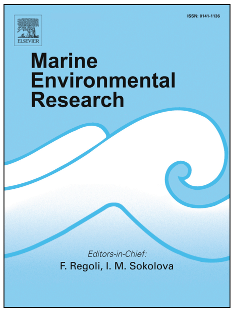

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Seasonal ecology in ice-covered Arctic seas - considerations for spill response decision making

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ABSTRACT

Due to retreating sea ice and predictions of undiscovered oil and gas resources, increased activity in Arctic shelf sea areas associated with shipping and oil and gas exploration is expected. Such activities may accidentally lead to oil spills in partly ice-covered ocean areas, which raises issues related to oil spill response. Net Environmental Benefit Analysis (NEBA) is the process that the response community uses to identify which combination of response strategies minimises the impact to environment and people. The vulnerability of Valued Ecosystem Components (VEC's) to oil pollution depends on their sensitivity to oil and the likelihood that they will be exposed to oil. As such, NEBA requires a good ecological knowledge base on biodiversity, species' distributions in time and space, and timing of ecological events. Biological resources found at interfaces (e.g., air/water, ice/water or water/coastline) are in general vulnerable because that is where oil can accumulate. Here, we summarize recent information about the seasonal, physical and ecological processes in Arctic waters and evaluate the importance these processes when considering in oil spill response decision making through NEBA. In spring-time, many boreal species conduct a lateral migration northwards in response to sea ice retraction and increased production associated with the spring bloom. However, many Arctic species, including fish, seabirds and marine mammals, are present in upper water layers in the Arctic throughout the year, and recent research has demonstrated that bioactivity during the Arctic winter is higher than previously assumed. Information on the seasonal presence/absence of less resilient VEC's such as marine mammals and sea birds in combination with the presence/absence of sea ice seems to be especially crucial to consider in a NEBA. In addition, quantification of the potential impact of different, realistic spill sizes on the energy cascade following the spring bloom at the ice-edge would provide important information for assessing ecosystem effects.

Keywords: Arctic ecosystem, NEBA, oil spill response, seasonal dynamics

1. INTRODUCTION

According to predictions, up to 30% of the worlds' undiscovered gas reserves and 13% of the worlds' undiscovered oil resources are located in the areas north of the Arctic Circle, mainly offshore in relatively shallow waters (Gautier et al. 2009). However, major parts of these areas are covered by sea ice, either permanently or seasonally (Fetterer et al. 2002). Activities associated with oil exploration and production will always be associated with a certain risk of oil spills. Oil spills may happen during drilling, production (extraction), transportation in pipelines or by ships, and from other vessels associated with oil activities (e.g., supply vessels). The presence of ships in the Arctic is expected to rise, not only as a consequence of increased oil exploration, but also because the decreasing ice coverage in the Arctic facilitates increased shipping in these areas (Glickson et al. 2014). An accidental oil spill in the Arctic may result in oil contamination of ice-covered areas, thereby affecting Valued Ecosystem Components (VEC's). In the case of an accidental spill, the response community should have tools available to support Arctic spill response decision making, in order to minimize the impact on VEC's.

Net Environmental Benefit Analysis (NEBA) is a process that is used by the response community to select the response strategy that minimizes the impact of an oil spill on the environment and communities and decreases the time needed for recovery (IPECIA, 2015). This process requires information on the spill (oil type, release rates, duration, trajectory, etc.), understanding of the relative impacts of oil and spill response actions, and an evaluation of the relative importance of social, economic and environmental factors. If an accidental oil spill occurs, physical parameters such as oceanographic and sea ice conditions will determine the fate of the drifting oil, and therefore have to be taken into account in the NEBA process. The vulnerability of an ecological feature (e.g., a species) to a certain stress factor (e.g., oil exposure) depends on its sensitivity to that stress factor (i.e., the degree to which the species responds to the stress factor) and the probability that it will be exposed to that particular stress factor (Zacharias & Gregr 2005). Furthermore, the probability of being exposed to oil depends in turn on the species' spatio-temporal distribution, which in the Arctic is affected by the time of the year and therefore the light conditions and the distribution of the sea ice.

Although being structurally much more complex than previously thought, Arctic ecosystems can be characterized by relatively low biodiversity, relatively simple ecosystem structure, and a high degree of specialization among species (Post et al. 2009; Kortsch et al. 2015). This lack of functional redundancy renders them to be more vulnerable than less specialized systems with a higher biodiversity. Arctic ecosystems also appear to be more strongly dominated by benthic than pelagic processes as compared to boreal ecosystems (Reigstad et al. 2011; Wiedmann 2014). We therefore summarize recent information about the dynamics, seasonality and spatio-temporal distributions of key species in the Arctic, in the light of prevailing physical processes, and evaluate the importance of this information to oil spill response decision making through NEBA.

2. RESPONSE OPTIONS

In the Arctic, particular environmental conditions (e.g., sea ice, low temperatures, strong winds, winter darkness, and remote locations) constitute the most important variables regulating the outcome of accidental oil spills. For instance, the remoteness of most of the vast Arctic marine areas makes early response challenging. Furthermore, spilled oil may be trapped by drifting sea ice and transported over long distances, severely complicating visual tracking as well as cleanup operations. In the case of small spills, natural attenuation (i.e., physical, chemical and biological processes) may be sufficient for removing the oil from the environment. Larger spills, on the other hand, require human action in order to minimize the potential for environmental damage (Gabrielsen & Sydnes 2009). In order to remove oil slicks from the sea surface, a number of response methods have been developed, including mechanical recovery, dispersant treatment, and *in situ* burning. These response methods have in common that they are all most effective when applied as soon as possible after the spill (Fingas 2011). Each of the methods have their strengths and weaknesses which are dependent on factors such as the volume of the spill, the time needed to respond to the spill, environmental conditions and the proximity to the shoreline or VEC's..

Mechanical recovery (e.g., skimmers) may be used to remove thick layers of oil from a calm sea surface. As such, this method may be used close to shore in order to avoid oil drifting onshore, though it must be applied before the oil emulsifies (i.e., before the oil mixes with seawater and forms so-called "chocolate mousse") (Gabrielsen & Sydnes 2009).

Dispersant treatment involves the addition of chemicals in order to disperse the oil into smaller components that will mix with the water masses below the sea surface. Provided a rapid response (i.e., before the oil emulsifies), dispersants will effectively remove the oil from the surface, and are therefore more often used if there is a harming risk to VEC's e (e.g., seabirds). Recent research has shown that certain dispersants may perform effectively under wave action and low temperatures (Belore et al. 2009). However, since dispersed oil will still be present and toxic in the water column, it may continue to harm organisms living in the vicinity of the spill region (e.g., zooplankton, fish larvae) (Gabrielsen & Sydnes 2009).

In situ burning is often regarded as the best method to remove oil from Arctic waters (Fritt-Rasmussen & Brandvik 2011). This method requires a rapid response, before the lightest, highly flammable oil components (e.g., methane, ethane) evaporate and thereby raise the flame point of the remaining share of the oil (Gabrielsen & Sydnes 2009). However, the low Arctic temperatures lead to a slow rate of evaporation of these light oil components as compared to warmer areas, which makes *in situ* burning in the Arctic comparably efficient (Gabrielsen & Sydnes 2009). A disadvantage of *in situ* burning is that it creates considerable amounts of smoke and soot (Sydnes et al. 1994, Fritt-Rasmussen & Brandvik 2011), potentially increasing the melting rate of sea ice and thereby affecting ice-associated species.

As such, the choice of response methods represents a tradeoff between potentially affecting species at the surface vs. potentially affecting species found elsewhere in the ecosystem (e.g., in the water column).

3. THE ARCTIC ECOSYSTEM

3.1 OCEANOGRAPHY

The deep central Arctic Ocean is surrounded by 16 ocean regions, of which 12 are true Arctic seas and four are gateways between the Arctic and the Atlantic or the Pacific Ocean (Christiansen & Reist 2013) (Fig. 1).

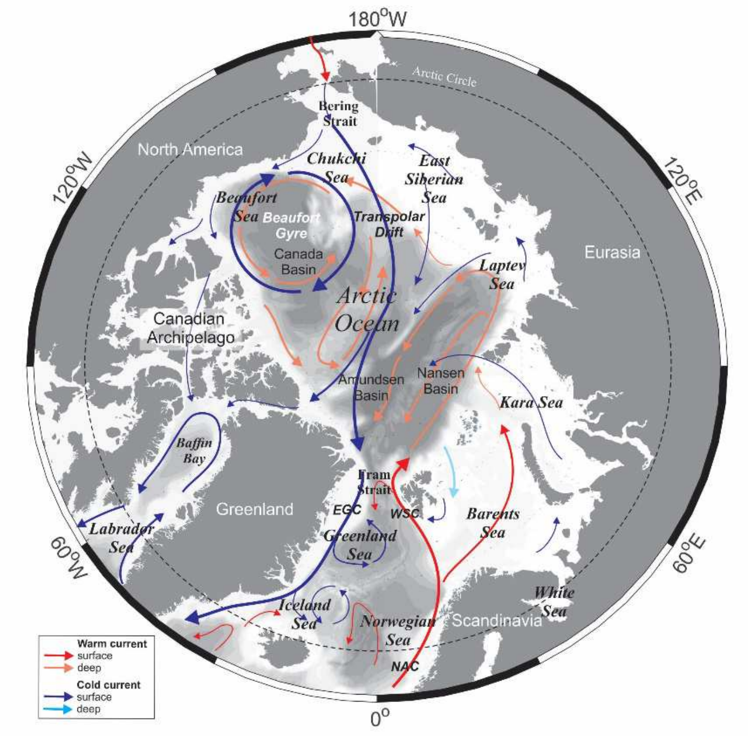

Fig. 1. Overview of the current system of the Arctic Ocean. Dashed line indicates the position of the Arctic Circle.

The spatial distribution of the Arctic sea ice displays high intra- and inter-annual variation. In March and April, the sea ice coverage is traditionally highest, in recent years typically covering ~14.5-16.0 million km^2, whereas in September and October, the sea ice coverage is smallest, typically covering ~3.5-8.0 million km^2 (Fetterer et al. 2002). Thus, the inter-annual variation in springtime sea ice coverage is relatively small, whereas the variation in sea ice coverage during autumn is relatively large (Fig. 2). The climate in the Arctic is strongly affected by the flow of water masses through the corridor between the Fram Strait and the Kara Sea (i.e., the “European Arctic corridor”), where >80% of the exchange occurs between the Arctic Ocean and the adjacent Atlantic and Pacific Oceans (Wassmann & Reigstad 2011). Warm, salty water masses flow into the Arctic Ocean from the Atlantic Ocean through the Fram Strait and the Barents Sea, whereas Pacific water masses enter the Arctic Ocean through the Bering Strait; the former being about 10 times greater in volume than the latter (Woodgate 2013). As such, warm periods in the Arctic are associated with a northward transport of Atlantic water (Smedsrud et al. 2013). Water masses flow out the Arctic Ocean via the Fram Strait and through various channels in the Canadian Archipelago (Woodgate 2013).

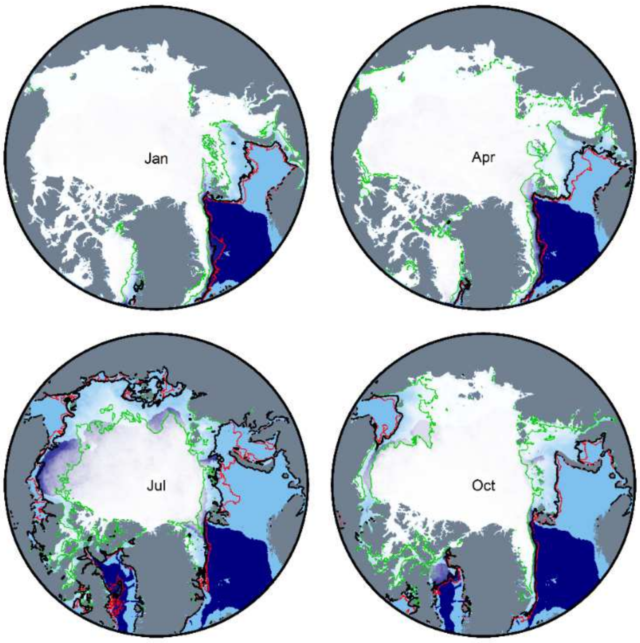

Fig. 2. Ice conditions in the Arctic in January, April, July and October. The ice shading is the average situation, the black line is average, green is minimum and red is maximum. Sea ice concentration data were obtained from the AMSRE2 product (Spreen et al, 2008), and were combined to create seasonal maps representing average ice conditions over the period 2003–2011.

3.1.1 Sea ice and open water masses

In the Arctic, the distribution of sea ice determines, to a large degree, the distribution of species. Some Arctic shelf seas (e.g. the Barents Sea) are not entirely covered by sea ice at any time of the year, whereas other areas (e.g. the Bering Sea) display sea ice well beyond the Arctic Circle (i.e., 66°33’45.8N). The summer sea ice extent has declined steadily since satellite records started in 1979, with a record minimum recorded in 2012. This is observed particularly in the Marginal Ice Zone (MIZ), defined as that part of the ice cover which is close enough to the open ocean boundary to be affected by it's presence (Wadhams 1986), often coinciding with the area between the summer minima and winter maxima of the ice extent. The MIZ covers most of the Arctic shelf and the shelf break. The increase in the area of open water is not only visible in the MIZ, but also as an increase in leads throughout the Arctic Ocean (Barber et al. 2015). This has directly affected the area were light is available for primary production, even underneath sea ice. As the ice extent and ice thickness decreases, the area of open water increases. Between 1990-1995 there was only a moderate increase in the area of open ocean for the months July to December, whilst since 1979 there has been a continuous increase for the period March to June. For the period after 1995, the area of open ocean has increased for all months (Barber et al. 2015).

There is a historical record of changes in the sea ice cover in the European Arctic from 1580 until today, based on the logbooks of European whalers and explorers and updated for the period 1979 to 2011 by data recorded from satellites (Vinje 1999, Falk-Petersen et al. 2015). During these 430 years, there have been several periods with extensive ice cover. The periods 1625 to 1660 and 1780 to 1920 were especially characterized by heavy ice conditions with summer ice as far south as 76^0 N. The periods 1670 to 1780 and 1920 until today were characterized by little ice, with years where the summer ice had retreated to North of 82^0N. The period after 1920 was characterized by a period with little ice where the ice edge was as far north as 80 to 82^0 N between 1930 and 1940 (Sverdrup 1933), followed by southward movement of the ice edge during the 1970s (Smedsrud et al. 2013). The ice cover has been retreating since the mid-1980s and the summer ice edge has been recorded north of 82^0 N several years since 2000 (Fig. 3). In combination with modern satellite monitoring of the sea ice extension, this record shows that the Arctic sea ice conditions are highly dynamic both on short and long time scales. Modelling and monitoring ice conditions is important to understand and assess behaviour and fate of oil after a spill. This is crucial information for spill response planning.

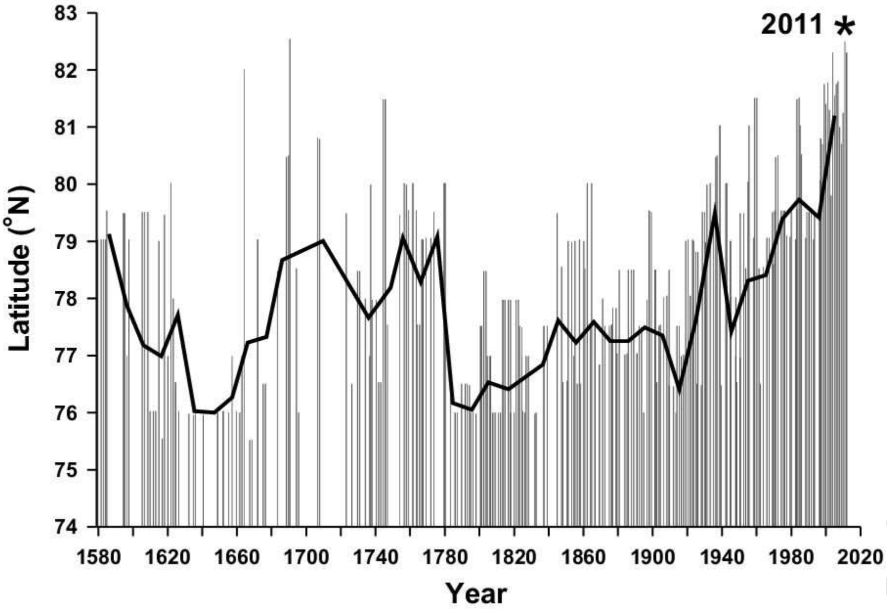

Fig. 3. The position of the ice edge in August between Svalbard and Franz Josef Land for the period 1553–2012 given by its mean latitude in the sector 20 – 45°E. Data were modified after Vinje (Vinje, 1999, http://acsys.npolar.no/adis/) and updated for the period 1979 to 2012 using satellite data. (Scanning Multichannel Microwave Radiometer (SMMR) and the Special Sensor Microwave Imager (SSM/I) daily and monthly mean sea-ice concentrations from satellite, gridded with a spatial resolution of 25x25 km. Data were obtained from the National Snow and Ice Data Center (NSIDC), see http://nsidc.org.

3.2 LIGHT CONDITIONS

Light availability is extremely seasonal at high latitudes and is key in controlling crucial ecosystem processes, including the timing of primary (and indirectly secondary) production, behavioral patterns and vision of animals. The light available for marine plants and animals is controlled by the seasonal variability of the solar angle, sea ice cover and snow cover on the ice, as well as cloud cover. North of the Arctic Circle, the sun is above the horizon for a 24 h cycle during certain periods in summer, and below the horizon for 24 h during parts of the winter. The further North, the longer the periods of midnight sun and polar night and at the North Pole, there is only one day and one night over the year. During summer time, the light available for primary producers is a prime factor controlling the biological energy production at the basis of the food web. During winter, low light conditions prevent not only photosynthesis, but impair optical foraging of visually oriented predators. During the Polar night, moving from south to north the light gradually declines and can be divided into 3 light zones; the *nautical polar night*, where the sun is 12^0 below the horizon (north of 78^0 N) basically covering the entire Arctic Ocean, the *civil polar night*, where the sun is between 6 and 12^0 below the horizon *(72 to 78^0 N),* and the *civil twilight*, where the sun is between 0 and 6^0 below the horizon (Arctic circle to 72^0 N). During the spring equinox (i.e., the 20th of March), the day length is approximately the same everywhere in the world. The return of the sun initiates spring in the Arctic Seas, when extremely shade-adapted algae start to grow on the underside of sea ice under extremely low light conditions (Hancke et al., 2018). Light dynamics modulate seasonal ecosystem dynamics in Arctic areas and explain, to a large degree, the ecological seasonal variations that are important to consider in NEBA evaluations. Furthermore, for oil spill response preparation plans, variable light conditions must be accounted for as clean-up actions may be hampered in the absence of daylight.

3.3 PRIMARY PRODUCTION AND CARBON FLUX

The above-described patterns in physical conditions have strong implications for photoautotrophic primary production that represents the basis of the entire marine food web. The bulk of it usually occurs only during one relatively short time window in spring/early summer, and represents the most important input of high quality food for grazers and higher trophic level marine animals during the year. Hence, the timing of this production pulse (relative to the timing of other ecological key processes, such as reproduction) is critical for the fate of the produced biomass, and the efficiency of trophic pathways.

As soon as there is enough light available ($< 1\ \mu mol\ m^{-2}\ s^{-1}$) in springtime, extremely shade-adapted algae start growing in the lowermost part of the sea ice that contains brine channels in which they can grow in a protected (though extreme) environment that experiences regular exchange with sea surface water, replenishing nutrients and inorganic carbon. The bottom sea ice algal bloom is usually the first vernal algae bloom, and represents the transition from winter to springtime (see Leu et al., 2015). The timing of its initiation and its development is controlled primarily by light availability early in the season. For example, under ice algae production has been recorded in both Rijpfjorden, Svalbard, and the Amundsen Gulf from the end of March (Figs. 4, 5; Różańska et al. 2009, Søreide et al. 2010). Since snow absorbs incoming irradiance much more efficiently than the sea ice, it seems to be the single most important environmental factor determining sea ice algal bloom phenology (Leu et al. 2015). Later on, the temperature-controlled melt process that changes the sea ice structure leads to the termination of this bloom. While it has previously been assumed that pelagic primary production only starts after sea ice retreat, pelagic algae blooms have been repeatedly reported to already initiate underneath sea ice in the vicinity to leads (Assmy et al., 2017), and occurring more frequently under degrading ice (Mundy et al. 2014, Arrigo et al. 2012). In particular this occurs when extensive melt pond formation strongly increases sea ice transparency. Arctic phytoplankton blooms are usually restricted by nutrient availability, and new production ends after the available inorganic nutrients are drawn down to the detection limit. In most cases, nitrate is the nutrient that will be depleted first. After that, regenerated primary production continues during summertime. Also, depending on the wind regime and mixing depth, autumn blooms might even occur as late as September (Ardyna et al. 2014, Falk-Petersen et al. 2008). With regard to response planning, a generally high biodensity as well as repeated peak production periods of ice-associated, low trophic level species should thus be expected from early springtime until autumn.

Fig. 4. Bottom ice algae bloom 10 April in the Amundsen Gulf, Canadian Arctic. Photo S. Falk-Petersen.

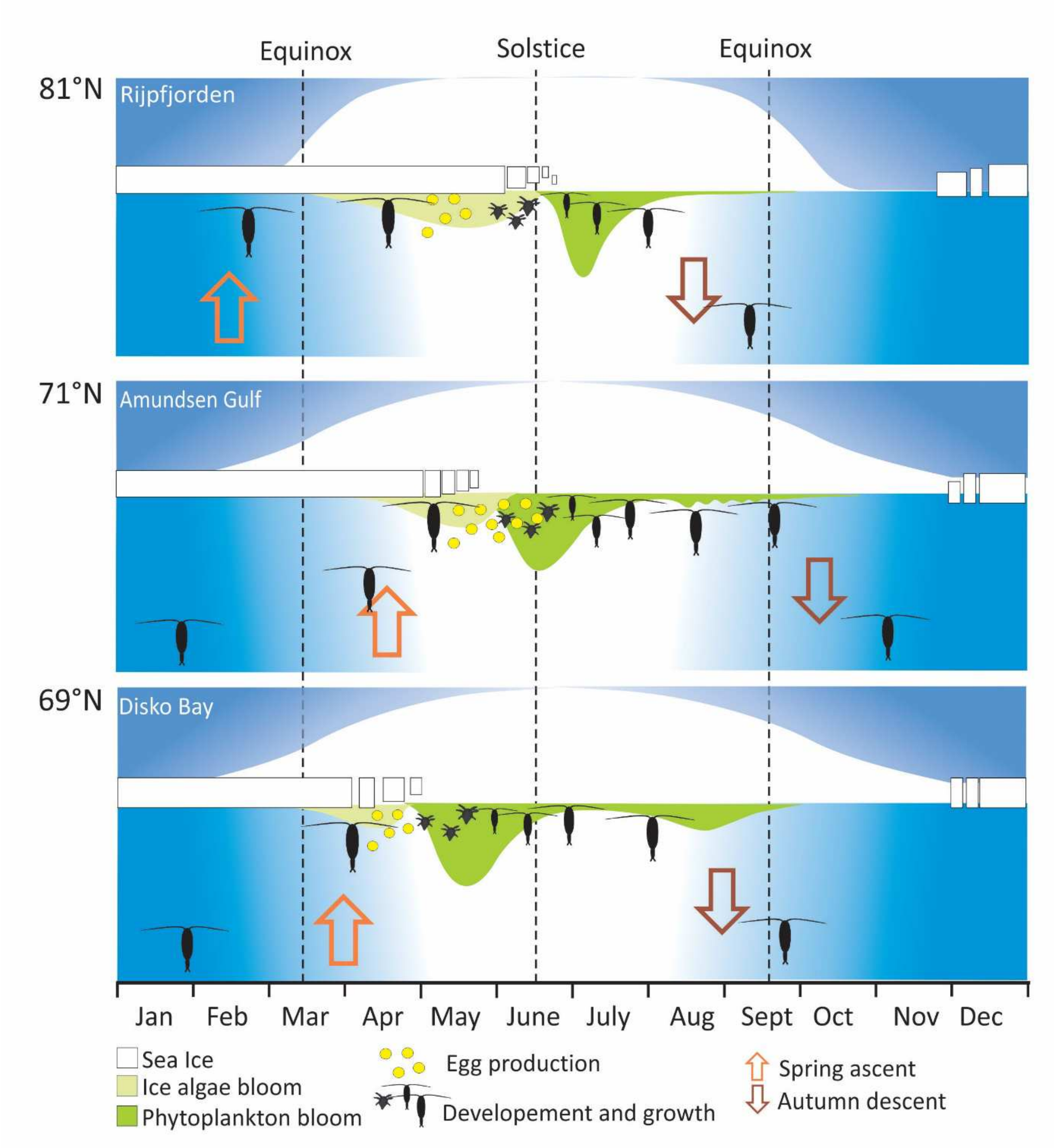

Fig. 5. Conceptual figure showing phenology of *Calanus glacialis* life history events at different locations and latitudes from the Arctic shelf. Modified from Daase et al. (2013).

The relative contribution of sea ice algal primary production to total production in a given area is very variable, and ranges from 1% in coastal areas with limited sea ice cover and strong freshwater input, to >50% in the central Arctic ocean (Gosselin et al. 1997). The ecological significance of this production is, however, much greater than these numbers suggest due to the importance of timing. Sea ice algae represent a high nutritional quality food source early in the season in sea ice covered areas. In and below the sea ice, they are grazed upon by meiofauna (Michel et al. 2002), and herbivorous zooplankton, such as the specialized pelagic grazer *Calanus glacialis*. This calanoid copepod is the key grazer in Arctic shelf sea areas, and can account for up to 70% of the total mesozooplankton biomass. *C. glacialis* females stay very close to the underside of the sea ice, where they actively graze upon the sea ice algae at the ice-water interface (Hop et al. 2011; Wold et al. 2011). Although this species is not reliant on food intake for reproduction (capital breeder strategy; Sainmont et al. 2014), it has been shown that maturation time decreases, and egg production increases when these copepods are fed (Smith, 1990; Hirche & Kattner, 1993; Kosobokova, 1999; Niehoff et al., 2002). Optimal recruitment of this key grazer is found when adult females are able to take advantage of the sea ice algal bloom for improving their productivity – and their offspring can utilize the pelagic bloom later on (Søreide et al. 2010).

Ice amphipods constitute another important link between the ice algae and upper trophic levels. For instance, *Apherusa glacialis* is a typical herbivore, whereas *Gammarus wilkitzkii*, *Onisimus glacialis* and *O. nanseni* are typical omnivores and carnivores (Melnikov 1997, Scott et al. 1999, Poltermann et al 2000, Hop et al. 2000).

When sea ice algae are released from sea ice, they are partly fed upon by pelagic grazers (Michel et al. 1996). Since ice algae often form large colonies thatsink rapidly, a substantial amount of this production reaches the sea floor, and represents an important food supply for benthic organisms (Renaud et al. 2015; Boetius et al. 2013). The efficiency of utilization of pelagic blooms depends also on the presence and abundance of grazers during the bloom phase. Ongoing warming of Arctic waters is supposed to favour a size-shift of dominating phytoplankton species towards smaller species (Li et al., 2009; Rokkan Iversen and Seuthe, 2010). This would strengthen the microbial loop, and regenerated production, thereby decreasing the direct vertical export of carbon from the euphotic zone. Based on modelling and fieldwork in the Barents Sea, Reigstad et al. (2011) estimated an annual gross primary production of ~160 g C m^{-2} $year^{-1}$ in ice-free, Atlantic water masses in the south west, whereas the annual gross primary production in seasonal ice covered Arctic waters further north was ~60 g C m^{-2} $year^{-1}$. However, Reigstad et al (2011) estimated that while only ~27% of the primary production in Atlantic water masses is transported towards the bottom, as much as ~53 % of the primary production in Arctic water masses is transported towards the bottom. As such, although the total flux of carbon to the bottom may be higher in Atlantic water masses, the proportion being transported towards the bottom is higher in the Arctic. Compared to Atlantic water masses, this may imply that the Arctic waters are more strongly governed by benthic processes than pelagic processes, and that the degree of ice coverage has a direct influence on the primary production rate in a given area (Reigstad et al. 2011). As such, inter-annual and long-term variation in ice and water mass conditions will have consequences for species distributions and ecosystem functioning, and are thereby relevant in a NEBA perspective.

3.4 SECONDARY PRODUCTION

The zooplankton community of the Arctic consist of about 300 species that spend their entire life cycle within the plankton (holoplankton) (Sirenko 2001; Sirenko et al. 2010). In addition, there are numerous benthic and fish species that have pelagic larval stages which join the zooplankton community for parts of the year (meroplankton). Brine channels in the sea ice sustain species-rich food webs throughout the year, but communities are generally most abundant and diverse in the spring and summer seasons (Arrigo 2014). Whereas many of these species are unique to the sea ice environment, other species originate from the benthic or pelagic realms and visit the sea ice in order to feed or hide from predators. These species include bacteria and protists, as well as species groups at higher trophic levels including cnidarians, copepods, amphipods, euphausiids and arthropods (Arrigo 2014, and citations therein). In the Arctic, copepods dominate in terms of species number (>50% of all Arctic holoplankton), abundance and biomass (Kosobokova and Hirche 2000; Hopcroft et al. 2005; Kosobokova et al. 2011).

Three herbivorous copepod species of the genus *Calanus* (the Arctic *C. glacialis* and *C. hyperboreus*, the Atlantic *C. finmarchicus*) are regarded as key species in Arctic and subarctic seas. *Calanus* spp. reside in surface waters during spring and summer where they feed on ice algae and pelagic phytoplankton to build up large lipid reserves (Conover 1988; Falk-Petersen et al. 2009). The ice algae bloom provides an early food source prior to the pelagic bloom, that is utilized, in particular, by the Arctic *C. glacialis* and *C. hyperboreus* who have tuned their life cycle to time reproduction and development with the occurrence of both blooms (Falk-Petersen et al. 2009; Leu et al. 2011; Daase et al. 2013). The lipid transfer from primary producers to secondary producers is very efficient with lipid levels increasing from 10-20% of dry mass in phytoplankton to 50 - 70% in the herbivorous grazers (Falk-Petersen et al. 1990) and the high lipid content makes these herbivores a rich energy source for higher trophic levels (Falk-Petersen et al. 2009; Wold et al. 2011). At the end of the productive season, *Calanus* descend to deeper waters to overwinter in a non-feeding state with reduced metabolism (Falk-Petersen et al. 2009).

The energy reserves sustain the organisms during periods of low food supply and may fuel gonad maturation and egg production to initiate reproduction prior to the spring bloom (Hirche 1997; Søreide et al. 2010). Such storage of energy rich lipids is generally considered an adaptation towards a strongly seasonal polar environment. They occur also in non-overwintering zooplankton species, such as krill species of the genus *Thysanoessa* (Sargent and Falk-Petersen 1981; Falk-Petersen et al. 1982), carnivorous hyperiid amphipods of the genus *Themisto* (Dale et al. 2006) and pteropods (Boer et al. 2005; Gannefors et al. 2005), which also make these species important food sources for fish, seabirds and marine mammals. Krill carry out typical zooplankton vertical migrations, being close to the seabed in daytime and in the upper water layers (20-60 m depth) during the night (Falk-Petersen and Kristensen 1985). Although net avoidance tends to make biomass assessment of krill demanding, it is assumed that they move towards deeper water masses (i.e., away from the potentially oil exposed surface layers) in wintertime (Orlova et al. 2011).

While surface waters are not entirely depleted of zooplankton species during winter, with many species being active all year round, NEBA should account for high densities of conspicuous and lipid rich zooplankton species in surface water masses and in association with the sea ice during the summer time, whereas lower densities may be expected in wintertime.

3.5 FISH

Marine fish diversity in the Arctic was recently reviewed (Mecklenburg et al. 2011; Christiansen & Reist 2013). Mecklenburg et al. (2011) identified 242 fish species in the Arctic. Most of these species are associated with the Arctic shelves. In the deep, central Arctic basin (average depth 2418 m), only 13 fish species have been recorded (Christiansen & Reist 2013). While 10% of the fish species present in the Arctic are being harvested and therefore to degree certain extent being assessed and monitored, the distribution, abundance, ecology and life history of the remaining 90% is poorly understood (Christiansen & Reist 2013). The three most species-rich families are the snailfish (Liparidae), eelpout (Zoarcidae) and sculpins (Cottidae) (Christiansen & Reist 2013). Ongoing phylogenetic studies suggest that eelpout, sculpins and several other groups of Arctic fish are taxonomically more strongly associated than previously thought. Updated taxonomies for these species may thus be expected (Imamura & Yabe 2002).

With regard to NEBA for Arctic seas, it is necessary to be aware of the species' presence in surface water masses and around sea ice. Two cryopelagic (i.e., living and spawning in association with sea ice) fish species live in the Arctic: the polar cod (*Boreogadus saida*) and the ice cod (*Arctogadus glacialis*) (Christiansen & Reist 2013). Both species have a circumpolar distribution and are endemic to the Arctic, but while the former is a highly abundant key species in the Arctic ecosystem, the latter is seldom recorded and less coupled to the sea ice (Aschan et al. 2009; Christiansen & Reist 2013). Young polar cod are commonly observed both underneath Arctic sea ice and in the pelagic (Lønne and Gulliksen 1989; Gradinger and Bluhm 2004; Geoffroy et al. 2011; David et al. 2016). Young age classes remaining close to the ice and are separated vertically from the larger congeners who reside in the pelagic (Geoffroy et al. 2016). In the Barents Sea, the polar cod spawn under or close to the ice edge during the period November-March, either in the southeastern Barents Sea or in the Svalbard area, and from these areas, the larvae drift along with the ocean currents in the surface layers (Ajiad et al. 2013). Graham & Hop (1995) showed that healthy polar cod larvae stayed in the upper 15 cm of the water column, whereas larvae that did not stay close to the surface did not mature.

Apart from the two above-mentioned Arctic pelagic species, most Arctic fish species have a typical demersal affiliation as adults. However, many of these Arctic demersal fish species, such as the shannies (Stichaeidae) and the sculpins, do have prolonged pelagic stages, thus are regularly present in the upper water masses (Fig. 6).

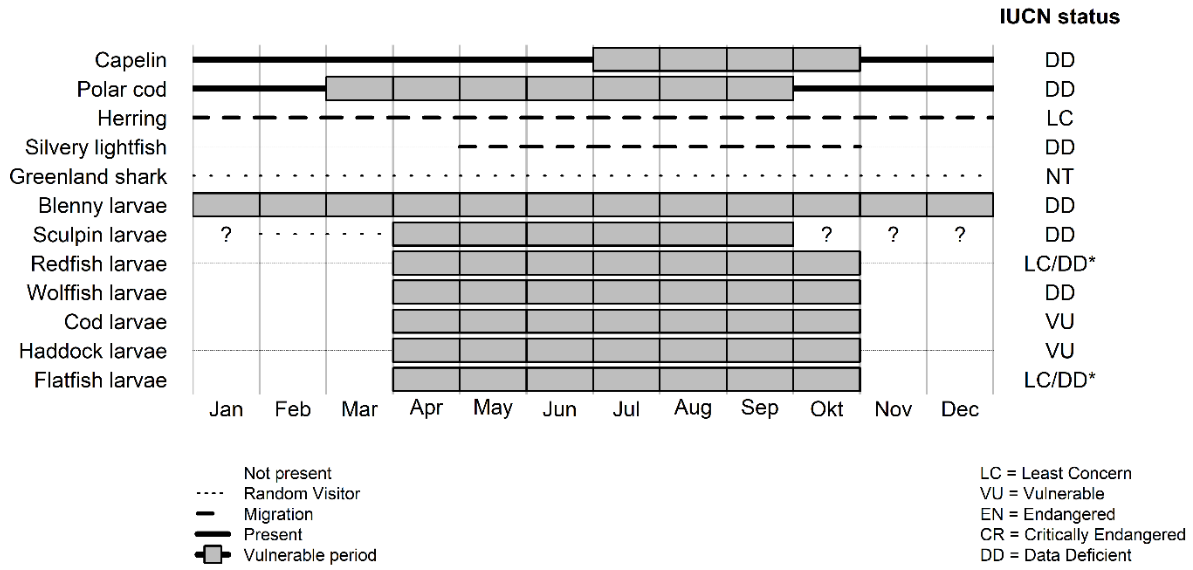

Fig. 6. Presence of fish in the upper water layers of the Arctic marginal ice zone. References for distribution: capelin, *Mallotus villosus* (Wienerroither et al. 2011, 2013; Prozorkevich & Sunnanå 2017); polar cod, *Boreogadus saida* (Wienerroither et al. 2011, 2013; Prozorkevich & Sunnanå 2017); herring, *Clupea harengus* (Wienerroither et al. 2011, 2013; Prozorkevich & Sunnanå 2017); silvery lightfish, *Maurolicus muelleri* (Wienerroither et al. 2011, 2013); Greenland shark, *Somniosus microcephalus* (Wienerroither et al. 2011, 2013); blenny, *Leptoclinus maculatus, Anisarchus medius* and *Lumpenus fabricii* (Ottesen et al. 2011; own data); sculpin, *Myoxocephalus scorpius*, *Icelus* spp. and *Triglops* spp. (own data); redfish, *Sebastes* spp. (Prozorkevich & Sunnanå 2017; own data); wolffish, *Anarhichas* spp. (Prozorkevich & Sunnanå 2017; own data); cod, *Gadus morhua* (Prozorkevich & Sunnanå 2017; own data); haddock, *Melanogrammus aeglefinus* (Prozorkevich & Sunnanå 2017; own data); flatfish, *Hippoglossoides platessoides* and *Reinhardtius hippoglossoides* (Prozorkevich & Sunnanå 2017; own data); snailfish, *Careproctus* spp., *Liparis* spp. (Prozorkevich & Sunnanå 2017; own data). *Species of these groups are either listed as "LC" or "DD". ? = unknown information.

In general, many Arctic demersal species fish have pelagic juveniles (i.e., be past the larvae and post larvae stages) before they are ready for a demersal life style (Ottesen et al. 2011). The larvae are pelagic in order to make use of the elevated biological production in the summer season. However, in the Barents Sea some species have prolonged pelagic larvae stages that may last for several year cycles, including wintertime. This is probably an adaptation to the particular physical conditions. The bottom of the Barents Sea generally consists of sand, mud, clay and silt (Wassmann et al. 2006) and such flat bottom conditions provide little shelter. Most of the species in the northern Barents Sea have a benthic affiliation as adults. For many fish larvae, the pelagic zone is therefore probably a less exposed and therefore safer habitat, with fewer predators and higher food availability, however in the case of an oil spill the larvae will more likely be exposed to oil. One such species is the daubed shanny (*Leptoclinus maculatus*), a fish species which is distributed across most of the Barents Sea, including the northernmost areas (Fig. 7, Ottesen et al 2011). The daubed shanny is pelagic for 2-3 years before they settle at the sea floor (Ottesen et al. 2011). Due to its presence close to the surface in early life stages, and due to its high abundance and high fat content, this species may constitute a valuable food source for species at higher trophic levels (e.g. seabirds) in times when the abundance of the important capelin (*Mallotus villosus*) is low.

Fig. 7. Larvae of the daubed shanny, *Leptoclinus maculatus*. The daubed shanny has a pelagic life stage lasting up to 3 years. This specimen is approximately 65 mm in length. Note the red lipid sac. © Camilla A. M. Ottesen.

Other examples of demersal fish species with prolonged pelagic phases include the shorthorn sculpin (*Myoxocephalus scorpius*), twohorn sculpin (*Icelus bicornis*), the stout eelblenny (*Anisarchus medius*), and species of the genera *Triglops* and *Liparis*. Several flatfish species and wolfish also have pelagic larval stages.

Eelpouts (*Zoarchidae* spp), a very abundant and diverse group of Arctic fish, probably do not have pelagic stages. When hatched, the larvae are often well developed. Furthermore, eelpouts display parental guarding of their eggs and larvae until these become juveniles (i.e. past the post-larvae stage) and less vulnerable to predation (Silverberg & Bossé 1994).

Several boreal, pelagic fish species migrate into the northernmost areas in summer time in search for food and favorable current and light conditions (Nøttestad et al. 1999). Seasonal migrations are often carried out by larger, planktivorous species, since smaller specimens spend relatively more energy than larger ones on long migrations, particularly if they must swim against currents (Nøttestad et al. 1999). The most important among these boreal, pelagic species is probably the capelin, a short-lived key species with a circumpolar distribution. The capelin is represented by different stocks in different areas, and life histories differ between the various stocks. Most notably, capelin stocks in the Pacific and Newfoundland areas spawn on beaches in summer (June-July), whereas the capelin stock in coastal areas in the Barents Sea spawn in late winter/early spring (March-April) and in Greenland between April-July (Rose 2005). In the Barents Sea, where there is a strong flow of Atlantic water masses towards the Arctic, the eggs of several boreal fish species are spawned along the coasts of Norway and Russia and carried northwards into the Barents Sea with the currents; this includes the eggs and larvae of species such as the Northeast Arctic cod and the Northeast Arctic haddock. The eggs and larvae are largely retained in Atlantic water masses, far from the ice zone (Sundby and Nakken 2008, Olsen et al. 2010), whereas adult individuals may conduct summer feeding migrations further north, mainly in deeper waters where they are less likely to be exposed to oil in the case of an accidental spill.

3.6 BIRDS

Seabirds are important components of the marine ecosystem inhabiting both offshore and inshore ecosystem. They forage on a great diversity of food items from zooplankton to fish, and some species also scavenge mammal carcasses. They are adapted to a life at sea and a great variety of feeding strategies are observed. However, two main foraging strategies are found; divers and surface feeders. Surface feeders are good flyers, have longer wings and can forage over huge areas of sea. Divers have shorter wings and some groups have the ability to fly underwater by using their wings for propulsion. Divers spend more time on the sea surface and therefore are more susceptible to encounter an oil slick, making them more vulnerable to an oil spill. Alternatively, a more comprehensive approach is to choose the six trophic assemblages suggested by the Circumpolar Seabird Expert Group. These are surface piscivores, surface planktivores, diving piscivores, diving planktivores, benthic feeders and omnivores (Irons et al., 2015). NEBA should at least consider four functional seabird groups: offshore divers, offshore surface feeders, inshore divers and inshore surface feeders.

Globally, seabird populations are on the decline. The overall decline in 19 % of the worlds monitored seabird populations was almost 70 % between 1950 and 2010 (Paleczny et al., 2015). As seabirds consume large quantities of seafood (Barrett et al., 2002), fishing and fish stock variation will ultimately affect seabird populations (Barrett et al., 2006b; Cury et al., 2011; Erikstad et al., 2013). However, the coupling of seabird populations and fish stock models is challenging as seabirds forage on small fishes and early life stages, while the fish stock models focus on fish of commercially catchable size (Cairns, 1992). Other threats to seabird populations include oil spills, global warming, coastal development and contaminants (Dickson and Gilchrist, 2002).

It is natural to expect a relationship between the size of an oil spill and numbers of oiled and dead seabirds, but a review of 45 oil spills from shipping accidents conclude that no correlation between volume of oil spilled and numbers of injured and killed seabirds exists (Burger, 1993). The prerequisite for a seabird to come into contact with oil after a spill is an overlap in space and time. Therefore, population size, density and geographical distribution are critical parameters to consider in a NEBA evaluation. These parameters depend on seasonal movements, life history traits and the availability of food. Together with ecological parameters, factors that determine the fate and distribution of oil, e.g. amount of oil on water, oil type, air and water temperature, wave height, wind velocity and ocean currents (Fingas, 2011) are also crucial to consider. Therefore, assessing the risk to seabirds depends on the distribution and density of birds at a specific spill location and the distribution and behavior of oil at that location.

The number of breeding seabirds of the North Atlantic is approximately 68 million (Barrett et al., 2006a). Within the North Atlantic, the Barents Sea holds about 16-20 million individual birds during the summer (Gabrielsen, 2009). The Lancaster Sound region of eastern Canada holds about 1.7 million seabirds (Welch et al., 1992), while the guillemot population is estimated to be about 7 million adult breeding birds (mostly Brünnich's guillemots, *Uria lomvia*) in the Eastern Canadian Arctic (Gaston and Jones, 1998; Nettleship and Evans, 1985). Data from the Beaufort Sea is missing as few colonial seabirds breed there (Gaston et al., 2009). The NEBA process preferably needs data on the actual presence of birds from overflights, and recent monitoring activities. Availability of online monitoring databases can be beneficial to get a first indication of the potential presence of birds. The level of organization differs between countries and areas, but through the Arctic Council working group Conservation of Arctic Flora and Fauna (CAFF), the Arctic Biodiversity Data Service was established and the Circumpolar Seabird Data Portal is running (Irons et al., 2015). This is a publicly accessible platform for information that has the potential for a good quality circumpolar data for modelling. Information about presence for 13 seabird species is shown in Fig. 8.

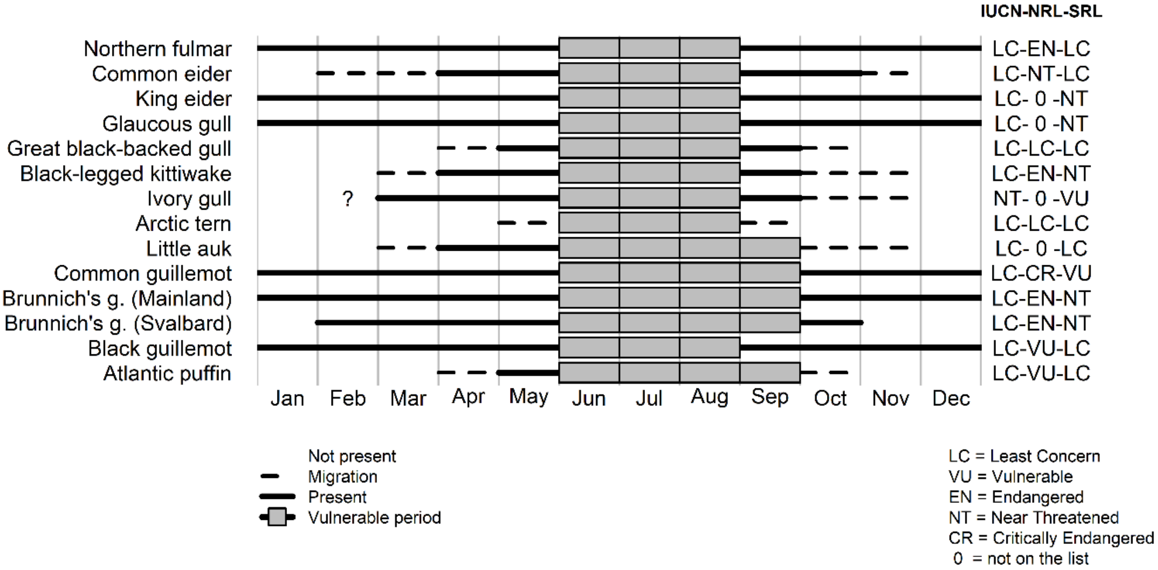

Fig. 8. Presence and vulnerability plot for 13 seabird species of the north Atlantic (Svalbard area). The vulnerability period is defined as breeding and for auks also the moulting period. The red list status is given for IUCN (International Union for Conservation of Nature) and the Norwegian red list for the mainland (NRL) and Svalbard (SRL) (Kålås et al., 2010). References for distribution: northern fulmar, *Fulmarus glacialis* (Fauchald, 2011); common eider, *Somateria mollissima* (Isaksen and Bakken, 1995); king eider, *Somateria spectabilis* (Mosbech et al., 2015); glaucous gull, *Larus hyperboreus* (Fauchald, 2011); great black-backed gull, *Larus marinus* (Isaksen and Bakken, 1995); black-backed kittiwake, *Rissa tridactyla* (Frederiksen et al., 2011); ivory gull, *Pagophila eburnea* (Gilg et al., 2010); arctic terns, *Sterna paradisaea* (Egevang et al., 2010); Common guillemot, *Uria aalge* (Steen et al., 2013); Little auk, *Alle alle* (Fort et al., 2013); Brünnich's guillemot, *Uria lomvia* (Steen et al., 2013); Black guillemot, *Cephus grylle* (Bakken and Mehlum, 1988); Atlantic puffin, *Fratercula arctica* (Fauchald, 2011). ? = unknown information.

3.7 MARINE MAMMALS

The rich ecosystem of the Arctic Ocean and adjacent seas, with large populations of zooplankton and fish, are an important resource for a variety of marine mammals. Among the approximate 10 pinniped species and 20 cetacean species that are regularly observed in these waters, some remain there year-round (e.g. white-beaked dolphins (*Lagenorhynchus albirostris*), beluga whales (*Delphinapterus leucas*), ringed seals (*Phoca hispida*) and bearded seals (*Erignathus barbatus*). Others undertake annual migrations to northern latitude feeding grounds during the productive summer months (e.g. minke whales (*Balaenoptera acutorostrata*), humpback whales (*Megaptera novaeangliae*) and fin whales (*Balaenoptera physalus*). Some species are distinctly coastal, such as bearded seals, harbour seals (*Phoca vitulina*), and beluga whales, while others reside primarily in the open ocean (e.g. most cetaceans, harp seals (*Pagophilus groenlandicus*) and hooded seals (*Cystophora cristata*).

Similar to other species, for marine mammals to be impacted by spilled oil, there must be an overlap between the species distribution and the spreading of the oil spill in both time and space. In addition to the exposure level, the degree to which specific species are impacted by exposure to oil also depends on their population status, local density within the impacted area, and their geographical distribution outside of these areas. The distribution of marine mammals is generally driven by the distribution and abundance of their main prey, but also depends seasonally on the migration timing and routes between feeding and breeding grounds. Detailed knowledge of such processes is considered to be of crucial importance for assessment of the ecological consequences in a NEBA process. Not much is known about how whales are affected by oil, but their feeding strategy will likely determine, to a large degree, their risk of being impacted by oil at the surface. Right whales, such as the North Atlantic right whale (*Eubalaena glacialis*) and the bowhead whale (*Balaena mysticetus*), are skim feeders, which means that they often swim in the surface with the mouth open, filtering zooplankton from the upper water masses. This feeding pattern obviously makes them more vulnerable to surface oil. On the other hand, baleen whales, such as the humpback whale (*Megaptera novaeangliae*), feed both at the surface and at depth, probably making them moderately vulnerable to drifting oil.

A recent review by Laidre et al. (2015) summarized the state of knowledge regarding 11 species (3 cetaceans, 7 pinnipeds and polar bears), which are referred to as truly Arctic Marine Mammals (AMMs). These include species that remain above the Arctic Circle for most of the year, and in addition some selected species that inhabit the Arctic on a seasonal basis, e.g. during summer feeding periods. Among these AMMs a distinction is made between species that are ice obligates (i.e. depend on sea ice for important life history events such as reproduction, moulting, resting) and species that are associated with the ice edge during parts of the year but do not depend on it directly for critical life history events. An important finding from Laidre et al. (2015) is the fact that for most species, abundance estimates are based on a single point estimate, often associated with very large uncertainty. For some species, abundance estimates are simply based on expert opinion with no uncertainty estimates. Fig. 9 summarizes the findings by Laidre et al. (2015) for subpopulations in the Northeast Atlantic sector.

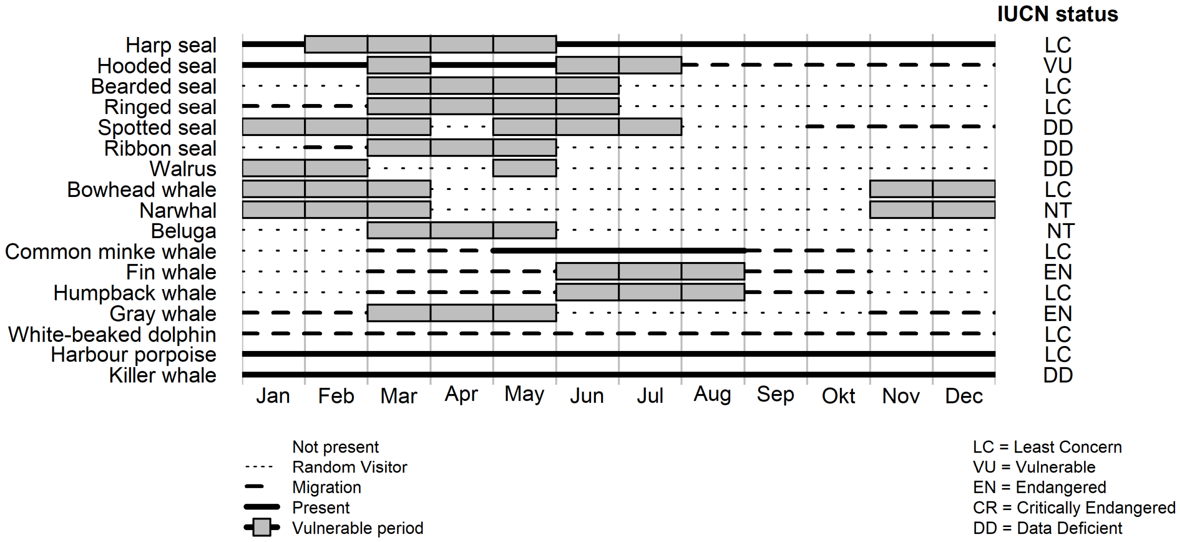

Fig. 9. Presence of sea mammals in the upper water layers of the Arctic marginal ice zone of the Arctic. References for distribution: Harp seal, *Pagophilus groenlandicus* (Lavigne and Kovacs, 1988); hooded seal, *Cystophora cristata* (ICES, 2014; Kovacs and Lydersen, 2008); bearded seal, *Erignathus barbatus* (Kovacs et al., 2004); ringed seal, *Phoca hispida* (Frost and Lowry, 1981; Reeves, 1998); spotted seal, *Phoca largha* (Quakenbush, 1988; Burkanov, 1990; Lowry et al., 2000); ribbon seal, *Histriophoca fasciata* (Burkanov and Lowry, 2008); walrus, *Odobenus rosmarus* (Lowry et al., 2008); bowhead whale, *Balaena mysticetus* (Laidre et al., 2008); narwhal, *Monodon monoceros* (Laidre et al., 2008; Laidre and Heide-Jørgensen 2005); beluga, *Delphinapterus leucas* (Leidre et al., 2008); common minke whale, *Balaenoptera acutorostrata* (Skaug et al., 2004); fin whale, *Balaenoptera physalus* (Øien,

2009); humpback whale, *Megaptera novaeangliae* (Øien, 2009); gray whale, *Eschrichtius robustus* (Moore and Huntington, 2008); white-beaked dolphin, *Lagenorhynchus albirostris* (Hammond et al., 2012); harbour porpoise, *Phocoena phocoena* (Bjørge and Øien, 1995); killer whale, *Orcinus orca* (Lawson and Stevens, 2014).

While the review of Laidre et al. (2015) is as comprehensive as current information permits, it highlights the knowledge limitations for the 11 species they consider, and it does not provide any knowledge updates for the large number of species (mostly cetaceans) which visit the Arctic on a seasonal basis, and which depend critically on resources in these waters to cover the energetic costs of growth, maintenance and reproduction. Many of these species spend several months during the spring and summer feeding in close proximity to the ice edge.

In general, there is limited information about the main migratory pathways and the timing of seasonal migrations of most species. Data from historical whaling records suggest that areas along the shelf edge in the Barents Sea are key feeding areas during the early summer season (Institute of Marine Research, 2012). Therefore, there is a need for updated information on migration patterns for marine mammals in general and in regions of interest for oil and gas exploration in specific. The availability and organization of data differs between countries, but there has been a strong effort from the Arctic Council to develop the Arctic Biodiversity Data Service (ABDS). This platform aims at increasing the access to arctic biodiversity data at different scales (spatial, temporal and taxonomical). It has also been combined with the Ocean Biogeographic Information System (OBIS) as its Arctic node, and can become a valuable source of information for future modelling initiatives and management decisions. Also, various large-scale research programmes have been set up with the specific aim to study the ecology and distribution of marine mammals and other ecosystem components. These programmes include the Chukchi Sea Environmental Studies Program (https://www.chukchiscience.com) and the Joint Norwegian-Russian Ecosystem Survey (Michalsen et al. 2013) which provide regional information as an input to Environmental Impact Assessments e.g. conducted as a part of NEBA.

3.8 UNIQUENESS AND PARTICULAR PROPERTIES OF ARCTIC ECOSYSTEMS

Arctic ecosystems differ from boreal ones, and the uniqueness of an ecosystem can be assessed by focusing on food web properties. Recently, analyses of a food-web matrix for the Barents Sea including 244 taxa from all trophic levels (Planque et al. 2014), suggest that there are major structural differences between boreal and Arctic communities (Kortsch et al. 2015). In the arctic part of the Barents Sea, phytoplankton and polar cod were the components with the highest number of feeding links to other taxa (i.e., the highest degree of centrality in the food web). Consequently, perturbation of these two ice-associated taxa would potentially affect a high number of other ecosystem components. However, compared to typical boreal generalist such as the cod, polar cod can be regarded as a specialist, and in general the Arctic was indeed characterized by a lower than average number of feeding links per species as compared to members of the boreal community (Kortsch et al. 2015). In general, Arctic species tend to display particular adaptations to a life in the polar environment, where the food availability is highly seasonal. As such, Arctic species differ from boreal species with regard to their life history strategies and in the ways in which they contribute to ecosystem functioning.

With regard to fish, such adaptations include small, elongated bodies, large eggs and low fecundity. Species being present along broad latitudinal ranges may show differing life histories depending on where a particular specimen resides. For instance, two shannies (the daubed shanny and the stout eelblenny), which are present both in UK waters and in the Arctic parts of the Barents Sea, display a lipid sac in the Barents Sea, but not in UK waters. This may be an adaptation to a life in the Arctic, where prolonged periods of low food availability are likely. As such, Arctic ecosystem management plans and NEBAs should be based on trait data from field studies carried out in Arctic environments, in order to convey realistic ecosystem information.

3.9 LIFE IN THE ARCTIC DURING THE POLAR NIGHT

Ecological processes in the Arctic are largely governed by sea ice and light dynamics. As such, low light intensity and accordingly low photosynthetic activity in wintertime has led to the general perception that there is very little biological activity in Arctic marine surface layers during this time of the year. However, recent studies conducted in the Svalbard area in January 2012-2015 revealed that the biological activity in the Arctic in wintertime is higher than previously assumed (Berge et al. 2015a, b; Falk-Petersen et al. 2015). For instance, omnivorous and carnivorous zooplankton (including copepod nauplii) were present in the entire water column, with the highest density in the upper water layers. Interestingly, herbivorous *Calanus* copepods were also found to migrate up from overwintering depth earlier than previously recorded and were already found in the upper water masses in late January (Blachwiach-Samolyk et al. 2015; Daase et al. 2014). Large boreal gadoids such as cod and haddock were able to feed during the polar night, while the boreal, pelagic herring were present but not feeding, which may indicate that the herring is not sufficiently adapted for an entire year cycle in the Arctic (Berge et al. 2015a). Although the fish community in the Arctic is dominated by small, demersal species, with few pelagic fish species being present in the Arctic in wintertime, larvae of several demersal fish species are present in the upper water layers throughout the year. As noted in the fish section, this appears to be particularly true for a typical demersal species, the daubed shanny, which possesses post-larvae that live pelagically in the upper water masses for up to 3 years before they settle at the bottom (Ottesen et al. 2011). These new data suggest that species wintertime distributions are highly relevant in a NEBA perspective, and therefore warrant further investigation.

3.10 FUTURE SPECIES DISTRIBUTIONS

Environmental change induces changes in sea ice distribution and water mass composition. The distribution of species depends on the environmental conditions. Thus, such environmental changes are reflected at all trophic levels of the ecosystem, and are for example associated with alterations in species compositions and distributions. In the Barents Sea, a clear shift in the water mass composition has been evident in recent years (Johannesen et al. 2012), as well as an associated north-eastwards shift in the distribution of many boreal fish species (Fossheim et al. 2015). Many boreal species now appear to be established in areas previously considered as Arctic, at least in summer time. For instance, this applies to the North-east Arctic cod (Johansen et al. 2013) and the mackerel, the latter now being regularly caught in Svalbard (Berge et al. 2015b). It is important that as part of the NEBA process all relevant valued ecosystem components (VEC's) are properly identified and included in the evaluation.

4. DISCUSSION

The information presented herein on species distributions is based on various sources, including published books and papers, grey literature and unpublished data. Focusing on all trophic levels, the overall intention was to restrict the scope to the most important species present in upper water layers in seasonally ice-covered Arctic seas, in order to identify data needs for NEBA and provide suggestions for input. An important point concerning such distributions is that the resolution of species distributional data is generally low. Whereas some commercial fish species (e.g., cod and haddock) are being monitored twice every year in some areas (e.g., the Barents Sea), information on the distribution of most other species is based on annual surveys, or even less frequently. Surveys are usually conducted in summer, when the weather at high latitudes is most stable and the ice coverage is at a minimum. We therefore have a much better understanding of species distributions during the Arctic during summer than in wintertime, and this represents a substantial challenge to the response community since operations in the Arctic occur to an increasing extent throughout the year.

The vulnerability of a species to oil spills depends on the overlap in time and space between the species and the oil, as well as the sensitivity of the species to oil exposure. Furthermore, the vulnerability of the population also depends on factors such as the biodensity, the fraction impacted, the population resilience and recovery potential. As these latter factors are governed by the seasonal variability in the ecosystem, they are particularly dynamic in the highly seasonal Arctic. As such, seasonal variation is considered to be a key issue that needs to be accounted for in a NEBA process when executed for the Arctic. In this paper, we highlight the seasonal variation in the presence of key ecological components in Arctic surface waters (Figs. 5, 6, 8 and 9). This presence is species dependent; it can be highly variable throughout the seasons, and it can be of regular, migratory or random nature. In order to properly execute a NEBA, data on the spatial and temporal distributions of species need to be compared to the distribution of oil and should ideally include temporal, horizontal and vertical dimensions, especially because spill response options will have an influence on the distribution of oil in all these dimensions.

Whereas drifting oil slicks may affect species associated with the water surface, treatment of the oil, such as the application of dispersants, will move oil from the surface layer towards the water masses below the surface, and thereby temporary increase the oil concentration in the water column. Depending on the scale and timing of the spill, the use of dispersants may therefore increase the risk of exposing groups of species found in the pelagic zone to oil components as compared to a scenario where oil is left as a slick at the water surface. Organisms with low mobility, such as phytoplankton, zooplankton and fish eggs and larvae, may not be able to avoid exposed areas. On the other hand, some groups of species (e.g., larger fish, krill and marine mammals) are possibly capable to swim away from exposed areas (Sydnes et al. 1994), whereas others (e.g., seabirds) may be attracted.

Species groups such as phytoplankton and zooplankton typically constitute the base of the food web. Experimental exposure studies indicate that lipid rich species such as *Calanus* may potentially bioaccumulate oil compounds (Nørregaard et al 2015, Agersted 2018). However, little is known how these groups are affected by oil exposure in the long term, or if such effects propagate through the food chain. The long-term impact on plankton and the potential cascading effects on higher trophic levels would certainly depend on the size of the spill, and this could for instance be assessed and quantified by means of numerical modelling in a future model study. Such numerical information would be highly valuable when executing a proper NEBA.

Although different Arctic shelf areas display slight variations in the timing of low trophic level biological events, which are dependent upon the ice and light conditions, the succession of such biological events is rather similar among regions (Fig. 5; Daase et al. 2013). As such, this succession governs the likelihood of oil affecting the various low trophic level ecosystem components. Many species are most sensitive to oil toxicity and oil related damage during early life stages (e.g., Kennish, 1997). In peak production situations, on the other hand, large proportions of a given population may potentially be at risk. For instance, an oil spill in early spring would have a higher risk of affecting the copepod *Calanus glacialis*, which migrates towards the surface in February-March and stays in these upper water layers until the autumn (in August-October, depending on the region). The ice algae bloom, which lasts for 1-2 months, starts around mid-March, with a peak just after the sea ice starts to break up. When the sea ice is about to disappear, the phytoplankton bloom in the upper water layers takes place, with a main peak occurring less than a month later. In *C. glacialis*, the egg production normally lasts for more than 2 months and peaks about the time when the ice breaks up. The subsequent peak in copepodite stage CI abundance occurs towards the end of the main phytoplankton bloom. As such, there are consecutive blooms of lower trophic level species during the entire summer season, from early spring until late autumn. Whereas many species complete these events well before sea ice starts to form again in October-November, many species are still active in autumn and winter and reproduce all year round.

Ecosystem surveys currently reveal an ongoing borealization of Arctic marine areas, with many boreal species extending their northern distribution limits into Arctic shelf areas (e.g., Fossheim et al. 2015). This is likely a result of the ongoing environmental change, with higher water temperatures and associated enhanced possibilities for boreal species to survive in the Arctic. Furthermore, recent wintertime field studies unexpectedly show a presence of species at most trophic levels close to the surface (e.g., Berge et al. 2015a). For instance, several abundant fish species (e.g., the daubed shanny) display pelagic juvenile stages that may persist continuously for several years (e.g. Ottesen et al. 2011). As such, a continued monitoring of the Arctic plankton community, with surveys that cover both the summer and the winter seasons, may be necessary in order to obtain a comprehensive understanding of this ecosystem component.

Provided that there is a spatio-temporal overlap between the species and oil, behavior may for some species determine the degree to which they are harmed by the oil. With regard to seabirds, which are present in the Arctic throughout the year, we suggest that the species should be assessed in the light of at least four functional groups: offshore divers, offshore surface feeders, inshore divers and inshore surface feeders. The divers spend most time at the surface, and are therefore probably most vulnerable to oil spills, and seabirds in general are most vulnerable in summer time when they are breeding and moulting. Unlike seabirds, marine mammals do not have a particular period of the year when most of the species are present in the Arctic: some species are present and vulnerable in summer time, whereas others are present and vulnerable at other times of the year. However, in general the number of marine mammal species, as well as the proportion of their populations present in arctic waters increases during summer feeding periods and decreases as seasonally migrating species again leave the high-latitude feeding grounds for winter breeding periods at more southerly latitudes. Seals have fur that may be exposed to oil fouling in the same way as birds, while whales may be less vulnerable to such fouling of their skin. Fur is important for insulation of seals, in water and even more in air (Kvadsheim and Aarseth 2002). For pups in particularly, fur is the main contributor for thermal insulation and exposer to oil will be detrimental. Fouling of the fur in adults will likely increased energy expenditure due to reduced thermoinsulation and partly through affecting hydrodynamics, cause discomfort, and increases the risk of ingestion by suckling pups. When it comes to whales, their behavior (e.g., their foraging strategy) appears to be an important modulator of their vulnerability to oil pollution. Skim feeders, such as right whales and bowhead whales, often swim in the surface with the mouth open, and are thereby likely more vulnerable to surface oil than whale species that to a larger extent feed in deeper water masses. This illustrates that not only the species' distributions, but also their behavior is important to consider when assessing the potential impact as part of a NEBA for the Arctic.

5. CONCLUSIONS

In an attempt to identify parameters and processes that are crucial to consider in an Arctic NEBA for oil spill response decision making, this paper described key ecological features in the surface waters of seasonally ice-covered Arctic shelf seas. We provide recommendations that will address current knowledge gaps, and which can be used to identify the best response options in the case of an accidental oil spill in the Arctic. It is important that as part of the NEBA process the horizontal, vertical and temporal distributions all relevant VEC's, and in some cases their behavioral traits, are properly identified and included in the evaluation. Special focus should be on higher level, less resilient, species such as marine mammals and sea birds, whose spatio-temporal distributions are generally more challenging to model as compared to those of organisms found at lower trophic levels (e.g., phytoplankton).

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Highlights

- Net Environmental Benefit Analysis (NEBA) is a process used to identify which combination of response strategies minimises the impact of oil spills to environment and people.
- Biological resources found at marine interfaces are in general vulnerable because that is where oil can accumulate.
- In spring-time, many boreal species migrate northwards in response to sea ice retraction and increased production associated with the spring bloom.
- Some Arctic species are present in upper water layers in the Arctic throughout the year.