concept to a realistic setting. Finally, we present a scenario-based investigation of how the degree of spatial variation in natural mortality affects the impact over a gradient of oil spill sizes. Including the effects of spatial variations in natural mortality tends to widen the impact distribution, hence increasing the probability of both high and low impact events.

1. Introduction

The risk of large marine oil spills, such as the Exxon Valdez oil spill (Peterson et al., 2003) and the Deepwater Horizon disaster (Crone and Tolstoy, 2010; Kerr et al., 2010), is often perceived as a threat to fish stocks. Very few studies have demonstrated increased mortality of fish as a result of oil spills (Fodrie et al., 2014; Hjermann et al., 2007; IPIECA, 1997). Nevertheless, fish stocks may be especially vulnerable to oil spills close to the spawning grounds or egg and larval drift areas (Hjermann et al., 2007; Rooker et al., 2013). Fish eggs and larvae are typically vulnerable to toxic oil compounds due to their small size, poorly developed membranes and detoxification systems as well as their position in the water column. A number of laboratory studies have shown that oil or oil compounds (mainly polycyclic aromatic hydrocarbons, PAHs) at low concentrations can kill or cause sub-lethal damage to fish eggs and larvae (Carls et al., 1999; Hicken et al., 2011; Meier et al., 2010; Scott and Sloman, 2004; Sørhus et al., 2015). Sub-lethal effects include, e.g., morphological deformities, reduced feeding and growth rates, and are likely to increase vulnerability to predators and starvation. The few existing in situ studies of fish mortality at spill sites indicate sub-lethal effects or elevated mortality of eggs and larvae (deBruyn et al., 2007; Hose et al., 1996; Incardona et al., 2012; McGurk and Brown, 1996).

Studies of biological impacts of oil spills are of two types: retrospective studies investigating the impact of a spill, and, prospective studies estimating the probable outcome of potential future oil spills. In this paper, we focus on the latter. Assuming that an oil spill mainly kills fish at the egg or larval stage (Hjermann et al., 2007), the impact of an oil spill on a fish stock depends on (*i*) the proportion of the eggs and larvae killed by the oil spill, and (*ii*) how early-stage mortality affects cohort survival in subsequent stages. In practice, the availability of methods and data tends to guide assessment of spill impacts. Regarding (*i*), there typically exist data on the spatial distribution of fish eggs and larvae, as well as physical and chemical modeling of advection, spreading, evaporation, dispersion and emulsification of oil (e.g. Hjermann et al., 2007 and references therein). Together with information on which concentrations or exposure (cumulative concentrations over time) to oil are lethal, one can estimate the percentage of eggs or larvae that are killed (French-McCay, 2004; Vikebø et al., 2014). Regarding (*ii*), modelers typically rely on population models (French-McCay et al., 2003; Ohlberger and Langangen, 2015). Further important issues regarding (*ii*), such as spatial variations in vital rates have largely been ignored in impact assessments. There is an appreciation of these matters

* Corresponding author.
E-mail address: oysteol@ibv.uio.no (Ø. Langangen).

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in the scientific community and acknowledgment that the main reasons for leaving these effects out in impact assessments are lack of relevant data and reliable models.

In this study, we focus on the effect of spatial patterns in early-stage natural mortality on cohort survival. In prospective studies, one is concerned with the range of possible outcomes and in particular the probability of adverse effects. Estimating such probability requires an understanding of the combined effect of natural mortality and mortality related to the exposure to oil. Current oil spill risk assessments typically ignore spatial variability in survival, and assume a constant mortality rate across the distribution area or a probability distribution around an average (e.g. Brude and Sverdrup, 2011). However, without empirically based studies it is impossible to estimate effects of spatial variability in mortality.

Here, we first present a hypothetical "thought experiment" to illustrate the concept. Second, we further illustrate the importance of including spatial variations in mortality into the assessment, by considering an example of a spatially bounded mortality event for the stock of Northeast Arctic (NEA) cod (*Gadus morhua*). Third, based on the NEA cod example, we quantify the possible change in impact of an oil spill by considering different scenarios.

2. Materials and methods

2.1. Thought experiment to illustrate the concept

A typical example, motivated by the NEA cod, of drift and natural mortality of the planktonic early life stages of a fish is illustrated in Fig. 1. The spawning grounds are at the left side of the figure, and we have assumed spawning to be particularly concentrated in two areas (marked 1 and 2). The eggs develop into larvae and juveniles as they drift along the currents. Due to variation in drift speed, direction, and diffusion, the extent of the distribution of eggs, larvae and juveniles increases with time. If the mortality is uniform in space, drift and diffusion are the primary determinants of the distribution (Fig. 1, thought experiment 1). Here, the two spawning grounds contribute approximately equally to the juvenile abundance (right hand side of Fig. 1, marked 1 and 2). Alternatively, spatial variation in natural mortality may be present. If we assume higher survival close to the mainland (Fig. 1, thought experiment 2), the density in the juvenile stage (right side of Fig. 1) is highest closer to the coast. The cohort impact (proportion affected) of an oil spill at the egg stage (left side of Fig. 1) affecting either area (1 or 2), killing approximately the same amount of eggs, will translate to about the same impact at the juvenile stage in thought experiment 1. In contrast, in the second thought experiment, an oil spill affecting the egg stage will have a considerable impact at the juvenile stage if area 2 is affected, and an insignificant impact at the juvenile stage if area 1 is affected. The concept may also generalize to any spatially bounded event resulting in elevated mortality, e.g. extreme weather events such as storms (Lough et al., 1996) and predatory species invasions (Nentwig, 2007). We here define the *effective density* as the density weighted with the future survival probabilities. Thus, two regions with the same actual density of eggs have different effective density if the currents transport the eggs and larvae into areas with different natural mortality. To determine the significance of spatial variability in natural mortality on the assessed impact of an oil spill, empirical examples must be considered.

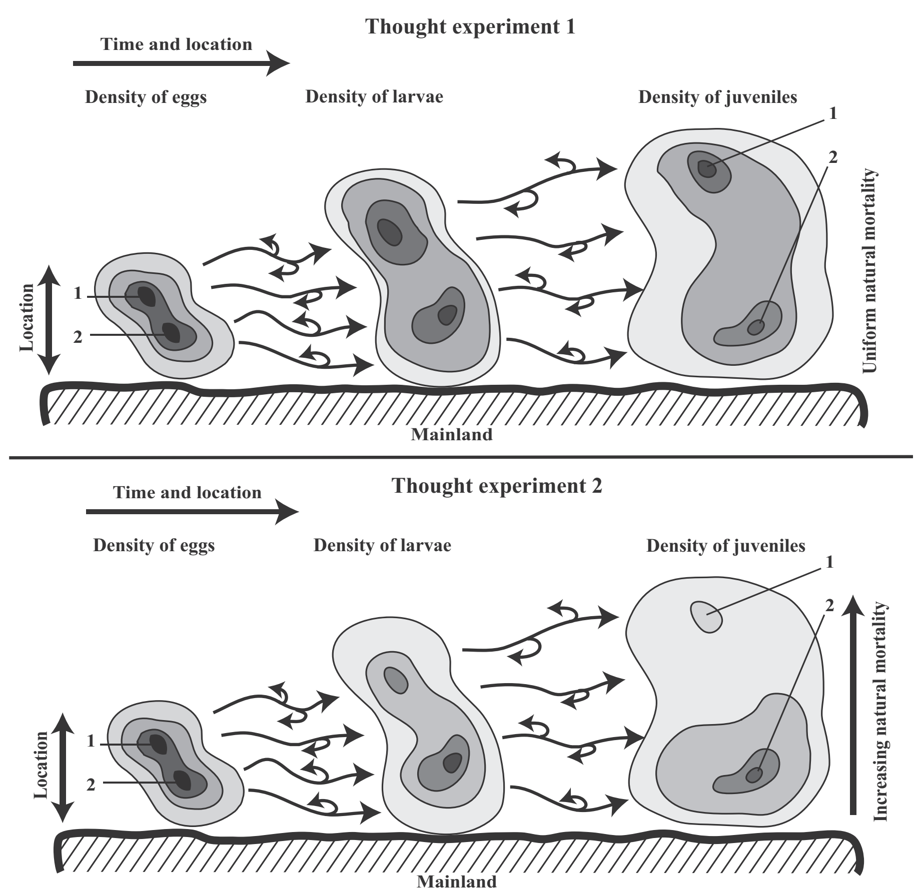

Fig. 1. Conceptual model of effective density. The changes in density (darker shade = higher density) of early life stages of a fish with pelagic eggs and larvae drifting in a current (indicated by arrows, from left to right) are illustrated. The changes in density are due to advection and diffusion (Thought experiment 1) and also spatial differentiated natural mortality (Thought experiment 2, with mortality for illustration purposes assumed to be increasing with distance from the mainland). See main text for further details.