Master of Science Thesis

Assessment of the impacts of an oil spill on the populations of common guillemot (*Uria aalge*) and long-tailed duck (*Clangula hyemalis*) – an expert knowledge based Bayesian network for the Gulf of Finland

Riikka Venesjärvi

University of Jyväskylä
Department of Biological and Environmental Science

Aquatic Sciences
2012

UNIVERSITY OF JYVÄSKYLÄ, Faculty of Science

Department of Biological and Environmental Science
Aquatic Sciences

VENESJÄRVI RIIKKA, M.: Assessment of the impacts of an oil spill on the populations of common guillemot (*Uria aalge*) and long-tailed duck (Clangula hyemalis) – an expert based Bayesian network for the Gulf of Finland
Master of Science Thesis: 56 p. + attachments 6 pcs (26 p.)
Supervisors: M. Sc. Inari Helle, Prof. Juha Karjalainen
Inspectors: Dos. Harri Högmander, Prof. Juha Karjalainen
March 2012

Keywords: The Gulf of Finland, oil spill, *Uria aalge*, *Clangula hyemalis*, Bayesian networks

ABSTRACT

The amount of operated oil transports continues to increase in the Gulf of Finland and in the case of an accident hazardous amounts of oil may be spilled into the sea. The oil accident may be harmful for the common guillemot and long-tailed duck populations. In this study expert knowledge regarding the behaviour and population dynamics of common guillemot and long-tailed duck in the Gulf of Finland was used to build a model to assess the impacts of an oil spill on the mortality and population size of these species. The Bayesian networks were used in the modelling. Based on the results the breeding colony of guillemots in Aspskär may survive in the consequence of recolonization. In conclusion, sufficient cleaning of the breeding site is important. The loss of one year offspring production may not have severe impact on the population size, the survival of adult breeders is more significant. The Baltic Sea population of long-tailed duck suffer from high nesting mortality at the breeding sites in the Northern Arctic Ocean. Thus the population has low offspring production; in the lack of chicks the possible oil spill may be directed only to adult breeders. The loss of experienced breeders during their migration may be harmful for the population. The models of common guillemot and long-tailed duck created and their results may be utilized in later oil impact studies on sensitive species.

JYVÄSKYLÄN YLIOPISTO, Matemaattis-luonnontieteellinen tiedekunta

Bio- ja ympäristötieteiden laitos
Akvaattiset tieteet

VENESJÄRVI RIIKKA, M.:	Öljyonnettomuuden vaikutusten arviointi etelänkiislan (*Uria aalge*) ja allin (*Clangula hyemalis*) populaatioihin asiantuntijatietoon perustuvien Bayes-verkkojen avulla – esimerkkinä Suomenlahti
Pro gradu:	56 s. + liitteet 6 kpl (26 s.)
Työn ohjaajat:	DI, FM Inari Helle, Prof. Juha Karjalainen
Tarkastajat:	Leht. Harri Högmander, Prof. Juha Karjalainen
Maaliskuu 2012	

Hakusanat: Suomenlahti, öljyonnettomuus, *Uria aalge*, *Clangula hyemalis*, Bayes-verkot

TIIVISTELMÄ

Tässä tutkielmassa käytettiin asiantuntija-arvioita kahden Suomenlahdella esiintyvän linnun, etelänkiislan ja allin, käyttäytymisen ja populaatiodynamiikan mallintamiseen. Kerätyn tiedon pohjalta rakennettiin Bayes-verkkomallit, joiden avulla arvioitiin öljyonnettomuuden vaikutuksia kyseisten lajien kuolleisuuteen ja populaatiokokoon. Suomenlahdella kuljetettavan öljyn määrän ennustetaan lisääntyvän koko ajan, ja näin ollen myös haitallisen öljyonnettomuuden todennäköisyys kasvaa. Onnettomuuden seurauksena etelänkiislan ainoa merkittävä pesimäluoto Suomessa on vaarassa saastua ja linnut altistua öljylle. Yhden vuoden poikastuotannon menetyksellä ei ole suurta vaikutusta populaation säilymiselle, sillä eteläiseltä Itämereltä saapuvalla immigraatiolla on palauttava merkitys Aspskärin populaatiokokoon. Rekolonisaatio voi onnistua, jos saastuneet alueet puhdistetaan ennen seuraavaa pesimäkautta. Itämerellä talvehtiva alli kärsii korkeasta poikaskuolleisuudesta pohjoisen pesimäalueilla ja Suomenlahden yli muuttaessaan aikuisiin kohdistuva öljyonnettomuuden aiheuttama kuolleisuus voisi vaikuttaa haitallisesti koko populaatioon. Rakennettuja malleja ja niiden tuloksia voidaan hyödyntää myöhemmissä herkkien lajien öljyvaikutustutkimuksissa.

Contents

1. INTRODUCTION

The Baltic Sea and its drainage basin create together a complex ecological-economic system (Sweitzer *et al.* 1996). There are 85 million people living in the Baltic Sea area.

One of the most important marine transport areas within the Baltic Sea is the Gulf of Finland, the easternmost basin of the sea. It is a politically safe area for Russian oil transports, and this is one of the reasons why it is one of the most operated sea areas in the world. The amount of operated oil transports continues to increase in the Gulf of Finland because of the new prospects created by the oil terminals in the north-eastern Baltic Sea coast (Kuronen *et al.* 2008, Hänninen and Rytkönen 2004). This development is a consequence of the global economic growth and its oil dependence. The main terminals are Sköldvik in Porvoo, Primorsk and Tallinn (Kuronen *et al.* 2008). The slow growth scenario assumes that the transports in Finland will stay at same level as in 2007: Estonia will transport only its own petroleum products (including crude oil and oil products) and Russia will act after its growth strategy. With this scenario the amount of petroleum products transported will be 158 millions of tonnes in 2015 (Kuronen *et al.* 2008). The strong growth scenario assumes that the economic growth will be strong in Russia and Estonia, and in Finland the economics will follow long-term growth; the transportations of petroleum products will increase to 262 millions of tonnes (Kuronen *et al.* 2008). As the transports increase, the probability of an oil spill grows simultaneously.

A scenario which oil combating is based on in the Gulf of Finland is a collision of two tankers – this could result in rupture of two cargo tanks and a spill of 30 000 t of crude oil (Hietala and Lampela 2007). In the case of an accident, large and hazardous amounts of oil may be spilled into the sea and it can create a serious risk to sea environment. The impacts depend on the amount of oil spilled, the chemical characteristics of oil, the prevailing weather conditions and also whether the oil remains in the sea or is washed ashore (Albers 2002, ITOPF 2002, Urho and Ahvonen 1990). The Gulf of Finland is a sensitive sea environment where the impacts of oil may cause a serious risk on aquatic species such as seabirds.

During recent years in Europe there has occurred two large oil spills which created a large damage; in 2002 M/T *Prestige* sunk in the coast of Spain and spilled 60 000 tons of emulsified oil affecting to more than 800 km of the northwest Spanish coast (Gonzàlez *et al.* 2006). In 1999 M/T *Erika* broke apart on French coast resulting in a spill of 10 000 tons of oil. Also other tankers took advantage of the *Erika* spill and cleaned out their tanks along the coast. The estimates of killed birds in France vary between 80 000 and 150 000, and 80% of these birds were common guillemots (*Uria aalge*) (Cadiou *et al.* 2004).

One of the most known oil accident occurred in Alaska when M/T *Exxon Valdez* ran aground in 1989 and approximately 42 000 tonnes of crude oil was spilled into the sea (Brown *et al.* 1996). The Gulf of Alaska is a large, subarctic marine ecosystem with benthic and pelagic fish communities that support large populations of marine mammals and birds and it is the basis for commercial fisheries (Laur and Haldorson 1996). The spill contaminated 1 990 km of shoreline in the Prince William Sound (Wiedmer *et al.* 1996). Both the short- and long-term effects of the spill have been studied comprehensively. In all 250 000 seabirds, 1 800 sea otters and 302 harbour seals died immediately in the days following the spill. The spill was harmful to entire populations: it has been estimated that more than 50% of the common guillemot population existed in the sound was killed caused by that spill including also one colony with over 100 000 birds (NRC 2003, Piatt and Ford 1996, Piatt *et al.* 1990). Larger marine mammals and ducks, meanwhile, suffered long-term negative effects because their prey was contaminated. In addition great amounts of pacific herring (*Clupea harengus*) eggs and pink salmon (*Oncorhynchus gorbuscha*) juveniles were exposed to oil resulting in a collapse of local fisheries (Brown *et al.* 1996, Wiedmer *et al.* 1996).

The Gulf of Finland is an important migratory route for arctic sea ducks such as long-tailed ducks (*Clangula hyemalis*) (Ellermaa, pers. comm.). A large number of birds fly over the sea before and after their breeding season. A possible oil accident might expose the resting ducks to oil and cause high mortality. The common guillemot is a species which can also be found in the Gulf of Finland and only one viable breeding colony exists (Hario 1982). The oil spill could expose the colony to oil, and the birds and the existence of their colony would be in high risk. In the case on an accident not only the adult birds are at risk, but also the offspring of these two species.

Bayesian networks (BNs) are a kind of probabilistic graphical models that are valuable to researchers and managers due to the powerful probability theory involved, which makes them able to deal with a wide range of environmental problems (Aguilera *et al.* 2011). Explicit accounting for uncertainty adds substantial insight to problems and the graphical presentation of model structures and probability distributions are useful (Uusitalo 2007).

The objective of this study is to create two BNs which model the impacts of an oil spill on the common guillemot breeding in the Gulf of Finland and on the long-tailed duck migration through the area in spring and autumn. The network structures will be based on literature and the probability distributions for the networks will be collected via expert interviews. The expert knowledge is used in this study since no published references of this nature can be found. The impact on mortality and the effect of the loss to the later population sizes of both species are studied.

2. BACKGROUND

2.1. The Gulf of Finland

The Gulf of Finland (hereafter denoted the GOF) (Fig. 1) is the easternmost part of the Baltic Sea and its coastal states are Finland, Russia and Estonia. The drainage area of the GOF is 420 990 km^2 maintaining a population of 12.5 million inhabitants (Sweitzer *et al.* 1996). Since its physical properties the GOF is a vulnerable sea area.

The western front of GOF is the line between the Hanko peninsula and the island of Osmussaar. This is more a convention than a physical boundary to the Baltic Sea proper (Alenius *et al.* 1998). The length of GOF is 400 km and its width varies between 48–135 km (Alenius *et al.* 1998). The coast of Southern Finland is indented due to the last ice age but the coast of Estonia is more straight and also steep (Pajanen *et al.* 2005, Alenius *et al.* 1998). The GOF is shallow, mean depth being only 37 m and the largest depth is 123 m. The volume of GOF (1 103 km^2) is only 5% of the Baltic Sea volume (Alenius *et al.* 1998).

Salinity in the GOF as in the whole Baltic Sea varies vertically and horizontally; average surface salinity is 0‰ in the east and 7‰ in the west. In the sea bottom salinity can approach 10‰ (Alenius *et al.* 1998). The permanent halocline (i.e. zone where salinity increases rapidly) can be found at depths of 60–80 m in the western GOF (Alenius *et al.* 1998). Saline water supply to the GOF comes from the Baltic Sea main basin (Huhtala *et al.* 2005). The fresh water supply is mostly provided by rivers of which the River Neva accounts for the most. Other significant rivers are e.g. the River Kymi and the River Narva (Alenius *et al.* 1998). Stratification of the GOF is caused mainly by the water temperature.

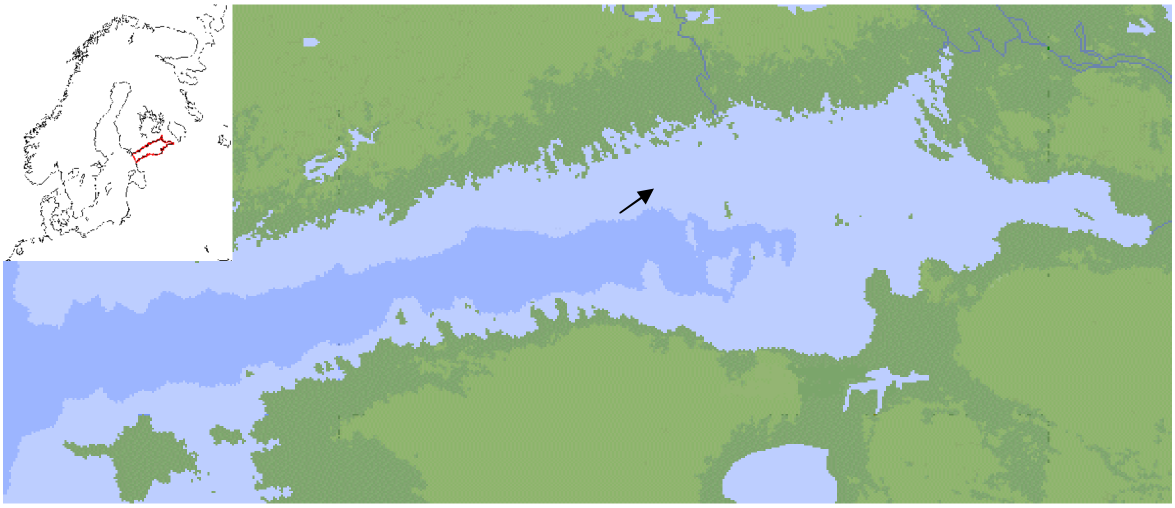

Figure 1. The Gulf of Finland, Aspskär is pointed by the arrow.

The winds and density-driven currents cause water circulation in the GOF: the strongest inflow is in the Estonian coast and the outflow is in the Finnish coast. There are differences in circulation patterns in different depths (Andrejev *et al.* 2004). No tides can be found in the GOF, but changes in the sea level can be distinct (Alenius *et al.* 1998). The size of waves varies within seasons (Pettersson 2007). Average number of ice days in the GOF is 40 in the west and 130 in the east (Alenius *et al.* 1998).

The species diversity of the Baltic Sea is very low compared to oceans or lakes and rivers, because the brackish water makes it a very harsh living environment. Young geological age of the basin and the lack of certain habitats, such as tidal zone, cause also the low diversity of species (Furman *et al.* 1998). However some subspecies e.g. Baltic herring (*Clupea harengus membras*) can only be found in the whole Baltic Sea. The GOF is an important migratory route for arctic bird species and many birds breed in the shoreline during summer including e.g. endangered black-backed gull (*Larus fuscus*). Some marine mammals e.g. grey seal (*Halichoerus grypus*) live in the GOF as well.

Environmental problems in the GOF are e.g. eutrophication, which is caused by internal and external load of nutrients, the lack of oxygen in the bottom layers of the sea, and the accumulation of the environmental toxicants e.g. dioxins to the food-web (Pitkänen *et al.* 2001, Furman *et al.* 1998). Also the invasive non-indigenous species may disturb the ecosystem (Golubkov 2009). In the GOF there exist conservation areas such as Natura2000 areas, Important Bird Areas (IBAs) and national parks held by Finnish state-owned enterprise Metsähallitus.

The vulnerability of the GOF is recognized among the coastal states and they also pursue to protect it. The International Maritime Organization (IMO) named the Baltic Sea excluding the Russian waters as the Particularly Sensitive Sea Area (PSSA) in 2005. Areas with the PSSA status need special protection through action by the IMO because of their significance for recognized e.g. ecological and cultural reasons which may be vulnerable to damage by international maritime actions (MARPOL 73/78). When an area is approved as a PSSA, specific measures can be used to control the maritime activities in that area such as routing measures and equipment requirements for ships (MARPOL 73/78).

Control systems which are monitoring shipping movements are working in the GOF; Gulf of Finland Reporting System (GOFREP) has been shared by Finland, Estonia and Russia since 2003. The GOFREP covers international waters of the GOF and territory waters of Finland and Estonia. The system is able to provide information about navigational hazards and weather conditions which can be causes for oil spills (Huhtala *et al.* 2005). Automatic Identification System (AIS) identifies and locates vessels and it is mandatory for all vessels over 300 gross tonnages which denote in practice all cargo vessels (SOLAS 1974). With AIS it is possible to provide information that can prevent collisions. The double hull requirement is in force for all the tankers operating in the GOF (MARPOL 73/78). According to this requirement the using of single-hull vessels is not permitted (MARPOL 73/78).

2.2. Birds in sea environment

Seabirds, which in this thesis also include sea ducks, have adapted to marine environment and can live in the open sea or in the coast and even spend part of the year on land (Gaston 2004).

The waterproof structure of the plumage of seabirds is essential for their survival. The ability to keep the water off their skin, where it would cause a rapid loss of heat, partly depends on the water-repellent capacity of the feathers and partly on the resistance to water penetration between the feathers (Gaston 2004). The soaking of the skin of birds would cause hypothermia and eventually death in cold water. The mechanical structure of the barbules on the feathers is such that water cannot penetrate them because of the surface tension. The preen oil makes it easier for the feathers to retain their proper shape, and it also increases their water-repellence. The tiling arrangement of the feathers, overlapping one another in rows, helps to shed water (Gaston 2004).

Most of the seabird species breed in colonies where a number of birds nest much closer together than a random dispersal on the coast would dictate. The size of a colony varies; separate nests can be distributed on a wide area or the density of nests can be very high on a small islet. Occasionally different species may nest in same colony in their own niches (Gaston 2004, Schreiber and Burger 2001). Adaptations for marine environment, such as webbed feet and long wings, weaken the mobility on land. Hence the ability to escape from predators has decreased. When nesting in colonies, the birds are at safe from the catching (Gaston 2004). These dense colonies can also be held as information centres for birds where the information of food is changed (Ward & Zahavi 1973). Most species have high site fidelity and individuals breed every year at the same site. From nesting sites the adult birds make fishing journeys in near distance (Schreiber & Burger 2001).

Most of the seabirds nest at high latitudes and migrate to south for winter. Birds often migrate over sea so they can land resting, and feed themselves whenever they want (Gaston 2004). Seabirds have on average higher survival and lower fecundity than the birds living on land. Fecundity of seabirds also varies within age (Gaston 2004). The breeding success and effort increases when bird gets older since the possibility to breed in later years decreases. When ageing, birds get valuable information about the breeding sites and mates of good quality and learn to take care of their offspring better (Gaston 2004). In average seabirds are sexually mature earliest at the age of four and lay one egg per breeding season. The survival of adults is 90% and therefore the breeding populations consist greatly of birds with a few years breeding experience (Gaston 2004).

Some characteristics of sea ducks differ from seabirds in common: long-tailed duck for example may lay 10 eggs instead of only few. Sea ducks also attain reproductive maternity after two years (Johnsgard 1965). They are marine mainly outside the breeding season; breeding usually occurs in tundra pools, marshes or lakes.

2.2.1. Common guillemot

Common guillemot is a sturdy and shuttle-shaped seabird with a short neck (Fig. 2). Its webbed feet are situated in the rear end of the body. Hence common guillemots can fly fast near the sea surface. These birds are skilful swimmers, divers and fishers and spend time on land only when nesting. Common guillemot is the largest of the Finnish auks – its length is 40 cm and wingspan 64–70 cm (Lundevall and Bergström 2005).

Figure 2. Common guillemot (photo by Petri Päivärinta)

Common guillemots living in the GOF are part of the Baltic Sea population – a population consists of ca. 45 000 individuals (Olsson *et al.* 2000). The Baltic Sea population most likely has its origin in the Atlantic populations and it may have been established 4000 years ago. It is one of the smallest populations of guillemots in the world and it is considered to be a particular subspecies: *U. a. intermedia* (e.g. Salomonsen 1944 ref. Olsson *et al.* 2000). After Olsson *et al.* (2000) the population stays in the Baltic Sea all year round, i.e. birds nest in the colonies around Baltic proper and winter in the southern Baltic Sea. In winter the birds are concentrated in the following areas: around Gotland and Öland, the Gulf of Danzig, the sea around Bornholm, Hanöbukten, Rügen and the Pomarian Bay, and the Danish islands (Olsson *et al.* 2000).

The breeding phenology of guillemots in the Baltic Sea is roughly the following: egg-laying starts in May and the peak period when the fledglings jump from the cliffs only partly grown, and departure, escorted by adult males, occurs in late June and early July. The fledglings and males leave the breeding area and start swimming together (without the females) to wintering grounds in southern Baltic Sea. Throughout July many immature birds are present in the colony, but in August the colony becomes empty. From September to February birds are mainly in wintering areas. The breeding season starts in the second half of April, prior to laying and ends in the first half of July when the most fledglings leave the colony (Olsson *et al.* 2000).

Common guillemots are long-living seabirds with a low annual reproductive output; hence annual adult survival is a significant parameter for the sustainability of the population (Österblom *et al.* 2004). Adult survival is high in the absence of diseases such as avian cholera. However, unpredictable catastrophic events, such as disease outbreaks or large oil spills in the vicinity of the colony, may have a large deleterious impact on the population (Österblom *et al.* 2004). Small clutch and delayed adulthood make the development of population relatively more sensitive to changes in the probabilities of adult survival than to changes in offspring production and survival of young birds (Olsson *et al.* 2000). Birds start breeding at an age of 5 years, lay one egg and continue nesting until death, even to the age of 20 years (Hudson 1985). In addition to oiling, by-catches and large-scale oceanographic, i.e. North Atlantic Oscillation (NAO), or food-web changes are commonly considered to be potential major threats to the adult common guillemot survival (Österblom *et al.* 2004).

Common guillemots show adaptive site choice (Österblom *et al.* 2004, Birkhead and Hudson 1977). Breeding sites in use are of higher quality than those which are not and birds leave low-quality sites to increase their breeding success (Kokko *et al.* 2004). An individual guillemot generally uses the same nest-site from year to year but a minority moves (2 m) between seasons (Kokko *et al.* 2004). Population performance can be reduced through adaptive behavior of individuals if they float i.e. spend a season as a non-breeder instead of breeding at a low quality site (Kokko & Sutherland 1998).

Only one breeding site is known for common guillemot in the GOF, the Aspskär bird colony in Pernaja (Fig. 1). Breeding was first recorded there in 1957 (Hario 1982). In Aspskär birds breed in sheltered hollows under big boulders where eggs are easily counted (Hario 1982). The population was highest in 1990 when there were 73 pairs nesting in the GOF and 5–10 in Åland. The population declined one third in 1992 as a resultant of red tide caused by the dinoflagellate algal blooms (Hario 2009, pers. comm.). Dinoflagellates cause protein-induced loss of water proofing especially to fish foraging seabirds (Jessup *et al.* 2009). However, the population started to increase after that (Finnish Game and Fisheries Research Institute, unpublished). Red tides occurred in the GOF also in 2000 and 2006, and the amount of common guillemots declined in the Aspskär (Hario 2009, pers. comm.). The population in Aspskär is dependent on the recruitment from elsewhere, mainly from Stora Karlsö in Sweden (Hario 1982). It is estimated that more than a half of the pre-breeders seeks to breed elsewhere than their own colony (Frederiksen and Petersen 2000). In Finland common guillemot is classified as an endangered species (Rassi *et al.* 2010).

2.2.2. Long-tailed duck

Long-tailed duck is a small-sized sea duck. The illustration of the plumage of long-tailed duck depends on sex and age of the bird and time of year. However, it consists of black, brown and white colours (Fig. 3). The length of a male is 50–60 cm and a female is 40 cm, the wingspan of them both is 65–82 cm. The male has a tail length of 10 cm (Lundevall and Bergström 2005).

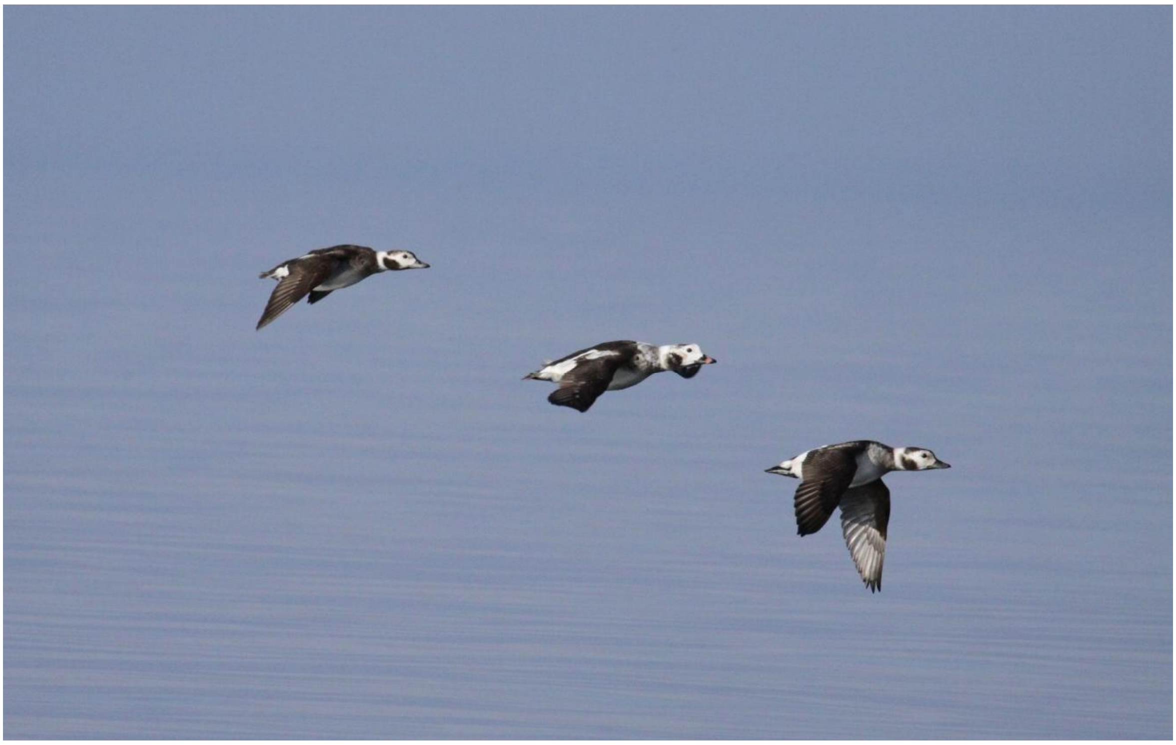

Figure 3. Long-tailed ducks (photo by Petri Päivärinta)

Long-tailed duck is an arctic circumpolar species, and it breeds in tundra and in the islands of Northern Arctic Ocean. When the bird is breeding, it can be easily seen because it stays in the open sea and it is loud (Lundevall and Bergström 2005). Long-tailed ducks nesting in the Siberian tundra winter in the Southern Baltic Sea and migrate over the GOF. The spring migration from the Baltic Sea to Russia starts in March and it moves from shoal to another. In April the birds are gathered in the Estonian coast near Saaremaa and when the first calm nights arrive in May, the birds migrate over the GOF. The spring migration mostly occurs at night time, but the birds migrate also during day, when the birds mainly migrate along the Finnish coast (Fig. 4) (Ellermaa, pers. comm.).

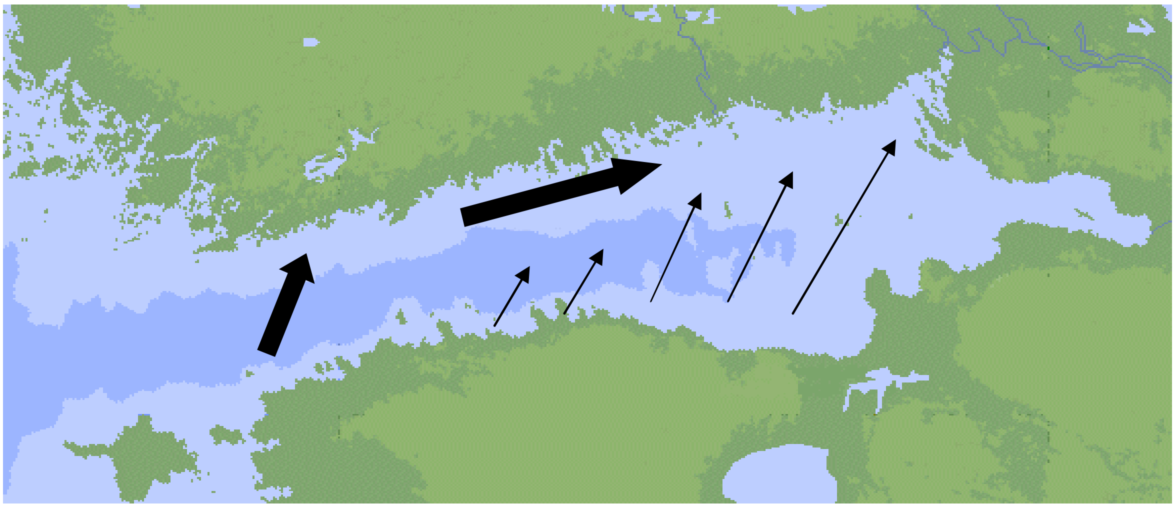

Figure 4. The spring migration of long-tailed duck over the GOF. Wide arrows represents the migration during day time and thin arrows during night time.

After the breeding season the autumn migration back to the wintering areas starts, lasting from September to November. The migration occurs at nightfall when the weather is clear, in which case long-tailed ducks fly low. They travel undivided from the White Sea to the Estonian coast (Fig. 5). The majority of birds winter in the Hoburgs bank, Gotland, south of Hiiumaa and the Gulf of Riga, minor part stays in the shoals of GOF (Larsson and Tydén 2005, Lundevall and Bergström 2005).

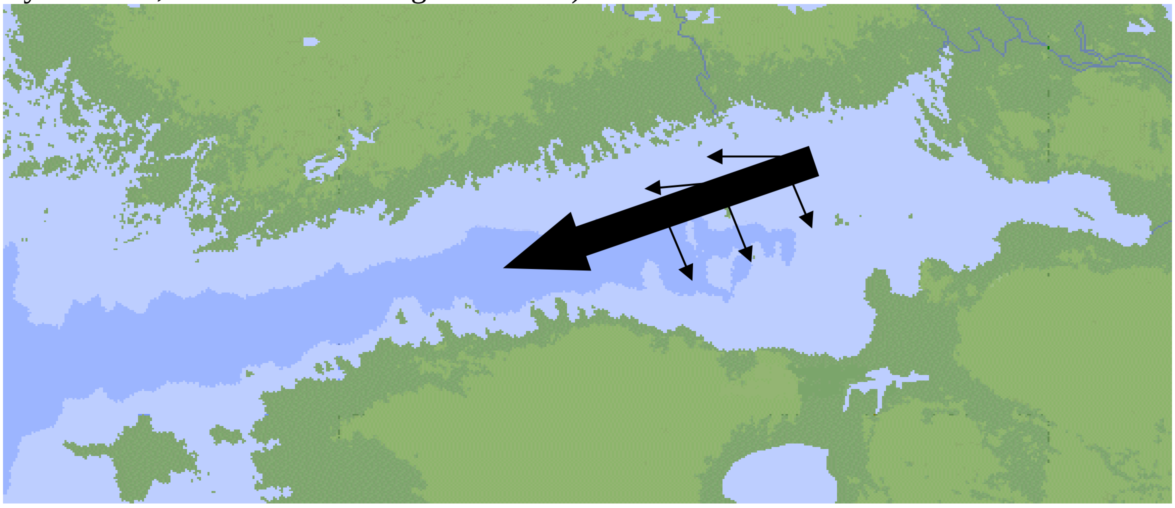

Figure 5. The autumn migration of long-tailed duck over the GOF. Wide arrow represents the main migration and the thin arrows birds that stay in the GOF during winter.

The estimates of the size of Baltic Sea population have varied within 2–4.7 millions of individuals (Andell *et al.* 1994, Durinck *et al.* 1994, Laursen 1989). The estimation of the population size is difficult because the counting is based mainly on migrating birds. The long-tailed ducks migrate over the whole width of GOF and the migration occurs both day and night time. Hence the propotion of counted birds is difficult to estimate from the total population. In the remigration the fledglings are also with the migrating birds.

The number of the long-tailed ducks in the Baltic Sea has decreased one third over the last decade. There has been a decline in winter population and a decrease in migration observations (Hario *et al.* 2009). During migrations in the 2007–2009 the number of long-tailed ducks was calculated to be 1.5 million individuals (Ellermaa, pers. comm.). The decrease in population size is caused by the low number of recruitment which is affected by high nesting mortality (Hario *et al.* 2009). This mortality may be resulting from the decrease of lemming population in Siberia: predators have changed to new prey (Hario *et al.* 2009). Also the mortality caused by oiling has been discovered to cause decreasing of the population in the Baltic Sea (Larsson and Tydén 2005). In May 2012 it will be suggested that long-tailed duck should get the status of internationally endangered species (Kauppinen 2012).

2.3. Oil in aquatic environment

2.3.1. The properties of oil

Oils are complex mixtures of hydrocarbons and other substances which vary widely in composition. They are divided into board groups according to their relative density, distillation properties, viscosity and melting point to light, medium and heavy oils (ITOPF 2002, Michel 1992). These characteristics also affect how the oil behaves once it is spilled (Michel 1992). The relative density describes the buoyancy of oil, distillation properties describe the ability of oil to evaporate from water, viscosity the resistance of flow and below the melting point the oil solidifies (ITOPF 2002). Crude oil can also be categorized after its origin, e.g. Russian Export Blend Crude Oil (REBCO).

Light oils, e.g. diesel, are quite volatile and will leave a residue and, especially distilled products, may contain moderate concentrates of toxic compounds. These oils may contaminate intertidal resources and are very susceptible for subtidal processes e.g. dissolution, mixing, sorption onto suspended sediments (ITOPF 2002, Michel 1992).

Most of the crude oils are included in the group of medium oils. One third of the volume of oil can evaporate within the first 24 hours, but evaporating may also continue for several days. The compounds are less soluble than in the light oils and contamination of intertidal habitats and sediments may be severe and long-term (Michel 1992). The medium-weight components of these oils pose the greatest environmental risks to organisms because those are more persistent and the polycyclic aromatic hydrocarbons (PAHs) in these oils have high toxicities (Michel 1992).

Heavy oils, e.g. bunker which is used as fuel by vessels do not evaporate or dissolve, but may sink into the bottom of the sea. The components pose little acute toxicity risks, except that due to smothering, because of the very low solubility of the individual components. However, these are the most persistent components of oil, and degradation rates are slow (Michel 1992). Contamination of intertidal habitats and sediments, and impacts on birds and mammals are often severe and long-term (Michel 1992).

2.3.2. Fate of oil in aquatic environment

When the oil is spilled into the sea it starts to spread and transform. This is called weathering (Fig. 6). The most visible action is the spreading over the sea surface. The speed of spreading is dependent on the viscosity of oil and the volume of oil spilled; it is also affected by tidal streams, wind speed and currents. The oil slick can spread over the surface several square kilometres only in few hours (ITOPF 2002).

The dominant weathering process removing oil from the marine habitat is evaporation. For light products e.g. gasoline evaporation may remove the entire spill from few hours to few days and light crude oils can lose up 40% of their volume during the first day. For medium oils 20–30% is lost to evaporation within the first 24 hours and for heavy oils the evaporation will remove only 5–10% of the spill (ITOPF 2002, Michel 1992). However, only the monoaromatics may evaporate, not the PAHs. The rate of evaporation is affected by ambient temperature and wind speed. Rough sea, high wind speed and warm air temperature increase the evaporation rate. The boiling point of the components of oil also affects to the evaporation: the greater the proportion of components with low boiling points, the greater the degree of evaporation (ITOPF 2002). Spreading and evaporation and the intensity of those have a high impact on the final environmental effect.

Another important process is emulsification. Formation of emulsions affects the behaviour of an oil spill in several ways. First, the weathering rate decreases when the viscosity of oil increases. Secondly, the volume of oil is increased by a factor of 2–3 because the emulsion is up to 70% water (Michel 1992). The emulsion is formed when in moderate to rough seas; most oils will take up water droplets and form water-in-oil emulsions under the turbulent action (ITOPF 2002). Emulsification reduces the rate of other weathering processes and is the main reason for the persistence of light and medium crude oils (ITOPF 2002).

Part of the oil slick can break into droplets, which are affected by waves and turbulence at the sea surface (ITOPF 2002). These droplets become mixed into the upper layer of the water column. Dispersion can also be promoted by chemicals in oil combating. The increased surface area presented by dispersed oil can affect dissolution, sedimentation and biodegradation by accelerating those (ITOPF 2002).

Dissolution of hydrocarbons into the water column poses risks to aquatic organisms because of the acute toxicity of compounds that have significant water solubility (Michel 1992). Monoaromatics e.g. benzene have the highest solubility, and of the PAHs, naphthalene is the most water-soluble (Michel 1992). However, these compounds are also the most volatile and especially monoaromatics are lost rapidly by evaporation (ITOPF 2002). The heavy components of crude oils are insoluble (ITOPF 2002).

If the oil has specific gravity higher than sea water, it sinks once it is spilled (ITOPF 2002). Most crude and fuel oils have low specific gravities and they remain afloat unless they interact with and attach to more dense sediment or organic particles. Adhesion to heavier particles most often takes place when oils strand or become buried on beaches (ITOPF 2002).

In photo-oxidation, hydrocarbons react with oxygen and form soluble products or persistent tars (ITOPF 2002). Tars can be seen on shorelines and usually consist of a solid outer crust of oxidized oil and sediment particles surrounding a less weathered interior (ITOPF 2002). Tars may drift a long way.

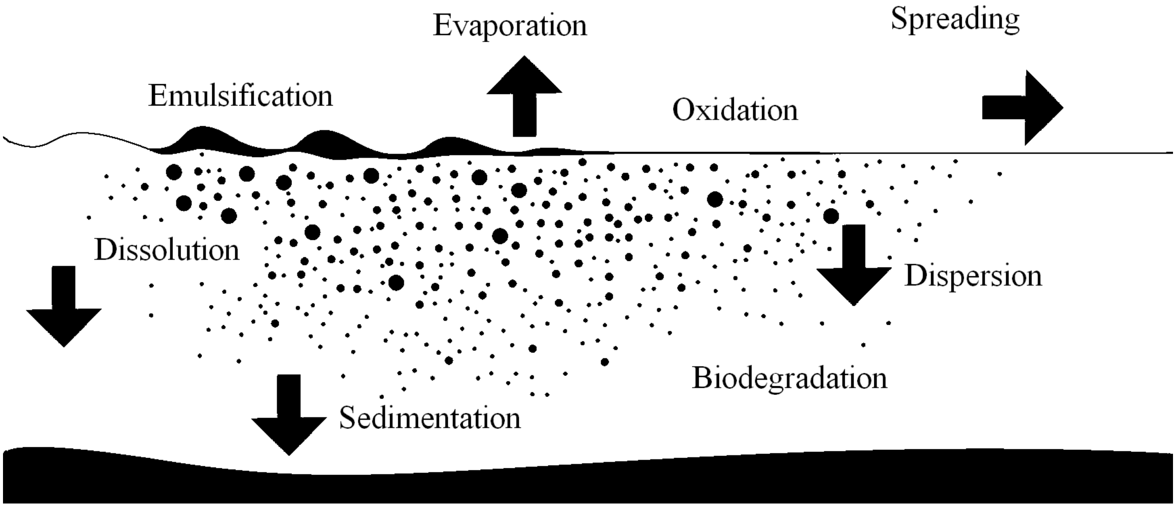

Figure 6. Processes acting on spilled oil (Helle 2009, modified).

2.3.3. The impacts of oil on seabirds

A number of different factors will determine the degree of effects that can be expected from an oil spill: location, volume of spill, weather conditions and time of year. Different habitat types are affected in distinctive ways; open habitats are at more risk than sheltered habitats. Population sizes may vary seasonally and in breeding time also the offspring are at risk. Weather can also affect the behaviour of different species (Scholz *et al.* 1992).

Seabirds living on the sea surface or near the shore may be exposed to oil that is floating or washed ashore. Smothering of plumage by oil (Fig. 7) may cause an acute death via hypothermia or drowning (Kennish 1997). The structure of the feathers is altered by oil which causes loss of their water-repellent characteristics. The oiled plumage becomes matted, allowing water to penetrate to the body surface. This results in hypothermia as well as loss of buoyancy (Scholz *et al.* 1992). It is believed that the hypothermia of heavily oiled birds is the most common reason to their mortality caused by oil spills (Wood and Heaphy 1991, Fry and Lowenstine 1985).

Figure 7. Oiled plumage of a long-tailed duck (photo by Julian Bell).

In addition, birds get oil to their system when drinking oiled sea water, consuming contaminated food and breathing toxic vapours. The effects of ingested oil include anaemia, pneumonia, intestinal irritation, kidney damage, altered blood chemistry, decreased growth, impaired osmoregulation, decreased reproduction and viability of eggs, abnormal parenting behaviour and decreased growth of the offspring (Albers 2002, Kennish 1997, Wood and Heaphy 1991, Eppley and Rubega 1989). Anaemia is defined as the most serious disease resulting in ingestion of oil in birds: the birds are not able to dive or forage for food and starve on shore. Even cleaning of birds does not decrease the mortality caused by anaemia (Scholz *et al.* 1992).

Some toxic effects may not be evident immediately or may not cause death. These are called sublethal effects and they can impact on birds' physiology, behaviour or reproductive capability. Sublethal effects may ultimately impact the survival rates of birds affected (Scholz *et al.* 1992). Birkhead *et al.* (1973) reported about oiled birds that cleaned themselves successfully several weeks after an oil spill. However, birds might have ingested oil while preening.

If the oil spill occurs during the breeding time, eggs may be exposed to oil. Adult birds may transfer the oil to nests or the nesting site may be exposed directly (Scholz *et al.* 1992). Direct exposure of eggs to oil has the greatest potential for damage, and the early stages of incubation are considered to be the most sensitive (Scholz *et al.* 1992). Oil may close the pores of an egg shell and cause delayed hatching, abnormalities and mortality of chicks (Scholz *et al.* 1992, Albers 1978). Studies show that even small quantities of oil applied to eggs reduces survival (Fry and Lowenstine 1985, Peakall *et al.* 1981). Adults that have ingested harmful doses of oil may produce decreased amounts of eggs or cease laying altogether (Scholz *et al.* 1992). Some of the seabird species have observed to leave their nesting site even after being exposed to small amount of oil (Scholz *et al.* 1992).

The effects of an oil spill differ considerably amongst bird species due to differences in behaviour, distribution and reproduction. Birds that continuously forage food by diving are at high risk. Also the birds that sleep in water, form large flocks and dense nesting colonies in vicinity of high risk spill areas, spend time at open sea, and which have low reproductive rate are very sensitive to oil spills (Scholz *et al.* 1992). During migration birds are highly vulnerable to oil spills as they use offshore and coastal marine waters for staging and overwintering (Scholz *et al.* 1992). After Lecklin *et al.* (2011) the auks and ducks are the most vulnerable groups to oil.

3. MATERIALS AND METHODS

3.1. Bayesian networks

A BN is a statistical multivariate model for a set of variables, and it describes probabilistic relationships between them (Aguilera *et al.* 2011, Jensen 2001). Each variable in the model is presented with directed links forming arcs between variables (Uusitalo 2007). Once the structure is defined, it is necessary to know how strong the relationships are; this is described by a conditional distribution for each variable given in the graph (Aguilera *et al.* 2011). The probability distributions are based on available and current knowledge. The posterior probability is calculated with the equation below (Eq. 1), the Bayes' theorem:

Equation 1.

$$P(A \mid B) = \frac{P(B \mid A)\, P(A)}{P(B)}$$

In Eq. 1, $P(A)$ is the prior probability or marginal probability of A. It is prior in the sense that it does not take into account any information about B. $P(A|B)$ is called the likelihood, i.e. the conditional probability of A, given B. And $P(B|A)$ is the conditional probability of B, given A. $P(B)$ is the prior or marginal probability of B and acts as a normalizing constant.

BNs represent one approach of Bayesian modelling, the other being the hierarchical simulation-based modelling (Uusitalo 2007, Gilks *et al.* 1994). In BNs, the probability distributions are expressed in discrete form and solved analytically, whereas in simulation models the distributions are estimated by generating samples from these by simulation. However, both of these share the idea of conditional dependence between variables and the updating of knowledge. Simulation model results can also be imported into BN in order to create a meta-model (Uusitalo 2007).

BNs are useful in many real-life data analysis and management questions. They provide a way to handle missing data, allow combination of data with domain knowledge, facilitate learning about causal relationships between variables, provide a method for avoiding overfitting of data, can show good prediction accuracy, and can easily be combined with decision analytic tools to aid management (Uusitalo 2007, Jensen 2001).

The BNs use different kind of information as probability distributions: posterior distributions from simulation models and expert knowledge as done in this study. Expert knowledge can also be combined with data (Uusitalo 2007).

3.2. Description of the models and variables

For both species a separate BN model was done/constructed (Figs. 8 and 11) with HUGIN software (Hugin Expert A/S). The probability distributions for the accident variables *Oil_type* and *Time_of_year* are from literature. The distributions for the rest of the variables are from expert interviews. For the probability distribution for *Recovery* in the common guillemot model a sub model was done with JAGS software (Jags Software Inc.). This sub model described the population dynamics of the species.

3.2.1. Common guillemot

The BN model for common guillemot consists of nine different variables (Table 1). It has three variables that have no parent variables: two accident variables which both demonstrate varying accident scenarios and one variable for different experts (Fig. 8).

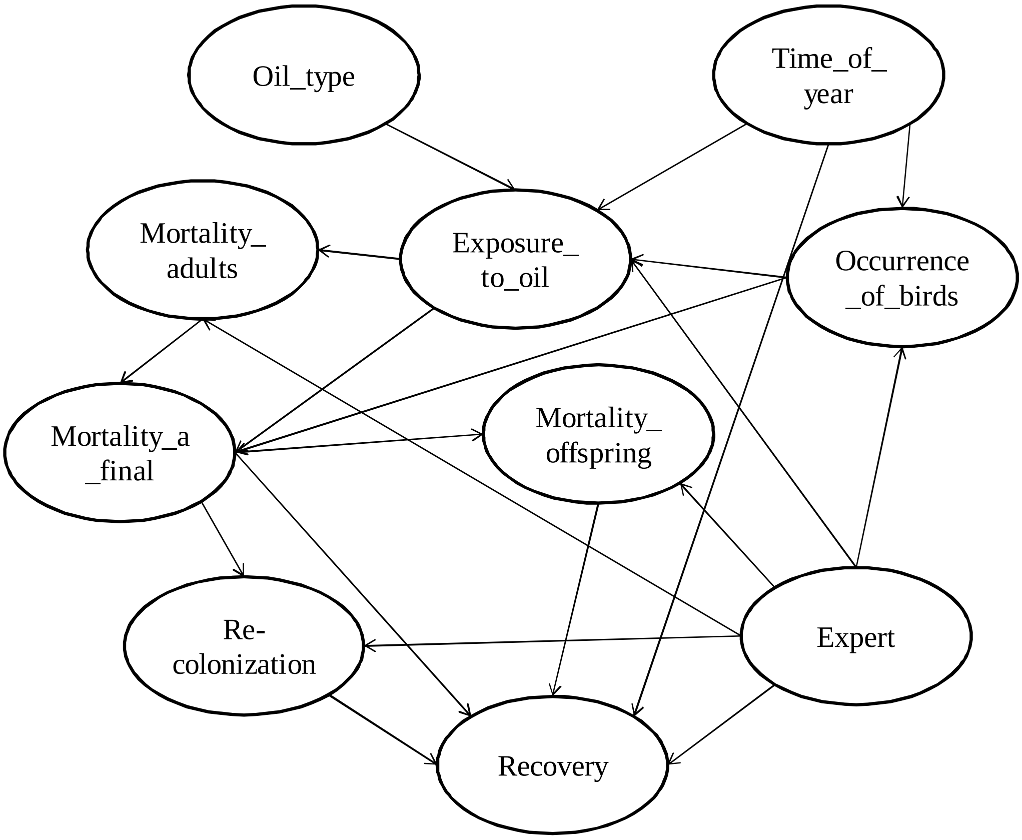

Figure 8. Graphical presentation of the BN structure for the common guillemot.

Table 1. Variables of the BN for the common guillemot model.

Variable	States
Oil_type	Light oil, Medium oil, Heavy oil
Time_of_year	Spring, Summer, Autumn
Expert	Expert 1, Expert 2, Expert 3, Expert 4
Exposure_to_oil	0–20 , 20–50, 50–80, 80–100 (%)
Occurrence_of_birds	0–20, 20–50, 50–80, 80–100 (%)
Mortality_adults	0–20, 20–50, 50–80, 80–100 (%)
Mortality_a_final	0–20, 20–50, 50–80, 80–100 (%)
Mortality_offspring	0–20, 20–50, 50–80, 80–100 (%)
Recolonization	0–20, 20–50, 50–80, 80–100 (%)
Recovery	0–20, 20–50, 50–80, 80–100 (%)

Oil_type has three different states: light, medium and heavy oil. Probability distribution is based on the amounts of transported oil types (%) in the GOF in 2007 (Kuronen *et al.* 2008).

Time_of_year has three different states: spring (from March to May), summer (from June to August) and autumn (from September to November). Only open water months were considered. Probability distribution is based on the number of accidents (%) happened in the GOF in 1989–2001 (HELCOM 2001, 2002).

Expert variable describes the differences between expert opinions. This variable does take into account the status of the prior knowledge of different experts. When no expert is selected, the mean values are considered.

Occurrence_of_birds describes the number of birds (%) present in the breeding population in Aspskär colony, based on phenology. Probability values are from expert interviews.

Exposure_to_oil describes the number of birds (%) of the present population that becomes directly exposed to oil. Even a small spot of oil in abdomen is considered as an exposure. Probability values are from expert interviews.

Mortality_of_adults describes the estimated mortality of adult individuals immediately after exposure to oil. Probability values are from expert interviews.

Mortality_a_final describes the loss of breeding adult birds in the colony after an oil spill. It combines the likelihoods of the oil induced mortality, exposure to oil and occurrence of birds. Probability values are from the calculation which multiplies variables *Occurrence_of_birds*, *Exposure_to_oil* and *Mortality_of_adults*. Later when the loss of adults is discussed, this variable is refered to.

Mortality_of_offspring describes a decrease in the number of eggs and fledglings (%) in the GOF after an oil spill. The acute mortality is dependent on the loss of adult birds. Probability values are from expert interviews.

Recolonization describes the estimated rate at which the birds recolonize breeding site that has been affected by an oil spill. Successful colonization is dependent on physical and chemical suitability of habitat (Begon *et al.* 2006). Only recolonization by the next breeding season is considered. The proximity of suitable recolonization sources is alleged. Probability values are from expert interviews.

Recovery is a variable denoting the state of the affected population ten years after an oil spill. The states of the variable compare the abundance of the birds after an oil accident (%) relative to a situation where no accident has occurred. Probability values are from the population model of the common guillemot.

3.2.2. Population model for the common guillemot

The conditional probability table for the variable *Recovery* was difficult to elicit from experts, as the human mind is not usually capable of handling conditional probabilities over more than one or two dimensions (Morgan & Henrion 1990). Therefore a MCMC (Markov chain Monte Carlo) simulation model was constructed to describe the population dynamics of the common guillemot in two cases: with and without an oil spill.

The simulation model consisted of two parts: the estimation part and the prediction part. The former was used to estimate the relevant population parameters, and the latter to evaluate the recovery of the population within ten years after an accident, i.e. the difference between the population sizes with or without an accident.

The population model was state-structured (Fig. 9). It was assumed that young birds are recruited to the breeding population at the age of five, and after recruitment and first breeding they become adults and continue to breed until they die. The number of survivors in the next stage is age dependent. Adults and recruits are assumed to produce in average 0.7 eggs per year.

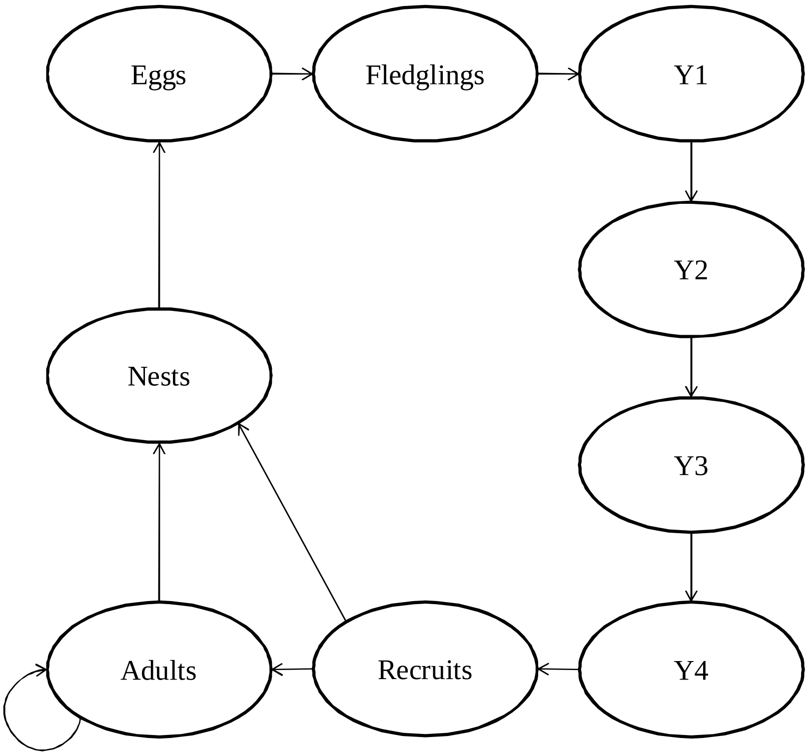

Figure 9. Graphical presentation of the population model for the common guillemot (Eggs = 0 yr, Fledlings=0–1 yrs, Y1=1 yr, Y2=2 yrs, Y3=3 yrs, Y4=4 yrs, Recruits=5 yrs, Adults=over 5 yrs, Nests=number of nests).

The probability distributions and prior assumptions for the parameters were gathered from literature and experts (Table 2). However, as there are no published values regarding the survival of 1–5 years old common guillemots, survival values were modelled by assuming that the survival increases gradually from fledgling state to adult birds.

In the prediction part the idea was to compare two different scenarios, the population sizes with and without an accident. In the former case, an oil spill was assumed to happen in 2011 and remove a certain proportion of common guillemots breeding in Aspskär. Within each mortality class (i.e. 0–20; 20–50; 50–80; 80–100%) the mortality was assumed to have a uniform distribution, i.e. in the first simulation run the mortality in the class 0–20% could be e.g. 5%, and in the second 17% etc. Same idea was applied with the variable *Recolonization*. If there was no spill, the prediction part of the model calculated the fate of the population without any disturbance in 2011. Finally, the recovery was calculated as a difference between the population sizes in these two scenarios.

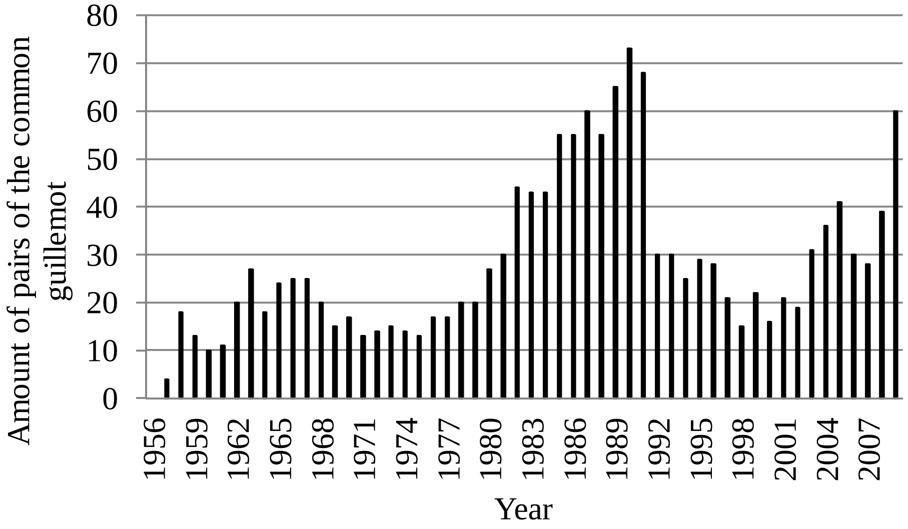

Figure 10. Number of pairs of the common guillemots nesting in the Aspskär breeding colony in years 1956–2009 (Finnish Game and Fisheries Research Institute, unpublished).

Table 2. Input population parameters for the common guillemot: *Rate of immigration* describes the mean immigration annually to the colony in Aspskär from other colonies in the Baltic Sea; *Clutch size* describes the mean number of eggs in one clutch; *Clutch probability* describes probability for the clutch to be found (%) and counted by the field biologists; *Adults* describes the mean number of adult breeders (>5 yrs) in the Aspskär colony; *Recruits* describes the mean number of adult first time breeders in the colony. Common guillemots are considered to start breeding in the age of 5 years; *Y1* is the mean number of 1 year old non-breeding adults in the Aspskär colony. The survival of non-breeders follows a beta distribution; *Y2* is the mean number of 2 year old non-breeding adults in the Aspskär colony; *Y3* is the mean number of 3 year old non-breeding adults in the Aspskär colony; *Y4* is the mean number 4 year old non-breeding adult in the Aspskär colony. ([a] Hario 1982, [b] Hario, pers. comm., [c] Finnish Game and Fisheries Research Institute, unpublished [d] Velmala, pers. comm.).

Parameter	Value
Rate of immigration[a]	8%
Clutch size[a]	0.7
Clutch probability[b]	95%
Adults[c]	72
Recruits[d]	10
Y1	0
Y2	4
Y3	6
Y4	8

3.2.3. Long-tailed duck

The BN model for long-tailed duck consists of nine different variables (Table 3). It has four variables that have no parents; *Oil_type*, *Time_of_year* and *Expert* are similar to the common guillemot model, but *GOF* represents different areas of GOF (Fig. 11).

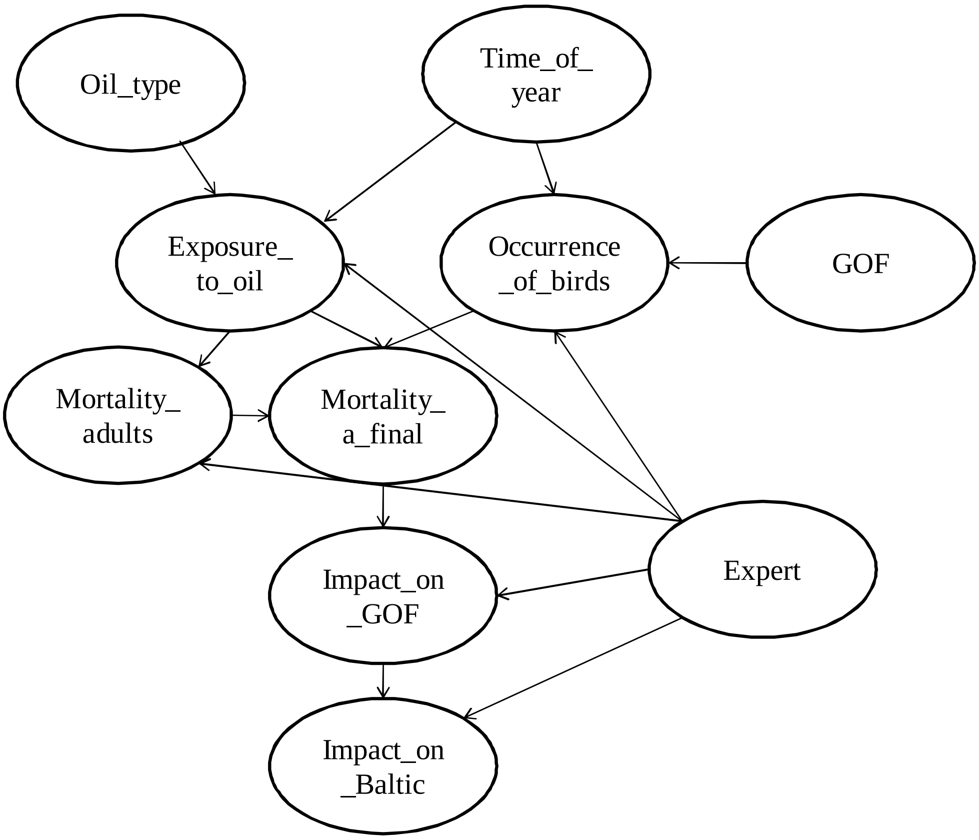

Figure 11. Graphical presentation of the BN structure for the long-tailed duck.

Table 3. Variables present the nodes in the Bayesian networks for the long-tailed duck model.

Variable	States
Oil_type	Light oil, Medium oil, Heavy oil
Time_of_year	Spring, Summer, Autumn
Expert	Expert 1, Expert 2, Expert 3, Expert 4
Exposure_to_oil	0-20, 20-50, 50-80, 80-100 (%)
GOF	East, West
Occurrence_of_birds	0–20, 20–50, 50–80, 80–100 (%)
Mortality_adults	0–20, 20–50, 50–80, 80–100 (%)
Impact_on_GOF	0–20, 20–50, 50–80, 80–100 (%)
Impact_on_Baltic	0–20, 20–50, 50–80, 80–100 (%)

Oil_type has three different states: light, medium and heavy oil. Probability values are based on the amounts of transported oil types (%) in the GOF in 2007 (Kuronen *et al.* 2008).

Time_of_year has three different states: spring (from March to May), summer (from June to August) and autumn (from September to November). Only open water months are considered. Probability distribution is based on the number of accidents (%) happened in the GOF in 1989–2001 (HELCOM 2001, 2002).

Expert variable describes the differences between expert opinions. This variable does not take into account the status of the prior knowledge of different experts. When no expert is selected, the mean values are considered.

GOF describes the division of the GOF in two parts; west: from Hanko to Pellinki, east: from Pellinki to St. Petersburg (Ellermaa, pers. comm.).

Exposure_to_oil describes the number of birds (%) present in the colony that becomes directly exposed to oil. Even a small spot of oil in abdomen is considered as an exposure. Probability values are from expert interviews.

Occurrence_of_birds describes the number of birds (%) present in the GOF. Probability values are from expert.

Mortality_of_adults describes estimated mortality of adult individuals directly after exposure to oil. Probability values are from expert interviews.

Mortality_a_final describes the loss of migrating adult birds in the GOF after an oil spill. It combines the likelihoods of the oil induced mortality, exposure to oil and occurrence of birds. Probability values are from the long-tailed duck model. Later when the loss of adults is discussed, this variable is refered to.

Impact_on_GOF describes the number of birds migrating over GOF ten years after spill. The states of the variable compare the abundance of the birds after an oil accident (%) relative to a situation where no accident has occurred. This variable takes into account the population dynamics of the species. Probability values are from expert interviews.

Impact_on_Baltic is denoting the number of birds wintering in the Baltic Sea ten years after spill. The states of the variable compare the abundance of the birds after an oil accident relative to a situation where no accident has occurred. The states of the variable describe the abundance of the birds (%). This variable is based on the number of migrating birds (%). Probability values are from expert interviews.

3.3. Behavior of the models

The information content of the models arises from the following structures: there are conditional probability tables after variables *Time_of_year* and *Oil_type* expressing the distributions of these. In other words, the tables under accident variables show distributions for these on every possible combination.

When none of the variable states is instantiated, the model is in the state where every possible value has an equal weight. However, the variable states may be examined separately i.e. the variable distributions will be changed by giving to one state the probability of 100%. This updates the model probabilities.

The value of all the variables can be fixed and the probabilities updated. This makes it possible to study e.g. how *Recovery* would change if *Recolonization* would get higher when *Mortality* is instantiated to one state.

3.4. Elicitation of expert knowledge

This study involved two different phases: eliciting knowledge from experts and modelling based on this knowledge. The expert elicitation was also organized in two phases. At first, one expert was asked to cooperate when providing the model structure in one separate session. After the model structure was pre-mediated, other experts were asked to provide estimates for the parameters, i.e. conditional probability distributions. In order to do this, experts must be familiar with the variables and agree with the model structure as they cannot be expected to provide sensible estimates if the model does not make sense to them (Uusitalo 2007). Both of the model structures were introduced to the experts before the elicitation process.

Four people participated in the interviews: Aleksi Lehikoinen from the University of Helsinki, Martti Hario from Finnish Game and Fisheries Research Institute, Petri Päivärinta from Kotka Maretarium and Markus Keskitalo from Metsähallitus. The selection of these experts was based on their professional and recreational interest in these species acquired over many years. In this study the experts are denoted as Expert 1, Expert 2, Expert 3 and Expert 4, not respectively. Before the expert interviews the networks and their node relationships were discussed with Margus Ellermaa from BirdLife Finland.

For each expert, a separate session was held and the interviews followed a similar scheme. This arrangement was made in order to ensure that the opinions and interpretations of each expert would not be affected by the judgment of others. Also the aim of this approach was to ensure that interviews were presented with same questions in the same order. The answers were reliably aggregated and comparisons between experts could be done with confidence (Kvale and Brinkman 2009). In this case, the data was collected by the interviewer. Materials shown to the experts were the networks for the both models, explanations for the network nodes and the probability tables to fill in. First the experts were asked to give probability estimates for the common guillemot model and then for the long-tailed duck model. The knowledge elicitation required approximately half an hour for the introduction and three hours for the input phase for the probability tables.

4. RESULTS

4.1. The common guillemot

4.1.1. Basic state of the model

The basic state of the model describes the situation where none of the variables is instantiated and nothing of the impacts of the accident is known; only that an accident will occur and the Aspskär islet will become exposed to oil is assumed. The basic state includes all uncertainty in the model.

The most probable time of year for the oil accident to occur in the GOF was spring and the most probable oil type was heavy oil (Figs. 12 and 13). When the prior distribution was considered the *Occurrence_of_birds* did not follow normal or unimodal distribution (Fig. 14). Exposure to oil of common guillemots did not exceed the probability of 40% in any states (Fig. 15). Thus the uncertainty was high in both variables.

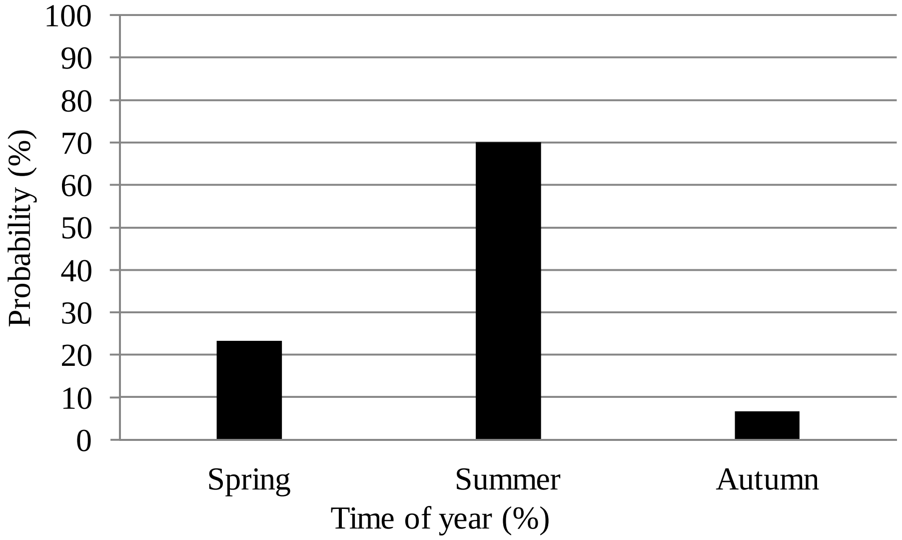

Figure 12. Prior distribution of the accident variable *Time_of_year* in the common guillemot model.

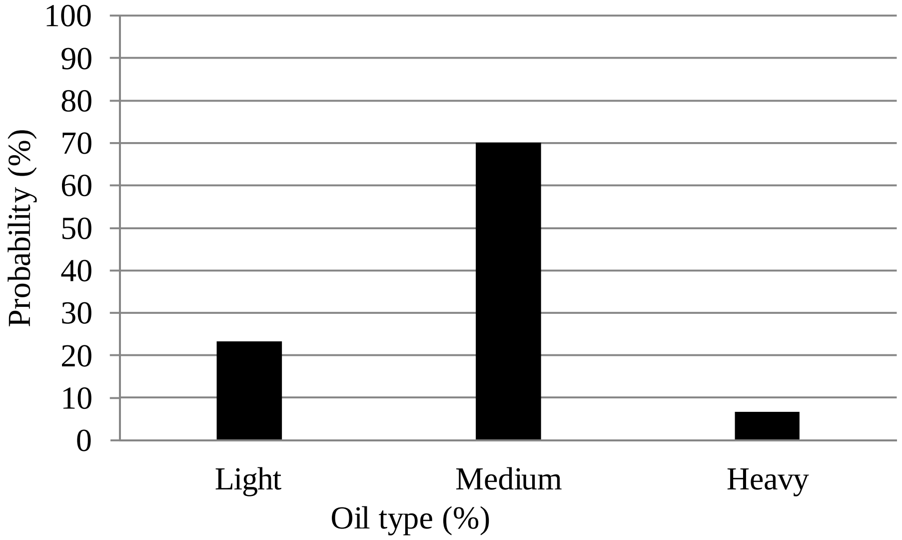

Figure 13. Prior distribution of accident variable *Oil_type* in the common guillemot model.

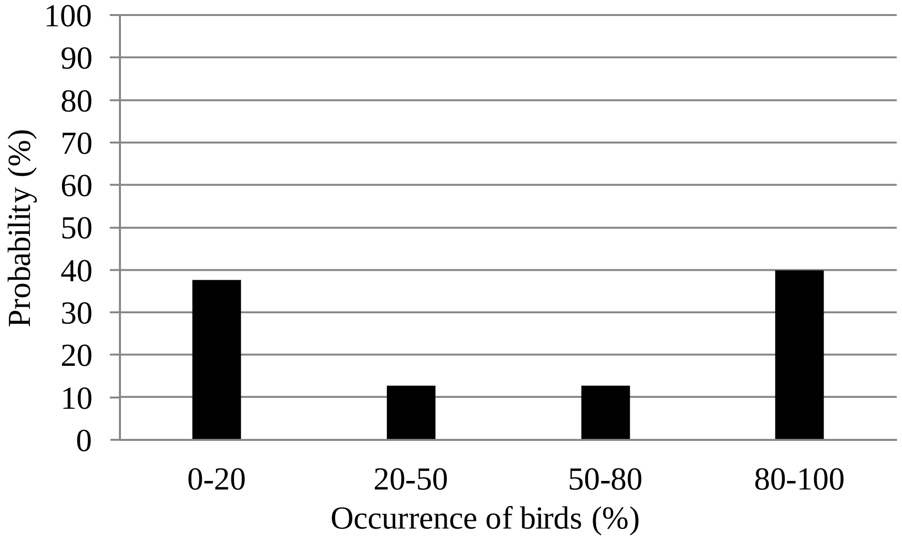

Figure 14. Prior distribution of *Occurrence_of_birds* in the common guillemot model, columns describe the number of birds of the population present.

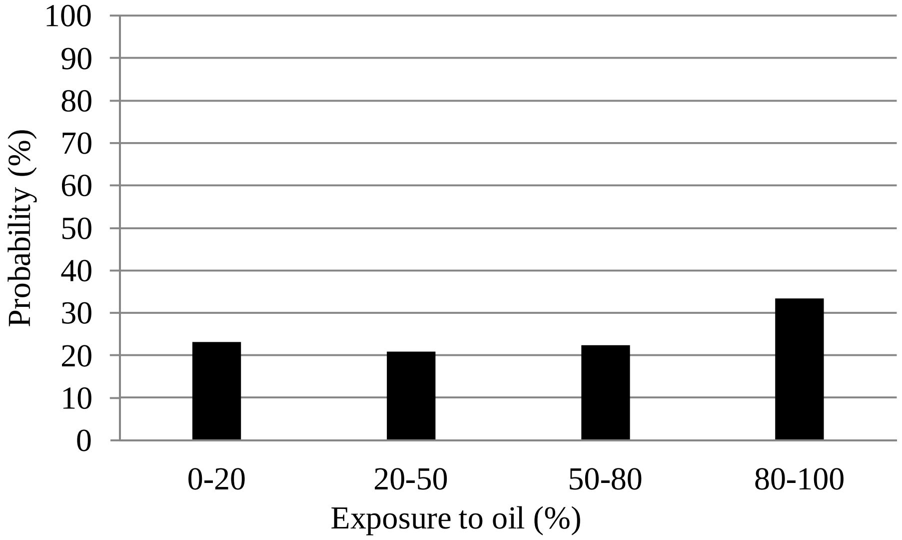

Figure 15. Prior distribution of *Exposure_to_oil* in the common guillemot model.

The mortality of adults after oil exposure was high with high certainty (Fig. 16). The loss of birds (Fig. 17) was noticed to be lower than the mortality of offspring (Fig. 18). In prior distributions, recolonization in the common guillemot population showed almost equal distribution (Fig. 19) and 80–100% of the population recovered (Fig. 20).

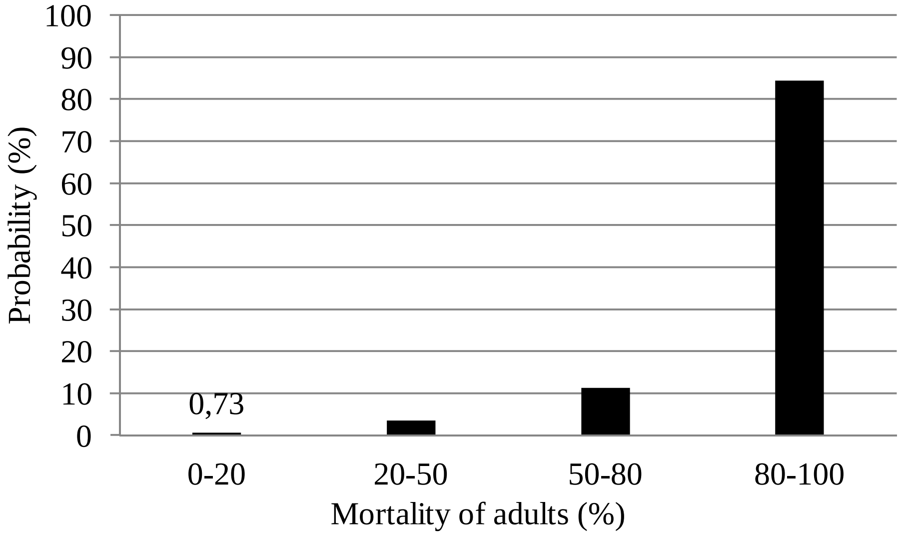

Figure 16. Prior distribution of *Mortality_adults* in the common guillemot model.

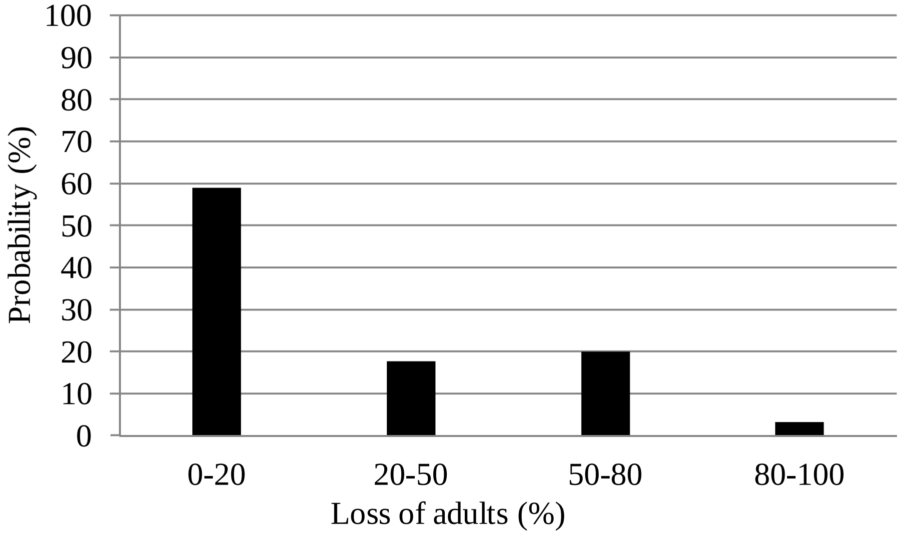

Figure 17. Prior distribution of *Mortality_a_final* in the common guillemot model.

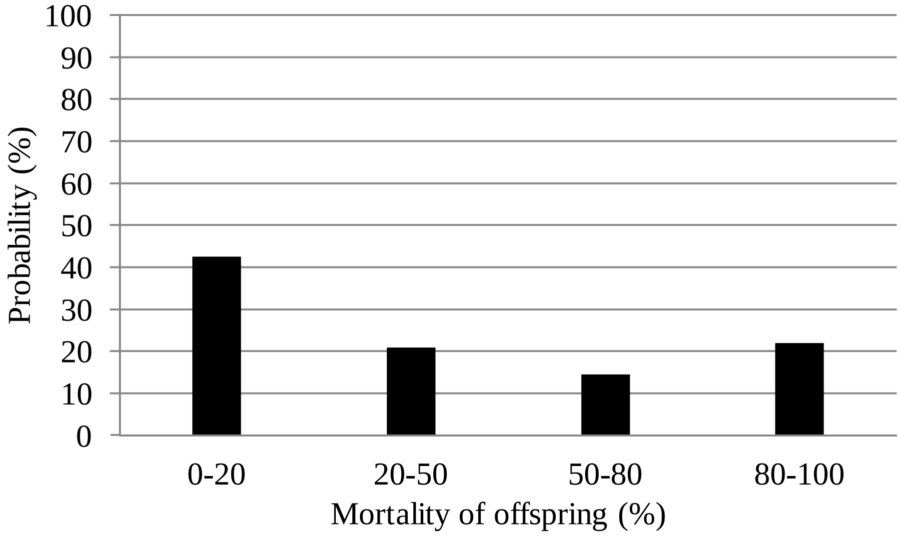

Figure 18. Prior distribution of *Mortality_offspring* in the common guillemot model.

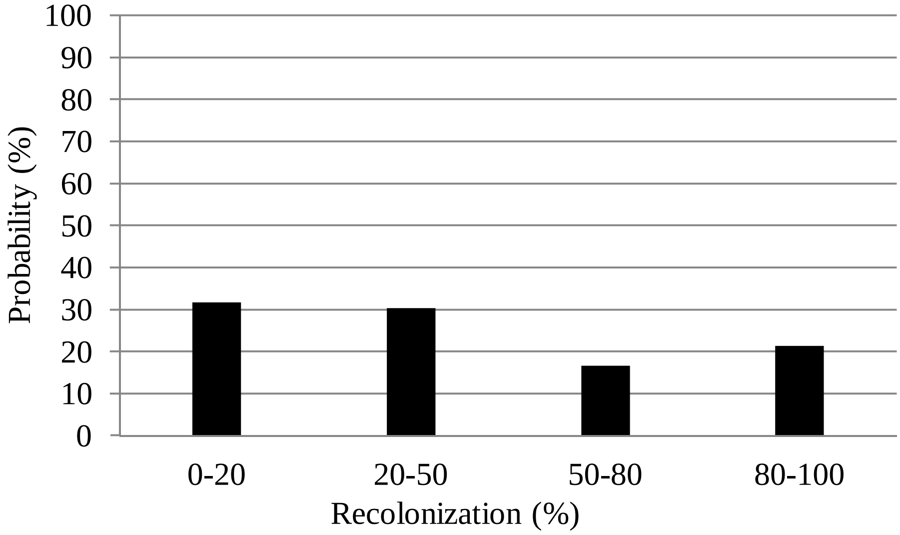

Figure 19. Prior distribution of *Recolonization* in the common guillemot model.

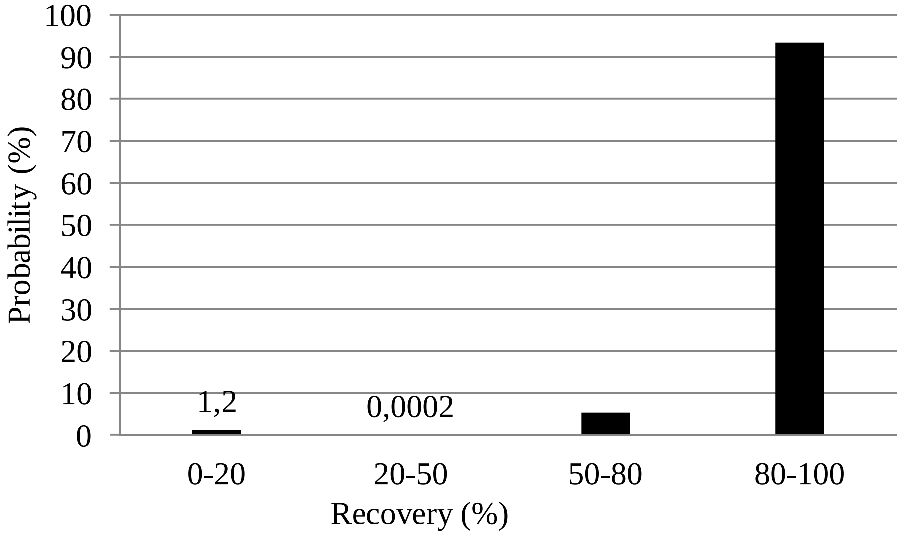

Figure 20. Prior distribution of *Recovery* in the common guillemot model.

4.1.2. The effect of oil spill: time of year and oil type

The results are also studied over different selected states of *Time_of_year* and *Oil_type*. In spring 80–100% of adult common guillemots were present in the colony with the probability of 42.5%, situation was similar in summer (Fig. 21), however, with even higher probability of 72.5%. In autumn the occurrence of the birds was 0–20% with the probability of 91.3%. In summer it was very probable that most of birds were present and in autumn only few. The highest uncertainty for birds being present was in spring.

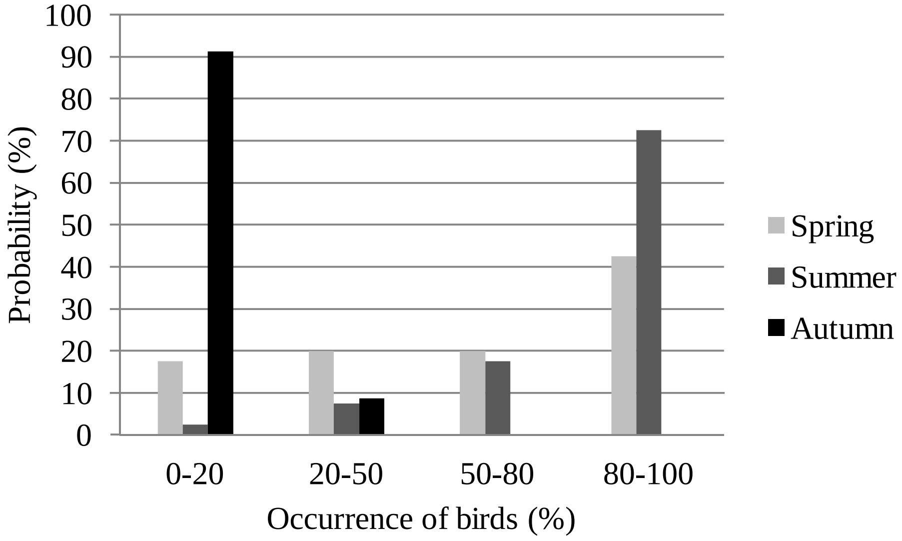

Figure 21. Probability distributions of the occurrence of the common guillemot model, columns describe the percentage of the population present during different times of year.

In spring oil type had no notable impact on the exposure of common guillemots (Fig. 22) whereas in summer and autumn some differences were noticed (Figs. 24–25). The more the distribution is rightward, the higher the exposure. It is important to notice that although the exposure e.g. with medium oil was 80–100% with the probability of 46.3%, the highest class (i.e. 80–100%) of adult loss had only the probability of 5.8%.

The distribution for mortality of offspring followed the one for loss of adults (Fig. 23). However, some weight was given also for the lower states. In all seasons mortality of adults was high after exposure, but when effects were considered, mostly loss of adults was studied.

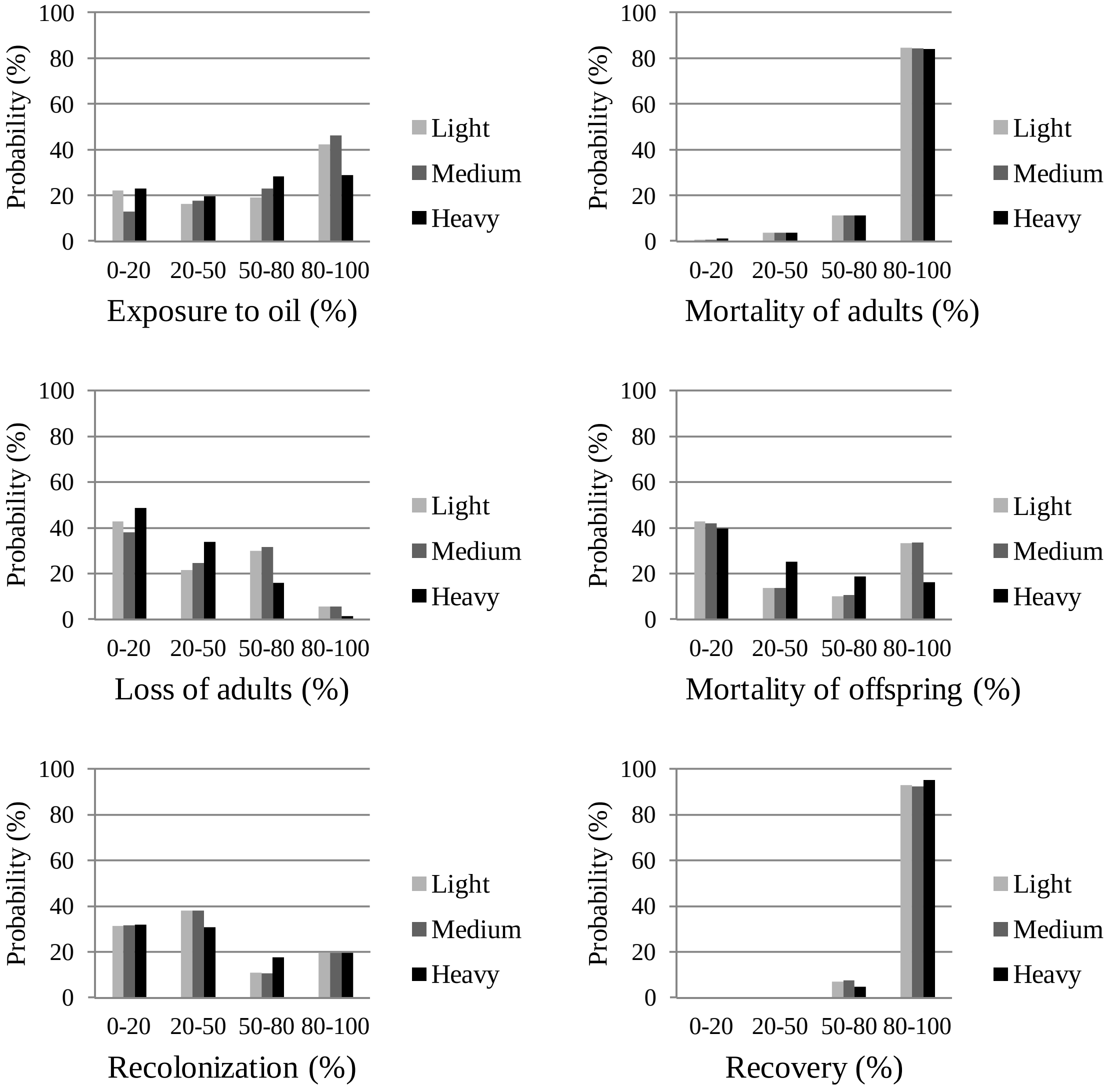

Figure 22. Probability distributions of the common guillemot model when *Time_of_year* is selected as spring in the common guillemot model.

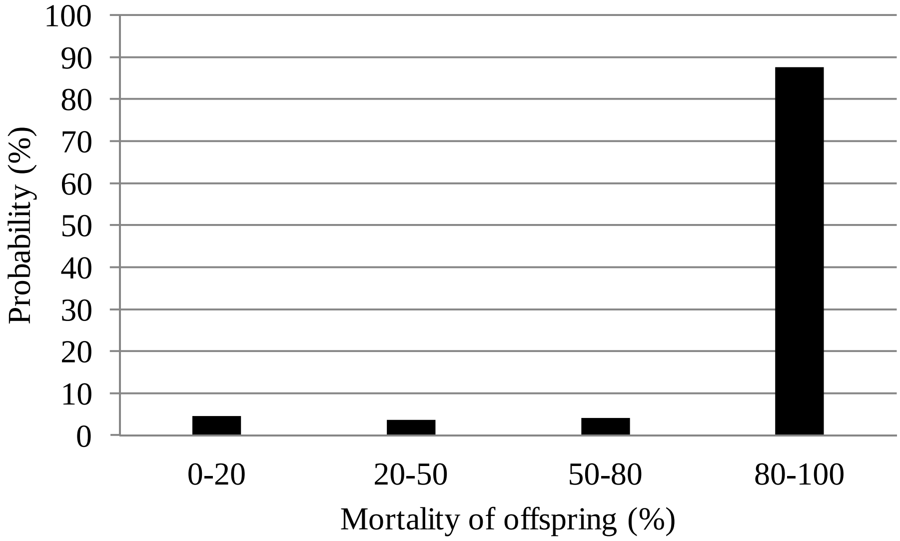

Figure 23. Probability distribution of the *Mortality_offspring* when *Time_of_year* is selected as spring and *Mortality_a_final* as 80–100 in the common guillemot model.

In summer, heavy oil seemed to be the most exposing oil type to birds (Fig. 24). Further, compared to springtime, the loss of adults seemed to be somewhat higher, i.e. the probability mass is slightly shifted towards higher classes. In other variables no clear differences were found.

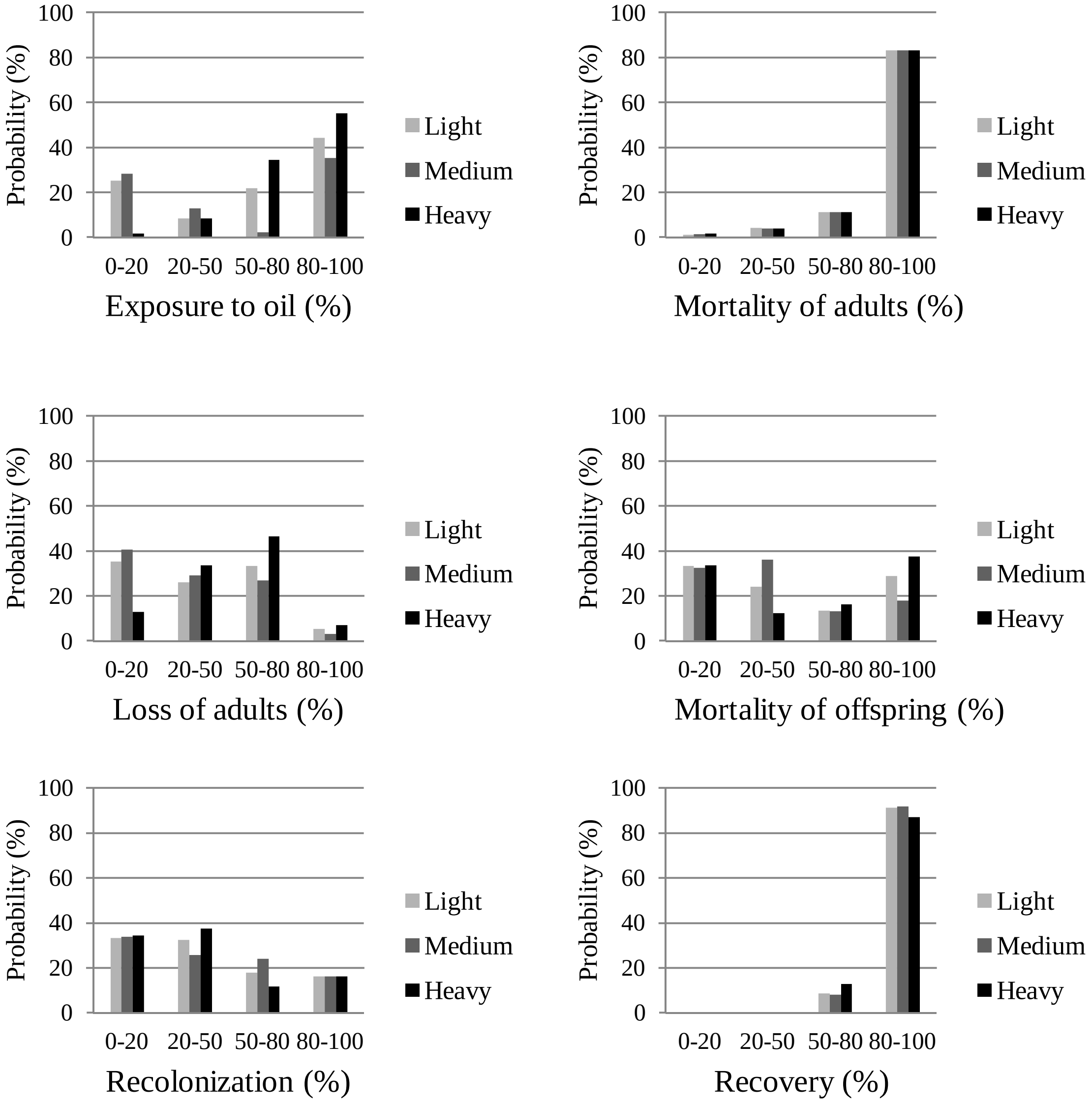

Figure 24. Probability distributions of the common guillemot model when *Time_of_year* is selected as summer in the common guillemot model.

Also in autumn, oil type had an impact on the exposure of birds; light and medium oil caused 0–20% exposure with the probability of 36.7 and 27.9%, respectively, and heavy oil caused 80–100% exposure with the probability of 26.3%.

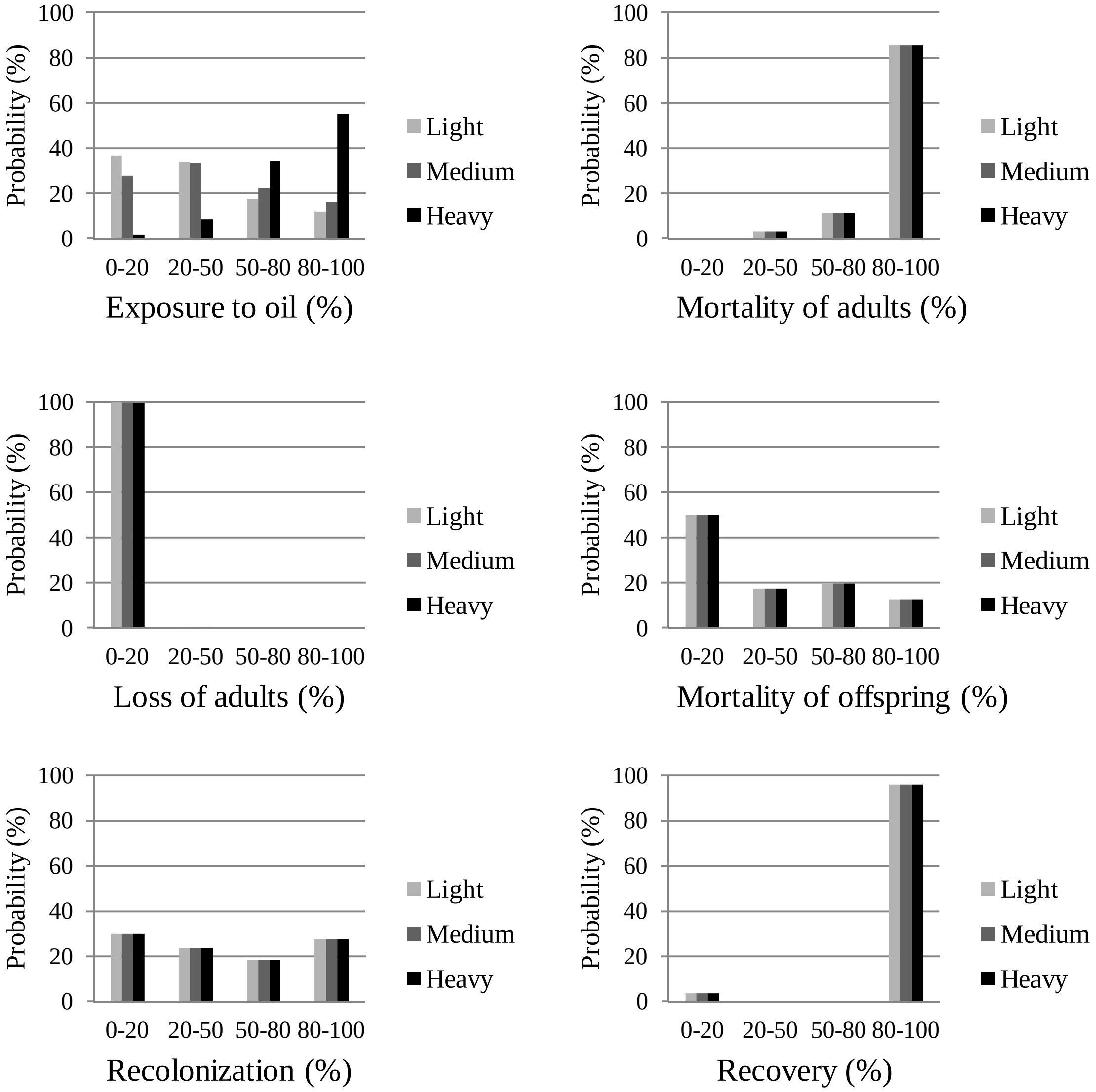

Figure 25. Probability distributions of the common guillemot model when *Time_of_year* is selected as autumn in the common guillemot model.

There was a clear difference in adult loss between autumn and other seasons, as in autumn the loss of adult birds was 0–20% with the probability of 99.6–99.8%. Nevertheless, the mortality of offspring was similar compared to spring and summer. *Mortality_offspring* had high uncertainty in all seasons: especially in autumn this was noticed when the colony was vacant with very high probability, offspring still died. To other variables than *Exposure_to_oil* oil type had no effect.

In all seasons and with all oil types the recovery of common guillemots was high: 80–100% of population had recovered ten years after spill in the GOF (Figs. 22, 24–25). Even though, the mortality of adults was very low in autumn, the distributions of *Mortality_offspring*, *Recolonization* and *Recovery* did not differ greatly from the ones in spring and summer. Recolonization did not substantially vary between oil types or seasons.

4.1.3. Worst case scenario

A worst case scenario for the common guillemot is when the accident occurred in summer, since then the occurrence of birds is the most probable. The occurrence of the offspring is also the most probable during summer. The spilled oil was selected as heavy, because it was the most exposing oil type for the common guillemots. In the worst case all birds were exposed to oil and this caused 50–80% mortality of adult birds (Fig. 26) with the probability of 63.2%.

High adult mortality caused an offspring mortality of 80–100 % (Fig. 27) with the probability of 51.5 %.

It seemed that the level of recolonization had a clear effect on recovery (Fig. 28). When low recolonization rate was assumed, there was an over 30% probability that the population would not be fully recovered ten years after the spill. However, even with a low recolonization rate, the probability that the difference between the population size before the accident and after the subsequent recovery would be over 50% was very low.

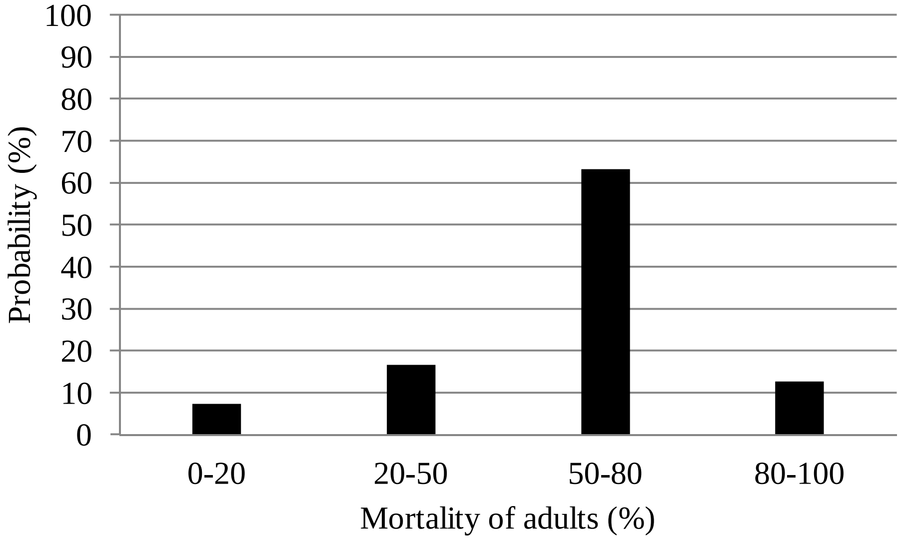

Figure 26. Probability distribution of the *Mortality_of_adults* when the time of year is summer, the oil type is selected as heavy oil and 80–100% of birds are exposed in the common guillemot model.

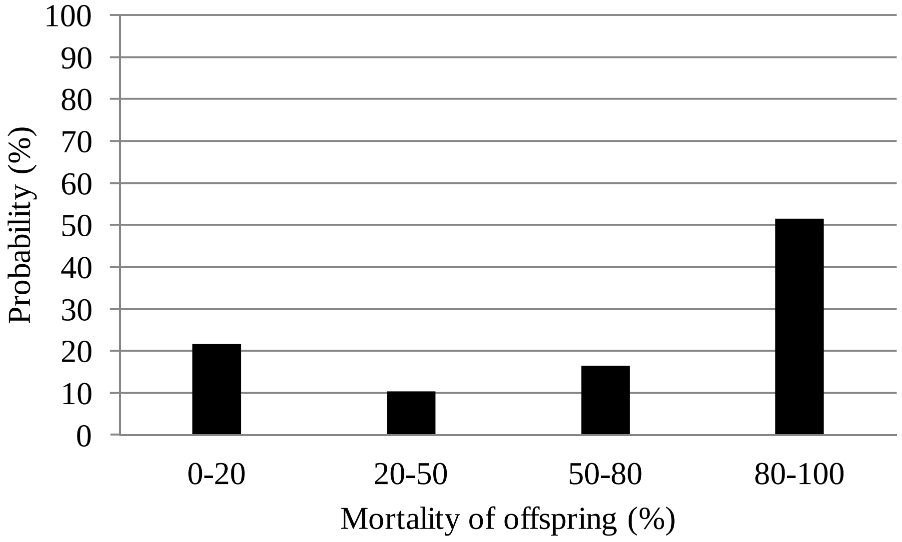

Figure 27. Probability distribution of the *Mortality_of_offspring* when the time of year is summer, the oil type is selected as heavy oil and 80–100% of birds are exposed in the common guillemot model.

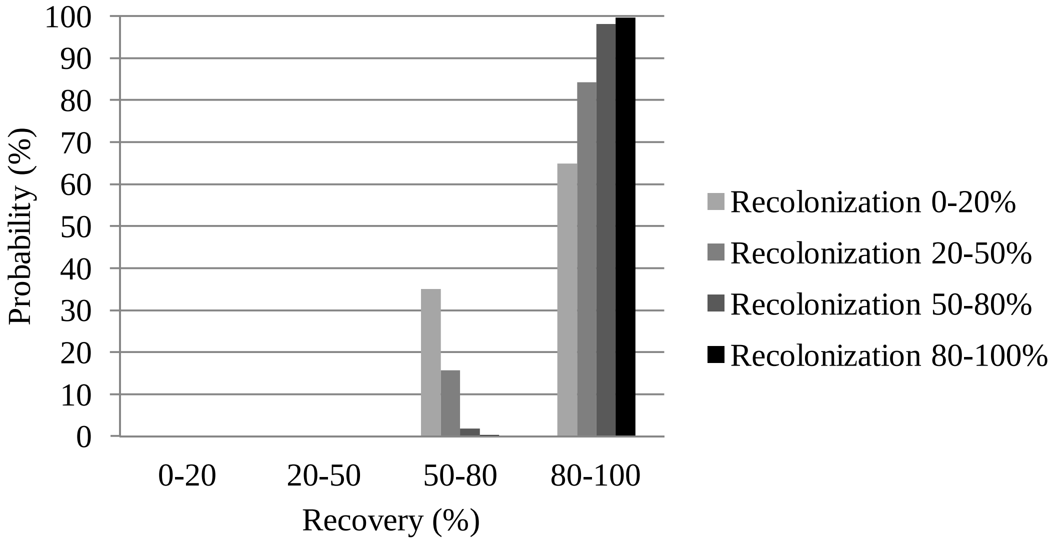

Figure 28. Probability distribution of the *Recovery* when the time of year is summer, the oil type is selected as heavy oil, 80–100% of birds are exposed and the amount of recolonization varies in the common guillemot model.

4.2. The long-tailed duck

4.2.1. Basic state of the model

The basic state of the model describes the situation where none of the states are selected and nothing of the impacts of the accident is known. Only that the accident will occur is assumed. The basic state includes all uncertainty of the model.

As the accident variables were same as in the common guillemot model, the probabilities were the same; the most probable time of year for the oil accident to occur in the GOF was spring and with the highest probability the accident involved heavy oil (Figs. 12 and 13). Prior distributions of other variables are given in Figs. 29–34. The occurrence of birds and exposure to oil were low (Figs. 29–20), but the mortality of adults was very high (Fig. 31). Recovery in the number of birds resting in the GOF and the Baltic Sea population was significant (Figs. 33–34).

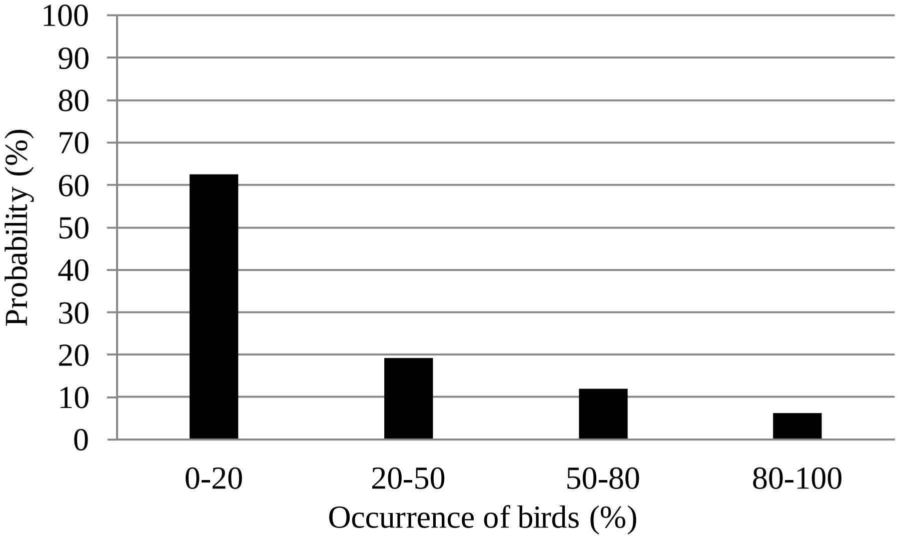

Figure 29. Prior distribution of *Occurrence_of_birds* in the long-tailed duck model, columns describe the number of birds resting in the GOF.

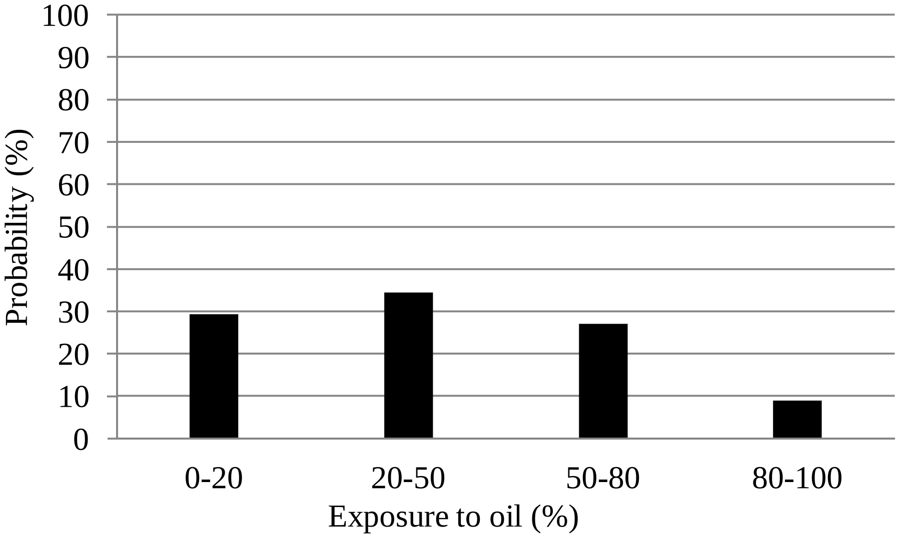

Figure 30. Prior distribution of *Exposure_to_oil* in the long-tailed duck model.

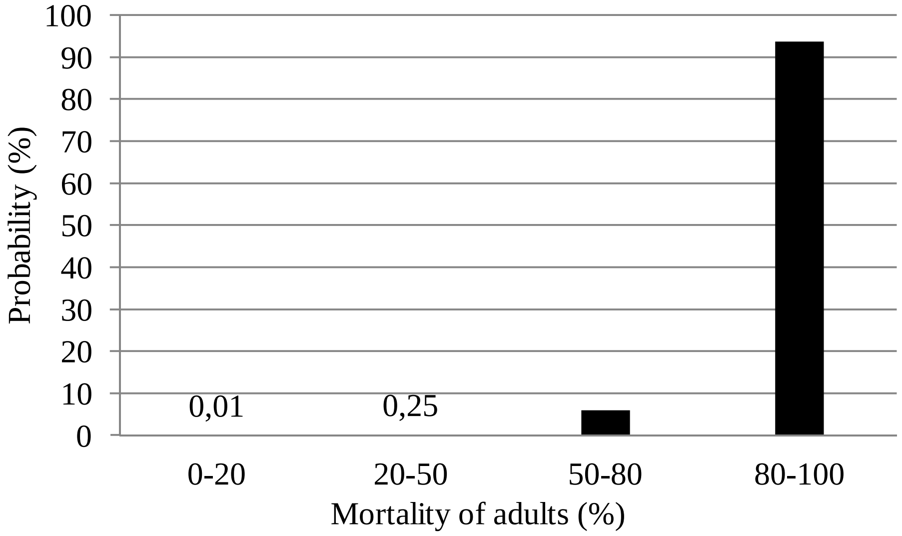

Figure 31. Prior distribution of *Mortality_adults* in the long-tailed duck model.

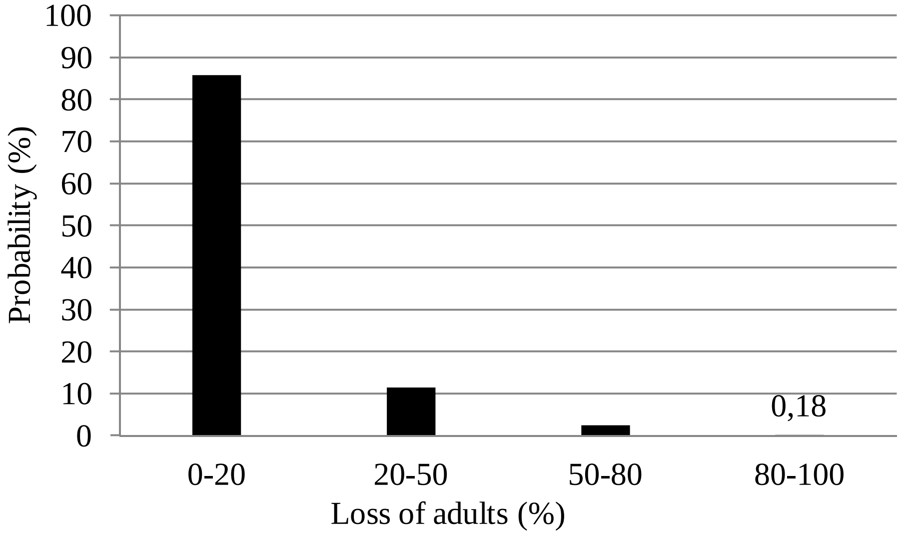

Figure 32. Prior distribution of *Mortality_a_final* in the long-tailed duck model.

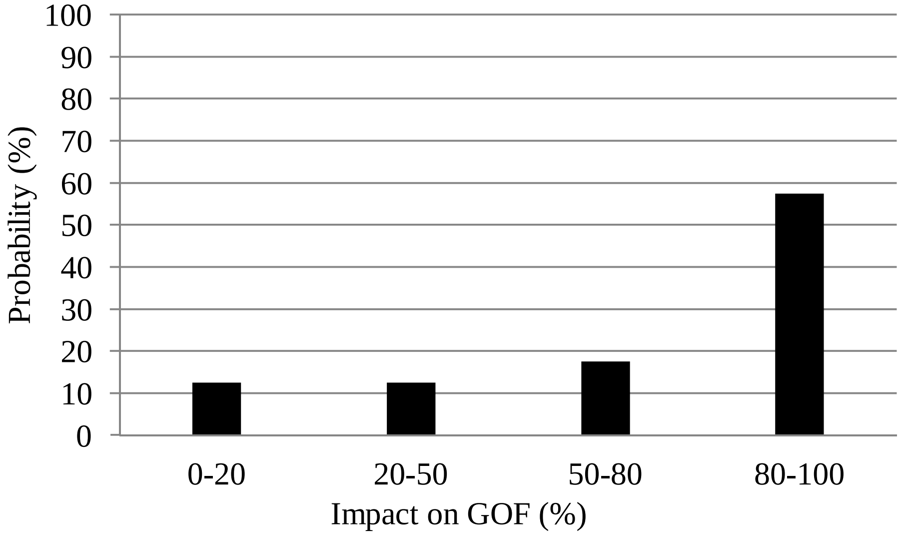

Figure 33. Prior distribution of *Impact_on_GOF* in the long-tailed duck model.

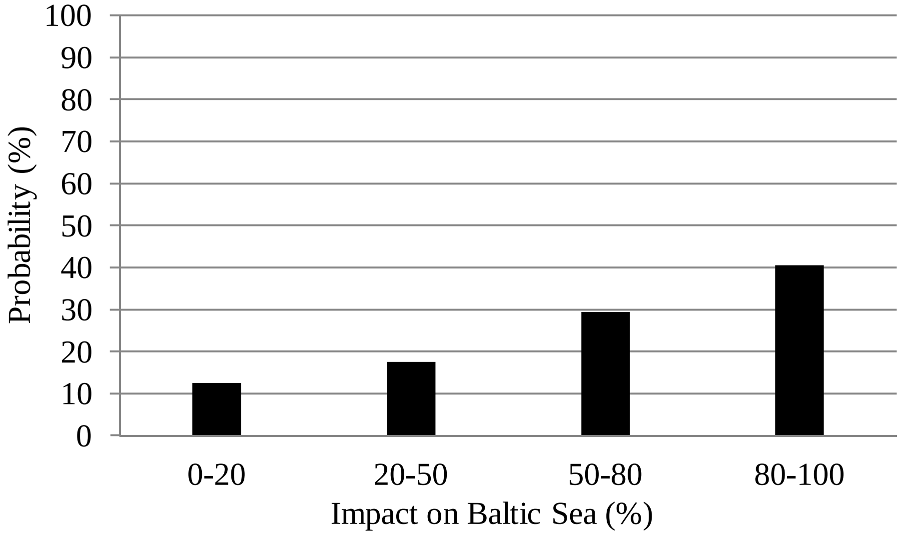

Figure 34. Prior distribution of *Impact_on_Baltic* in the long-tailed duck model.

4.2.2. The effect of oil spill: time of year and oil type

The results were studied over different selected states of *Time_of_year* and *Oil_type*. Oil type had impact only on exposure of birds; no differences between other variables were noticed. The most probable time of year for the occurrence of long-tailed ducks in the GOF was autumn (the distribution is least leftward (Fig. 35)).

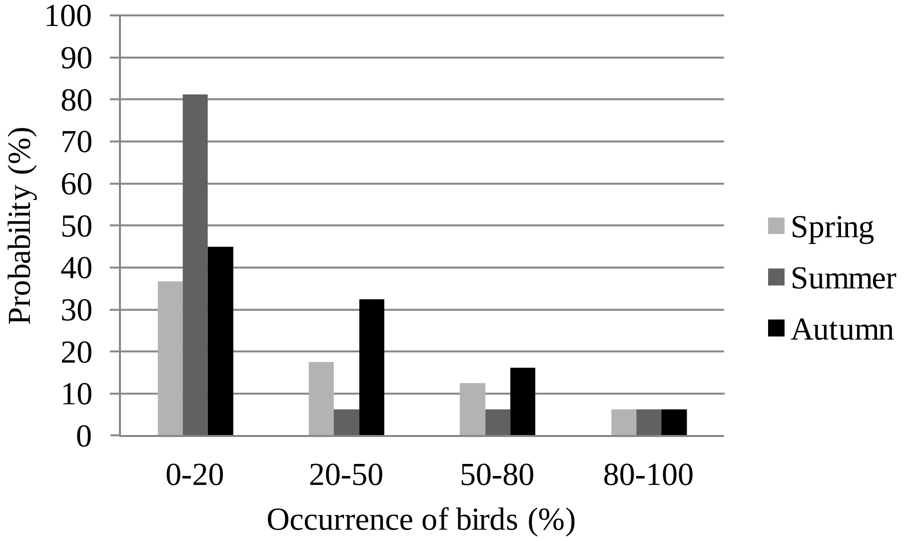

Figure 35. Probability distributions of the occurrence in long-tailed duck model in different times of year.

Oil type had impact only on exposure of birds (Fig. 36–38). However, *Exposure_to_oil* had the highest uncertainty. Exposed long-tailed ducks suffered from loss of 0–20% in all seasons. Only small differences between them were noticed.

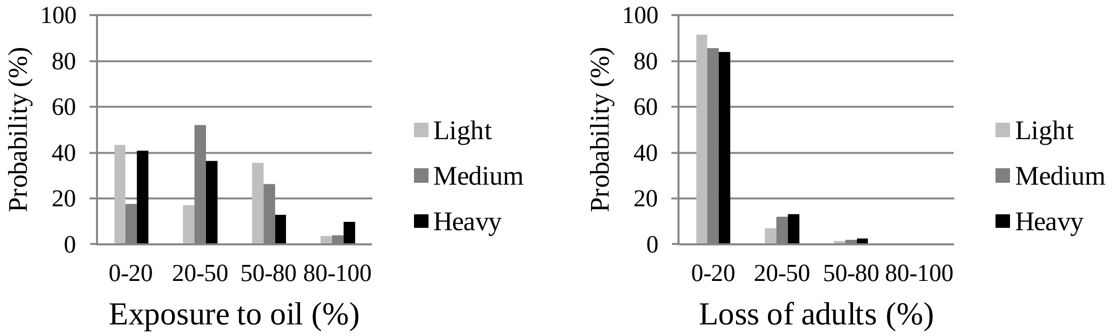

Figure 36. Probability distributions of *Exposure to oil* and *Mortality_a_final* in the long-tailed duck model when *Time_of_year* is selected as spring.

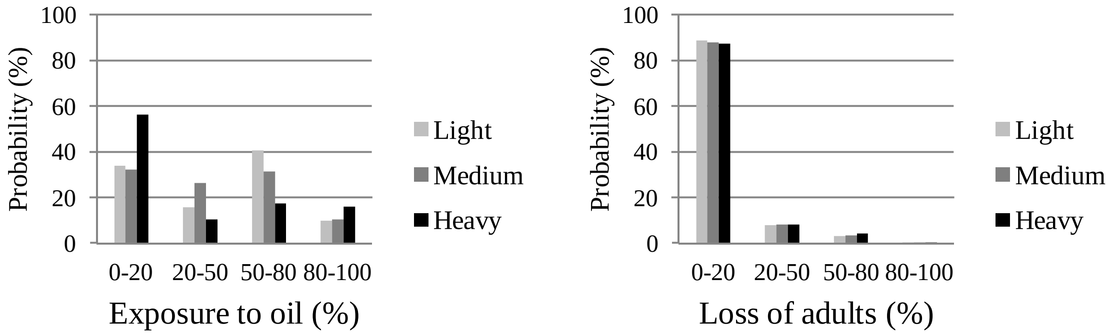

Figure 37. Probability distributions of *Exposure to oil* and *Mortality_a_final* in the long-tailed duck model when *Time_of_year* is selected as summer.

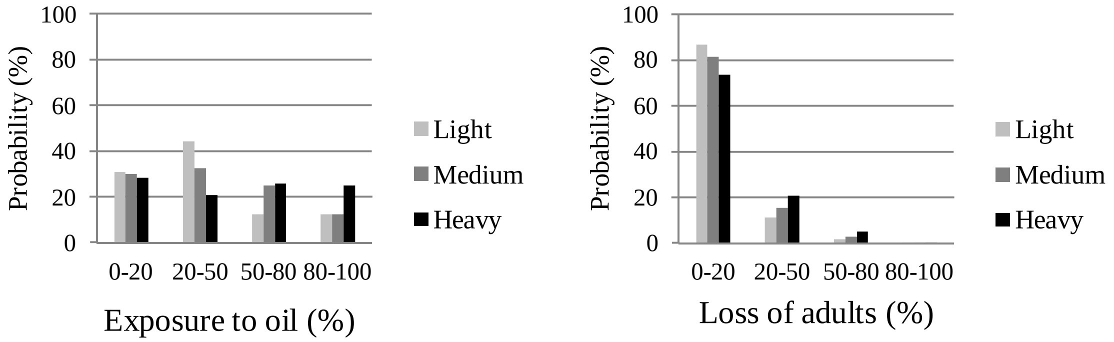

Figure 38. Probability distributions of *Exposure to oil* and *Mortality_a_final* in the long-tailed duck model when *Time_of_year* is selected as autumn.

When concerning posterior distributions, *Impact_on_GOF* or *Impact_on_Baltic* showed no difference compared to the corresponding prior distributions (Fig. 33–34). No differences between times of year or oil types were noticed.

4.2.3. Worst case scenario

A worst case scenario for the long-tailed duck is when the accident occurs in autumn during their migration and the spill is heavy oil. In autumn long-tailed ducks migrate over the eastern part of the GOF before they move to the Estonian coast, so *East* was selected as the route.

In the worst case all the birds were exposed to oil and this caused the 0–20% loss (Fig. 39). Most of the long-tailed duck population in the Baltic Sea was recovered with the probability of 40% (Fig. 40).

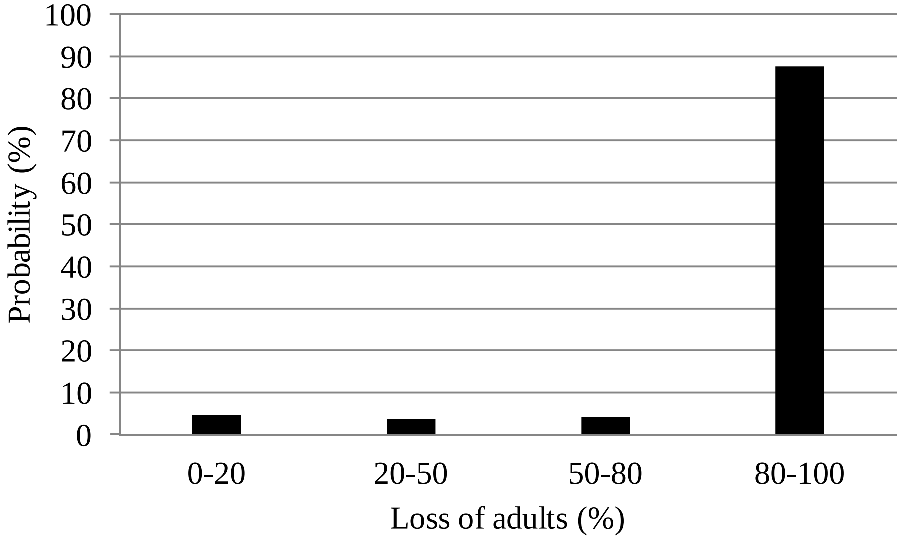

Figure 39. Probability distribution of the *Mortality_a_final* when the time of year is autumn, the oil type is selected as heavy oil and 80–100% of birds are exposed in the long-tailed duck model.

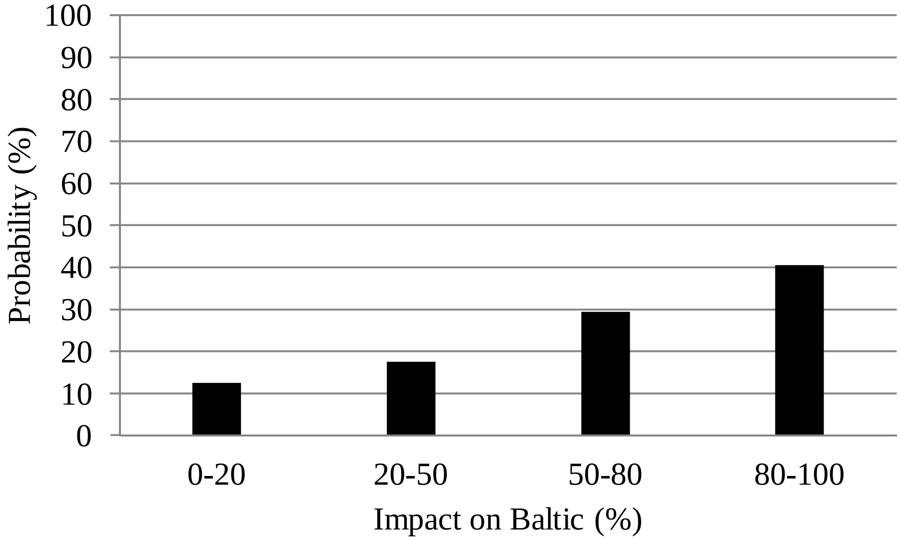

Figure 40. Probability distribution of the *Impact_on_Baltic* when the time of year is autumn, the oil type is selected as heavy oil and 80–100% of birds are exposed in the long-tailed duck model.

5. DISCUSSION

5.1. The common guillemot

In this study expert knowledge was used to build models that describe the fate of common guillemot and long-tailed duck populations in the Gulf of Finland after an oil accident. This study shows that the breeding colony of guillemots in Aspskär will probably not disappear due to an oil spill since the immigration from the southern Baltic Sea has a high impact on the population size. However, if the breeding site is not cleaned until the next breeding season, recolonization may not occur and the population may not recover. Only recolonization in the next year was considered in this study. The breeding population may still recover if the colony is cleaned three years after the accident; however this was not studied here. Delayed cleaning may occur if the natural cleaning is left as the only option or the cleaning actions have been unsuccessful.

After Lecklin *et al.* (2011), auks are the only group that may exhibit clear negative impacts 10 years after an oil accident in the GOF. The biological consequences considered in the study were the acute impact on population, the impact on offspring, recolonization, reproduction and the recovery of population (Lecklin *et al.* 2011). Although the study covers functional groups instead of single species, the results are at least to some extent applicable to a single species like common guillemot.

When the results of worst case scenarios of Lecklin *et al.* (2011) and this study are compared, differences are noticed; after Lecklin *et al.* (2011) the most probable state of recovery is 20–50% for the auk populations in the GOF, whereas in this study, there is a high probability that 80–100% of the common guillemot population will recover. In both studies the type of oil was heavy, but the season differed: in this study it was summer, while in Lecklin *et al.* (2011) it was spring. However, the probability distributions for the adult mortality were similar; only in this study the mortality of 50–80% is more probable. The differences in recovery may be explained by the fact that Lecklin *et al.* (2011) did not consider any trends in population dynamics other than those of oil-induced, while this study simulates population dynamics with and without oil spills. It is also possible that common guillemot has an exceptionally good recolonization capability within auks living in the GOF.

Most of the birds are able to avoid the oil washed ashore, and the smothering often occurs when the birds are affected by the floating oil (Hario, pers. comm.). In summer the exposure of the common guillemots is higher than in spring. However, in spring the adult birds spend time in the near vicinity of colony and in summer one of the parents make fishing trips farther away from the colony (Lehikoinen 2009, pers. comm.). Thus the birds may avoid the oil in shore in summer. The reason for the higher exposure in the summer may be affected by the estimation that more individuals are present in the summer (Fig. 21) and the shoreline may get crowded. It is also noteworthy that the birds avoid the oil only by chance; they do not understand to watch it (Keskitalo 2010, pers. comm.). The diurnal rhythm also affects where the birds spend time in the islet (Hario 2009, pers. comm.), however in this study no difference between day and night was set. The occurrence of birds is based on the species phenology; during spring the common guillemots arrive to the islet, in summer birds are mainly present and in autumn most of the adults and chicks have left.

In spring medium oil is more exposing to common guillemots than other types, in summer and autumn it is heavy oil (Figs. 22 and 24–25). This cannot be explained by the behaviour of birds, since in summer birds should avoid the washed-up oil and the heavy oil collects on the shore or sinks into the water column. The probability for the heavy oil accident is also low.

Mortality of common guillemots is significant in spring and summer. After Tuck (1961) even a small droplet of oil in abdomen of a murre may cause an acute death. Mortality of adults causes a mortality of offspring – in the absence of an incubating parent the offspring may starve or suffer a hypothermic death (Keskitalo 2010, pers. comm.). Even though the other parent survives, it cannot incubate and fish at the same time. The mortality of offspring in the model responds the mortality of adults in this manner. In autumn the mortality of birds is low, and this is affected by the low occurrence of birds.

The most disastrous time of year for the common guillemot colony in Aspskär is the summer when all the breeding adults and their offspring are present based on the worst case scenario created. After the prior estimations, the most probable time of year for the accident is spring and autumn.

Based on the modelling done in this study the common guillemot population in the GOF will probably not become extinct after an oil spill. The population size may be slightly decreased ten years after the spill or no difference may be noticed. However, the model used in this study only includes the acute mortality within one year after spill, no indirect effects or chronic impacts are considered. After Exxon Valdez oil spill the immediate impact on seabirds of all types was large. Losses were evidenced by the collections of oiled birds made by shoreline walks in the months following the spill (Piatt *et al.* 1990). In addition, decline in bird abundance were evident for many species in analysis of results of shoreline bird surveys made in several years following the oil spill compared to pre-spill surveys (Irons *et al.* 2000). Indirect effects were developed when sea ducks foraged contaminated shore invertebrates and seabirds foraged fish (Wiens *et al.* 1996). Subsequent study also showed that black oystercatchers (*Haematopus bachmani*) consumed oiled mussels and that parents gathering prey on oiled shores fed chicks more to achieve less growth than unoiled shores, which implies that energetic or developmental costs and reproductive impairment from ingestion of toxics appear three years after spill. Fledging late or at small size has negative impact chick survival (Peterson *et al.* 2003). Efficient oil combating is of a great importance.

It is plausible for the common guillemots in the GOF to suffer indirect or chronic effects after an oil spill via contaminated food or a polluted nesting site. These effects represent the greatest challenge to assessment of an oil spill impacts because of their unpredictability, undefined but extended time frames, and the ambiguity and uncertainty in their assessment protocols (Peterson 2000). Perhaps the only way to evaluate these delayed effects is through the intensive long-term study of populations after an oil spill and comparing those results to the pre-spill data. Hence the extensive data of especially threatened populations and habitats is required. From the common guillemot in the GOF this data are available (Finnish Game and Fisheries Research, unpublished) but from the long-tailed duck population the data are incomplete.

The immigration has a high impact on the population size of common guillemot in Aspskär (Hario 1982). Based on the expert knowledge used in the model the amount of immigration to Aspskär is 8%. However, from 2008 to 2009 the amount of pairs in the colony grew ca. 30% (Finnish Game and Fisheries Research Institute, unpublished). Based on the pair count data from Aspskär and the survival rates of common guillemots in the Baltic Sea, the immigration to Aspskär is caused by the good survival of birds in the Baltic Sea (Finnish Game and Fisheries Research Institute, unpublished, Olsson *et al.* 2000). It may be that when survival rate is high the birds seek new nesting sites and emigrate farther off from wintering areas. Significant colony dispersal could also mean that common guillemot populations have a strong capacity to recover after disasters. However, in species in which individuals show an attraction to conspecificity, a critical situation may happen when local breeding group decreases below a certain threshold size (Cadiou *et al.* 2004).

Also in this study, the immigration shows high importance. The recovery of common guillemots does not show great differences between the levels of mortality so the immigration to the colony must remain sufficient. It is noteworthy that the recolonization discussed in this study refers only to the replacing immigration, i.e. replacing the adults lost in the consequence of oil-induced mortality, not to the one defined in population dynamics. Nevertheless, the recolonization confirms the meaning of immigration to the survival of the Aspskär colony; for that the population would not recover with high mortality and low recolonization, the probability was low (Fig. 28), so the supplement must come somewhere else.

If the breeding success of common guillemots is 70%, the survival to breeding age of produced chicks must be 24% to maintain a stable population (Birkhead and Hudson 1977). A stable population indicates that density dependent regulation may be occurring in the population (Birkhead and Hudson 1977). In this study it is assumed that the common guillemot population is density dependent based on the Ricker model (Ricker 1954). Lack (1954) considered food to be the most important density dependent factor in the regulation of bird populations. However, no evidence of food shortage in the breeding area is noticed. It is also suggested that density dependent mortality may occur outside the breeding season when adults and immature birds compete for food. The adults may be more proficient and dominant over immature birds in feeding areas resulting in the higher mortality of younger birds (Ashmole 1971). Low fledging survival figures in the Aspskär colony may indicate the presence of heavy predation while chicks leave the nest to go to the sea. Hario (1982) suggested that herring gulls (*Larus argentatus*) may be the cause for this predation.

5.2. The long-tailed duck

The Baltic Sea population of long-tailed duck suffers from a high nesting mortality at the breeding sites in north (Hario *et al.* 2009). Thus the population has low offspring production and the possible oil spill may be directed to adult breeders. Based on this study even the low loss of experienced breeders caused by an oil spill during their migration may be harmful to the population. It is noteworthy that the uncertainty is high when the impact on the Baltic Sea population is studied, so the results of this BN should be interpreted with caution. The study by Lecklin *et al.* (2011) is consistent with this result.

It is probable that the resting long-tailed ducks alight on an oil slick; the slick may seem calm and thus attractive to birds (Hario 2009, pers. comm.). However, the oil may only attract birds when they are flying low (Keskitalo 2010, pers. comm.). The exposure to oil varies between oil types and hence the different oil types behave in different ways. The mortality of exposed birds is very high with all oil types since when alighting, the birds may alight directly on oil. The decreasing impact on the Baltic population may be more severe than the decrease in the GOF since new birds may rest on the GOF when competition declines. This may result in the situation where no impact is noticed if only the resting birds are considered.

A worst case scenario for the long-tailed duck was also created. The highest amount of birds is resting on the GOF during autumn; this may be caused by the bad weather usually occurring in autumn. In this scenario, long-tailed ducks suffer from a very high mortality.

Instead of the impacts of one large oil spill on the long-tailed duck, the impacts of small and continuous operational spills should also be studied. About 28% of the long-tailed ducks winter at the Hoburgs bank or east of the Gotland. A very important shipping route with dense traffic goes from the south-western Baltic Sea to the GOF. The route goes via the wintering sites of the birds (Larsson and Tydén 2005). Although discharges of oil are illegal, several oil spills are detected. The aerial surveillance done by the HELCOM detects oil spills of different sizes annually in the Baltic Sea mainly along the main shipping routes (HELCOM 2009). In addition, a considerable amount of spills may not be noticed. Surveys of oiled birds at southern Gotland and analyses of drowned birds have showed that tens of thousands of long-tailed ducks were injured by oil each year in the Central Baltic. Of drowned birds, 12% were oiled in their plumage (Larsson and Tydén 2005). The winter months should be considered also so the impacts in wintering areas would be studied comprehensively.

In the case of the Baltic Sea population of long-tailed duck it is difficult to evaluate the impacts of an oil spill on the population size if the prior knowledge is only vague estimates which may vary within million individuals (Andell *et al.* 1994, Durinck *et al.* 1994, Laursen 1989).

5.3. Expert knowledge as prior information

Expert knowledge is an important resource that may improve the reliability of the model and provide new information (Yamada *et al.* 2003). In this study it was particularly valuable, since no published data of this nature can be found. However, there remains uncertainty regarding its reliability (Yamada *et al.* 2003, Maddock and Samways 2000).

The experts participated in the knowledge elicitation process with a great deal of interest. This interest was particularly evident when they provided estimates to the mortality of birds. However, the subjective interests or the level of prior knowledge of experts might have been affecting to their estimates. This was seen when experts estimated e.g. the exposure of common guillemots to oil: estimates between experts varied a lot (Fig. 41). Estimating the exposure to oil was the most difficult to the experts, since it required the assessment of the behaviour of oil types and birds and combining these two. In the consequence of this, both BNs has the highest uncertainty in this variable. Differences in estimates between experts also caused bimodal distributions in some prior variables and increased uncertainty. The shape of prior distributions should have been confirmed by experts in a joined workshop.

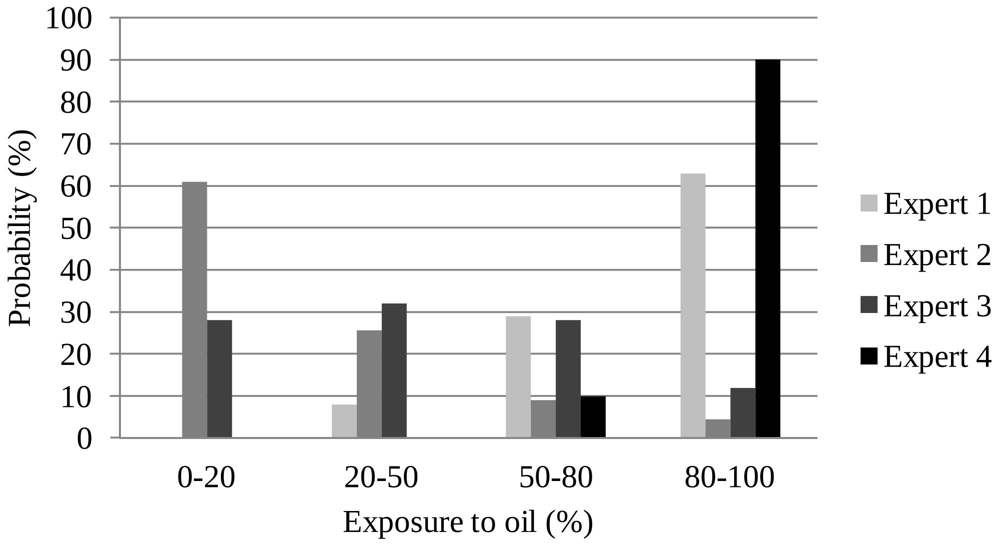

Figure 41. Probability distributions of *Exposure_to_oil* in common guillemot model between experts when *Time_of_year* is selected as spring and *Oil_type* is selected as light.

Some limitations hindered the interviewing process. Experts were commonly unfamiliar with the BNs, and hence there were some difficulties when explaining the research subject. It might also be that the theory of BNs only confused the experts; the graphical presentation of the model might have been enough for the explanation. The experts found it easy to provide the numbers, although many ecologists are not used to provide knowledge that can be converted into probability distributions (Uusitalo 2007). This may be an outcome from the fact that they are used to work with sampling and experimental data, and may find it difficult to provide numbers, which do not rely on any data. Also the researchers may be used to classical statistical analyses and find it difficult to change their knowledge to distributions rather than point estimates and confidence intervals (Uusitalo 2007). From this point of view the interview questions become very important.

After Morgan and Henrion (1990) human estimators may be prone to overconfidence, i.e. giving estimates that are too near zero or one. This phenomenon was not noticed in this study, most of the experts were rather underconfident, as also described in the previous study (Morgan and Henrion 1990). When experts consider the event improbable, they tend to provide too low estimates (Van der Laag *et al.* 2002). This may be the situation here since the experts were not most familiar with the accident probabilities.

The explanatory notes should have been more clear and specific so the experts would have completely understood those. For some experts the notes were not defined well enough and they required specifying. If the notes are not clear and the interviewer should have to explain something with own words, the explanations may vary within interviewing sessions. In the worst case scenario the experts would understand the issues differently and give estimates to different things. In the eliciting process experts had difficulties to distinguish the concepts of immigration and recolonization. This may have affected to the estimates by decreasing the degree of recolonization when it is mistakenly considered as immigration.

The model structure may have been too complicated in some parts for the experts to discuss. When designing the model structure, it needs to be remembered, that people may have cognitive difficulty in thinking of conditional distributions with several conditioning factors (Morgan and Henrion 1990). Hence, it is advisable to restrict the amount of conditioning factors to possible minimum (Uusitalo 2007). However, in the model structure used in this study, the number of these factors may have been too high. This makes the expert based population assessment complicated; the factors required for the complete model are too numerous compared to the suitable amount for the experts.

5.3. Model

The objectives of the study are mainly accomplished. The networks were created successfully and the impacts on mortality and population recovery were modelled. In addition to the common guillemot model a submodel was created to model the population dynamics. Creating the population dynamics model took extra time but gave valuable knowledge to the study.

The state intervals in the model were too extensive. If there is no impact based on the expert estimates, the model gives 0–20% as a result. Thus the result is biased. Division of the states of time of year also gives a wrong impression of the impacts. In the common guillemot model the variable should have been divided into two states: arriving (from March to April) and breeding (from May to July). In the current model the real breeding season of the species is divided into two imaginary states which lead to misinforming results. This is a common disadvantage: when using BNs, the continuous values should be discretized and this may cause the loss of characteristics of the original distribution (Uusitalo 2007).

Subsequently the impacts of the sub model used in the common guillemot model should be evaluated by including a similar model to the long-tailed duck model. Thus the differences in the expert based model and the model where expert knowledge and modelled population dynamics are combined may be compared.

The mortality of birds was conditioned only to their exposure to oil. In order to study the effects of different oil types to the mortality, the model structure should be constructed in the way that *Mortality* was also conditioned to the *Oil_type*. By this the impacts of oil types would have been possible to study regardless the amount of exposure.

5.3.1. Population model for the common guillemot

Since seabirds are long-living species exhibiting deferred maturity, the demographic impact of massive mortality would not be the same if the majority of lost birds are young non-breeders or breeding adults (Russel 1999). Thus the studies should be conducted to determine the population structure of the species impacted, i.e. sex-ratio, age ratio and sexual maturity (Cadiou *et al.* 2004). The model created in this study will be convenient to this; the distributions should only be defined more properly.

With this kind of modelling the impacts of oil spills on the recovery of sensitive species can be studied by calculating the difference in the size of population between normal scenario and oil-spill-scenario.

6. CONCLUSIONS

In this study two different BNs were created to model the impacts of an oil spill on the common guillemot breeding in the Gulf of Finland and on the long-tailed duck migrating through the area in spring and autumn. For the networks, the prior information was mainly accumulated from experts since no literature was found. The expert interviews were found to be suitable for this kind on study. The impact on mortality and the effect of the loss to the later population sizes of both species were studied.

The oil spill accident in the GOF may be harmful for the common guillemot and long-tailed duck populations. The breeding colony of the guillemots in Aspskär may survive from accident only if the immigration remains sufficient. This requires effective cleaning of the breeding site. The loss of one year's offspring production may not have severe impact on the population size; a high breeder mortality may cause the worse population decline compared to the lost of fledglings.

The Baltic Sea population of long-tailed duck suffers from a high nesting mortality at the breeding sites in the north. Thus the population has low offspring production and a possible oil spill may be directed to adult breeders. The loss of experienced breeders may be disastrous to population whose adults are long-living. No supplemental migration of recruits is noticed in the Baltic Sea. It should also be noted that during winter time from October to May, thousands of long-tailed ducks can be found from the GOF (Lehtiniemi, pers. comm). This is very important when oil spills are considered.

In the long-tailed duck model the expert estimates are more congruent with each other than in the common guillemot model. This may lead to the conclusion that more uncertainty can be found in the common guillemot model. However, according to the interviews the opposite should be considered. The experts may base their knowledge on the long-tailed duck on the same source of information and by this provide similar estimates. The highest uncertainty is noticed when the recolonization of common guillemot colony is considered.

To have a better view of the impacts of an oil spill on studied species, the effects of oil combating should also be modelled. Oil combating actions may affect to the behaviour of seabirds by disturbing them to leave the site and even alight on oil. And the use of dispersants may even be more harmful to birds than oil. However, dispersants are now illicit by recommendation of HELCOM (HELCOM 1980).

More concentration should be focused on the maritime transports which should be developed in a way that the risk of an oil spill would be as low as possible. The education of the maritime personnel in environmental matters should be increased and safe operational principles should be required. Even navigable routes near vulnerable areas should be redeployed. In the case of an accident the high risk areas, i.e. known resting areas of migrating birds, should be noticed and suitable oil combating methods used when breeding colonies are protected. In order to this, more study on oil combating and cleaning methods in the Baltic Sea and GOF is required.

In this study it is showed that BNs are workable methods for estimating the impacts of an oil spill on bird populations. The availability of experts around GOF is good and their knowledge can be utilized easily. When using experts, the interviewing methods are remarkably important. The networks may be based entirely on expert knowledge or those may be completed by referenced information.

ACKNOWLEDGEMENTS

At first I wish to thank my supervisors Inari Helle and Juha Karjalainen who both instructed my study. Then I would like to thank Professor Sakari Kuikka who gave me the opportunity to write my Master's Thesis on this interesting topic.

I also wish to thank the other members of the FEM group, especially Samu Mäntyniemi for all the help related to Bayesian modelling and Annukka Lehikoinen for the encouraging working environment in Kotka Maritime Research Centre.

And finally I would like to thank all the experts for participating to the elicitation process: Margus Ellermaa (BirdLife Finland), Martti Hario (Finnish Game and Fisheries Research Institute), Aleksi Lehikoinen (University of Helsinki), Teemu Lehtiniemi (BirdLife Finland), Markus Keskitalo (Metsähallitus), Petri Päivärinta (Kotka Maretarium) and William Velmala (University of Helsinki).

The Master's Thesis is funded by the Integrated Bayesian risk analysis of ecosystem management in the Gulf of Finland (IBAM) project and the work has been done in the Fisheries and Environmental Management Group (FEM) at the University of Helsinki. The IBAM is funded by BONUS Baltic Organizations Network for Funding Science EEIG.

REFERENCES

Aguilera P., Fernández A., Fernández R., Rumí R. & Salmerón A. 2011. Bayesian networks in environmental modelling. *Environmental Modelling & Software* 26: 1376 - 1388.

Albers P. 1978. The effects of petroleum on different stages of incubation in bird eggs. *Bulletin of Environmental Contamination and Toxicology* 19: 624 - 630.

Albers P. 2002. Petroleum and individual polycyclic aromatic hydrocarbons. In: Hoffman D. J., Rattner B. A., Burton G. A. Jr. & Cains J. Jr. (eds.), *Handbook of Ecotoxicology*. CRC Press, Boca Raton, pp. 342 - 408.

Alenius P., Myrberg K. & Nekrasov A. 1998. The physical oceanography of the Gulf of Finland: a review. *Boreal Env. Res.* 3: 97 - 25.

Andell P., Durinck J. & Skov. H. 1994. Baltic marine areas of outstanding importance for wintering seabirds. *WWF Marine Bulletin* 5: 2 - 9.

Andrejev O., Myrberg K., Alenius P. & Lundberg P. 2004. Mean circulation and water exchange in the Gulf of Finland – a study based on three-dimensional modeling. *Boreal Env. Res.* 9: 1 - 16.

Ashmole N. 1971. Seabird ecology and the marine environment. In: Farner D. & King K. (eds), *Avian biology Vol I*. London, pp. 224 - 271.

Begon M., Townsend C. & Harper J. 2006. *Ecology: From individuals to ecosystems*. Blackwell Publishing, Oxford.

Birkhead T. & Hudson P. 1977. Population parameters for the common guillemot *Uria aalge*. *Ornis Scand.* 8: 145 - 154.

Birkhead T., Lloyd C. & Corkhill P. 1973. Oiled seabirds successfully cleaning their plumage. *Brit. Birds* 66: 535 - 537.

Brown E., Baker T., Hose J., Kocan R., Marty G., McGurk M., Norcross B. & Short J. 1996. Injury to the early life history stages of Pacific herring in Prince William Sound after the *Exxon Valdez* oil spill. *Am. Fish Soc. Symp.* 18: 448 - 462.

Cadiou B., Riffaut L., McCoy K., Cabelguen J., Fortin M., Célinaud G., Le Roch A., Tirard C. & Boulinier T. 2004. Ecological impact of the *Erika* oil spill: determination of the geographic origin of the affected common guillemots. *Aquat. Living Resour.* 17: 369 - 377.

Dunrick J., Skov H., Jensen F. & Pihl S. 1994. *Important marine areas for wintering birds in the Baltic Sea*. Ornis Consult Ltd. & National Environmental Research Institute, Copenhagen.

Eppley Z. & Rubega M. 1989. Indirect effects of an oil spill. *Nature* 340, 513 - 515.

Frederiksen M. & Petersen A. 2000. The importance of natal dispersal in a colonial seabird, the Black Guillemot Cepphus grylle. *Ibis* 142: 48 - 57.

Fry D. & Lowenstine L. 1985. Pathology of common murres and Cassin's auklets exposed to oil. *Arch. Environ. Contam. Toxicol.* 14: 725 - 737.

Furman E., Hamari R. & Dahlström H. 1998. Baltic – Man and nature. Otava, Keuruu.

Gaston A. 2004. *Seabirds – a natural history*. Black Publishers Ltd., London.

Gilks W., Thomas A. & Spiegelhalter D. 1994. A language and program for complex Bayesian modeling. *The Statistician* 43: 169 - 177.

Golubkov S. 2009. Changes of biological communities in the Eastern Gulf of Finland during the last century. *Proceedings of the Zoological Institute RAS* 313: 406 - 418.

Gonzàlez J., Viñas L., Franco M., Fumega J., Soriano J., Grueiro G., Muniategui S., López-Mahía P. Prada D., Bayona J., Alzaga R. & Albaigés J. 2006. Spatial and temporal distribution of dissolved/dispersed aromatic hydrocarbons in seawater in the area affected by the Prestige oil spill. *Mar. Pollut. Bull.* 53: 250 - 259.

Hänninen S. & Rytkönen J. 2004. Oil transportation and terminal development in the Gulf of Finland, *VTT Publications* 547.

Hario M. 1982. On the size and recruitment of a peripheral breeding colony of the guillemot *Uria aalge*. *Ornis Fennica* 59: 193 - 194.

Hario M., Rintala J. & Nordenswan G. 2009. Dynamics of wintering long-tailed ducks in the Baltic Sea – the connection with lemming cycles, oil disasters, and hunting. *Suomen Riista* 55: 83-96. [In Finnish with English Summary]

HELCOM (Helsinki Commission). 1980. Recommendation on minimization of the use of dispersants, sinking agents and absorbents in oil combating operations in the Baltic Sea area. *HELCOM Recommendations 1/8.*

HELCOM. 2001. Compilation on ship accidents in the Baltic Sea area 1989–1999. Final Report.

HELCOM. 2002. Compilation of ship accidents in the Baltic Sea area in 2000 and 2001.

HELCOM. 2009. Annual 2009 HELCOM report on illegal discharges observed during aerial surveillance.

Helle I. 2009. *Modelling the resources of oil combating from an ecological perpective – a Bayesian network approach for the Gulf of Finland*. Master's thesis, Helsinki University of Technology, Helsinki.

Hietala M. & Lampela K (toim.). 2007. Öljyntorjuntavalmius merellä. *Suomen ympäristö* 41: 7-39.

Hudson P. 1985. Population parameters for the Atlantic Alcidae. In: Nettleship D. & Birkhead T. *The Atlantic Alcidae.* Academic Press, London, pp. 233 - 261.

Huhtala M., Vainio T., Niinivaara S., Lampela K. & Strandberg-Panelius C. 2005. Öljyntorjunnan osaamiskeskuksen perustamismahdollisuudet. *Ympäristöministeriön moniste* 145: 1 - 73. [In Finnish]

Irons D., Kendall S., Erickson W., McDonald L. & Lance B. 2000. Nine years after the Exxon Valdez oil spill: effects on marine bird populations in Prince William Sound, Alaska. *The Condor* 102: 723 - 737.

ITOPF (International Tanker Owners Pollution Federation). 2002. Fate of marine oil spills, *Technical information paper* 2.

ITOPF. 2005. The use of chemical dispersants to treat oil spills. *Technical information paper* 4.

Jensen F. 2001. *Bayesian networks and decision graphs – statistics for engineering and information science*. Springer Verlag, New York.

Jessup D., Miller M., Ryan J., Nevins H., Kerkering H., Mekebri A., Crane D., Johnson T. & Kudela R. 2009. Mass stranding of marine birds caused by s surfactant.producing red tide. PLoS ONE 4: 4550.

Johnsgard P. 1965. *Handbook of waterfowl behavior*. Comstock Publishing Associates, Cornell.

Kauppinen J. 2012. Allista maailmanlaajuisesti uhanalainen lintulaji? *Suomen Luonto* 2: p. 12. [In Finnish]

Kennish M. 1997. *Practical handbook of estuarine and marine pollution*. CRC Press, Boca Raton.

Kokko H., Harris M. & Wanless S. 2004. Competition for breeding sites and site-dependent population regulation in a highly colonial seabird, the common guillemot Uria aalge. *J. Anim. Ecol.* 73: 367 - 376.

Kokko H. & Sutherland W. 1998. Optimal floating and queuing strategies: consequences for density dependence and habitat loss. *Am. Nat.* 152: 354 - 36.

Kuronen J., Helminen R., Lehikoinen A. & Tapaninen U. 2008. Maritime transportation in the Gulf of Finland in 2007 and in 2015. *Publications from the Centre for Maritime Studies University of Turku* 45: 1 - 110.

Kvale S. & Brinkman S. 2009. *Interviews: Learning the craft of qualitative research interviewing*. SAGE Publications, Los Angeles.

Lack D. 1954. *The natural regulation of animal numbers*. Oxford University Press, Oxford.

Laur D. & Haldorson L. 1996. Coastal habitat studies: the effect of the *Exxon Valdez* oil spill on shallow subtidal fishes in Prince William Sound, *Am. Fish. Soc. Symp.* 18: 659 - 670.

Laursen K. 1989. Estimates of sea duck winter populations of the Western Palearctic. *Dan. Rev. Game Biol.* 13: 1 - 22.

Larsson K. & Tydén L. 2005. Effekter av oljeutsläpp alfågel Clangula hyemalis vid Hoburgs bank I centrala Östersjön mellan 1996/97 och 2003/04. *Ornis Svecica* 15: 161 - 171.

Lecklin T., Ryömä R. & Kuikka S. 2011. A Bayesian network for analyzing biological acute and long-term impacts of an oil spill in the Gulf of Finland. *Mar. Pollut. Bull.* 62: 2822 - 2835.

Lundeval C. & Bergström M. 2005. Fåglarna i Norden, Forma Publishing Group AB, Västerås. [In Swedish]

Maddock A. & Samways M. 2000. Planning for biodiversity conservation based on the knowledge of biologists. *Biodivers. Conserv.* 9: 1153 - 1169.

MARPOL (International Convention for the Prevention of Pollution from Ships). 1973.

Michel J. 1992. Oil behavior and toxicity. In: Hayes M., Hoff R., Michel J., Scholz D. & Shigenaka G. *Introduction to coastal habitats and biological resources for spill response, report HMRAD 92-4.* National Oceanic and Athmospheric Administration, Seattle.

Morgan M. & Henrion M. 1990. Uncertainty: a guide to dealing with uncertainty in quantitative risk and policy analysis, Cambridge University Press, Cambridge.

National Research Council. 1989. *Using oil spill dispersant on the sea*. National Academic Press, Washington.

National Research Council. 2003. *Oil in the Sea III: Inputs, Fates and Effects*. National Academic Press, Washington.

Olsson O., Nilsson T. & Fransson T. 2000. *Long-term study of the mortality in the common guillemot in the Baltic Sea*. Swedish Environmental Protection Agency, Stockholm.

Österblom H., Van der Jeugd H. & Olsson O. 2004. Adult survival and avian cholera in Common guillemots *Uria aalge* in the Baltic Sea. *Ibis* 146: 1 - 4.

Pajanen K., Soulanto M. & Sikk E. (eds.). 2005. *Suomenlahti – alkumerestä nykymereksi*. Enviroment Centre of City of Helsinki, Hämeenlinna. [In Finnish]

Peakall D. & Tremblay J., Kinter W. & Miller D. 1981. Endocrine dysfunction in seabirds caused by ingested oil. *Environ. Res.* 24: 6 - 14.

Peterson C. 2000. The Exxon Valdez oil spill in Alaska: acute, indirect and chronic effects on the ecosystem. *Adv. Mar. Biol.* 39: 3 - 84.

Peterson C., Rice S., Short J., Esler D., Bodkin J., Ballachey B. & Irons D. 2003. Long-Term ecosystem Response to the Exxon Valdez Oil Spill. *Science* 302: 2082 - 2086.

Pettersson H. 2007. Wave climate in the northern Baltic proper and in the Gulf of Finland 2006. In: Olsonen R. (ed.) *FIMR monitoring of the Baltic Sea environment – Annual report 2006*. Meri Report Series of the Finnish Institute of Marine Research 59: 13 - 18.

Piatt J. & Ford R. 1996. How many birds were killed by the Exxon Valdez oil spill? *Am. Fish. Soc. Symp.* 18: 712 - 719

Piatt J., Lensink C., Butler W., Kendziorek M. & Nysewander D. 1990. Immediate impact of the Exxon Valdez oil-spill on marine birds. *Auk* 107: 387 - 397.

Pitkänen H., Lehtoranta J. & Räike A. 2001. Internal nutrient fluxes counteract decreases in external load: the case of the estuarial Eastern Gulf of Finland, Baltic Sea. *AMBIO* 30: 195 - 201.

Rassi P., Hyvärinen E., Juslén A. & Mannerkoski I. (eds.) 2010. *The 2010 red list of Finnish species*. Ympäristöministeriö & Suomen ympäristökeskus, Helsinki.

Ricker W. 1954. Stock and recruitment. *J. Fish. Res. Board Can.* 11: 559 - 623.

Russel R. 1999. Comparative demography and life history tactics of seabirds: implications for conservation and marine monitoring. *Am. Fish. Soc. Symp.* 23: 51 - 76.

Scholz D., Michel J., Shigenaka G. & Hoff R. 1992. Biological resourses. In: Hayes M., Hoff R., Michel J., Scholz D. & Shigenaka G. *Introduction to coastal habitats and biological resources for spill response, report HMRAD 92-4.* National Oceanic and Athmospheric Administration, Seattle.

Schreiber E. & Burger J. 2001. *Biology of marine birds.* CRC Press, Boca Raton.

SOLAS (International Convention for the Safety of Life at Sea). 1974.

Sweitzer J., Langaas S. & Folke C. 1996. Land use and population density in the Baltic Sea drainage basin: a GIS database. *Ambio* 25: 91 - 99.

Tuck L. 1961. *The murres*. Canadian Wildlife Service, Ottawa, Canada, 260 p.

Urho L. & Ahvonen A. 1990. Öljyvahingon vaikutukset kaloihin ja kalastukseen, kala- ja kalastustutkimukset. Teoksessa: Hirvi J. (ed.) *Suomenlahden öljyvahinko 1987. Vesi- ja ympäristöhallinnon julkaisuja sarja A* 51: 149 - 191. [In Finnish with English summary]

Uusitalo L. 2007. Advantages and challenges of Bayesian networks in environmental modelling. Ecological Modelling 203: 312 - 318.

Uusitalo L., Kuikka S. & Romakkaniemi A. 2005. Estimation of Atlantic salmon smolt carrying capacity of rivers using expert knowledge. *ICES J. Marine Sci.* 62: 708 - 722.

Van der Laag L., Renooij S., Witteman C., Aleman B. & Taal B. 2002. Probabilities for a probabilistic network: a case study in oesphageal cancer. *Artificial Intelligence in Medicine* 25: 123 - 148.

Ward P. & Zahavi A. 1973. The importance of certain assemblages of birds as “information-centres” for food-finding. *Ibis* 115: 517 - 534.

Wiedmer M., Fink M., Stegeman J., Smolowitz R. Marty G. & Hinton F. 1996. Cytochrome P-450 induction and histo-pathology in preemergent pink salmon from oiled spawning sites in Prince William Sound. Am. Fish. Soc. Symp. 18: 509 - 517.

Wiens J., Crist T., Day R., Murphy S. Hayward G. 1996. Effects of the Exxon Valdez oil spill on marine bird communities in Prince William Sound, Alaska. *Ecological Applications* 6: 828 - 841.

Wood M. & Heaphy N. 1991. Rehabilitation of oiled seabirds and bald eagles following the Exxon Valdez oil spill. *Proceedings of the 1991 Oil Spill Conference, March 4-7 1991, San Diego,* pp. 263 - 266.

Woolbridge S. & Done T. 2004. Learning to predict large-scale coral bleaching from past events: a Bayesian approach using remotely sensed data, in-situ data, and environmental proxies. *Coral Reefs* 23: 96 - 108.

Yamada K., Eltih J., McGarthy M. & Zerger A. 2003. Eliciting and integrating expert knowledge for wildlife habitat modeling. *Ecological Modelling* 165: 251 - 264.

INTERWIEVS

Ellermaa M., 20.11.2009, Helsinki.

Hario M., 22.12.2009, Helsinki.

Lehikoinen A., 17.12.2009, Helsinki.

Lehtiniemi T., 29.10.2009, Helsinki.

Keskitalo M., 4.11.2010, Kotka.

Päivärinta P., 27.1.2010, Kotka.

Velmala W., 7.1.2010, Helsinki.

Appendix 1. Description of the variables given to the experts

Oil type
Light oil = moderately volatile, moderately toxic, may contaminate intertidal resources, potential for subtidal processes, dispersion no necessary, effective cleanup.

Medium oil = 1/3 evaporate within 24 hours, less soluble compounds, contamination of intertidal habitats may be severe and long-term, impacts on birds and mammals may be severe, dispersion possible within 1-2 days, fast cleanup most effective.

Heavy oil = no evaporation or dissolution, may sink to bottom, contamination of intertidal habitats may be severe and long-term, impacts on birds and mammals may be severe, long-term contamination of sediments, dispersion seldom effective, cleanup difficult.

Time of year
Spring = III-V
Summer = VI-VIII
Autumn = IX-XI

Exposure to oil
Number of birds present in the colony exposed to oil (0-20, 20-50, 50-80, 80-100 %).

Occurrence of birds
Number of birds of the population present in the colony (the common guillemot) or resting in the GOF (the long-tailed duck) (0-20, 20-50, 50-80, 80-100 %).

Mortality, adults
Mortality of adult birds after spill (0-20, 20-50, 50-80, 80-100 %).

Mortality, offspring
Mortality of eggs and chicks during nesting caused by spill (0-20, 20-50, 50-80, 80-100 %).

Recolonization
Number of recolonization next year after spill, adult birds from other colonies that are replacing the birds that died after the oil spill (0-20, 20-50, 50-80, 80-100 %).

Recovery
Number of birds nesting in the colony after 10 years compared to pre-spill size of the population (0-20, 20-50, 50-80, 80-100 %).

Impact on GOF
Number of birds resting in the Gulf of Finland 10 years after spill compared to pre-spill stage (0-20, 20-50, 50-80, 80-100 %).

Impact on Baltic
Number of birds migrating over the Gulf of Finland (and wintering in the Southern Baltic Sea) 10 years after spill compared to pre-spill stage (0-20, 20-50, 50-80, 80-100 %).

Appendix 2. Examples of the probability tables used in expert interviews

Mortality of adults

Exposure to oil	0-20	20-50	50-80	80-100
0-20				
20-50				
50-80				
80-100				

Mortality of offspring

Mortality of adults	0-20	0-20	0-20	0-20
Exposure to oil	0-20	20-50	50-80	80-100
0-20				
20-50				
50-80				
80-100				

Appendix 3. Type, causal relationships and states of the variables

The common guillemot

Variable	Type of variable	Parents	Children	States
Oil_type	Random	None	*Exposure_to_oil*	Light oil, Medium oil, Heavy oil
Time_of_year	Random	None	*Exposure_to_oil,* *Occurrence_of_birds*	Spring, Summer, Autumn
Expert	Random	None	*Mortality_adults,* *Mortality_offspring,* *Recolonization,* *Occurrence_of_birds,* *Exposure_to_oil*	Expert 1, Expert 2, Expert 3, Expert 4
Occurence_of_birds	Random	*Time_of_year, Expert*	*Exposure_to_oil*	0-20, 20-50, 50-80, 80-100
Exposure_to_oil	Random	*Oil_type, Time_of_year,* *Occurrence_of_birds,* *Expert*	*Mortality_adults,* *Mortality_offspring*	0-20, 20-50, 50-80, 80-100
Mortality_adults	Random	*Exposure_to_oil,* *Expert*	*Mortality_offspring,* *Recolonization*	0-20, 20-50, 50-80, 80-100
Mortality_offspring	Random	*Exposure_to_oil,* *Mortality_adults,* *Expert*	*Recovery*	0-20, 20-50, 50-80, 80-100
Recolonization	Random	*Mortality_adults,* *Expert*	*Recovery*	0-20, 20-50, 50-80, 80-100
Recovery	Random	*Mortality_adults,* *Mortality_offspring,* *Recolonization,* *Time_of_year*	None	0-20, 20-50, 50-80, 80-100

The long-tailed duck

Variable	Type of variable	Parents	Children	States
Oil_type	Random	None	*Exposure_to_oil*	Light oil, Medium oil, Heavy oil
Time_of_year	Random	None	*Exposure_to_oil,* *Occurrence_of_birds*	Spring, Summer, Autumn
Expert	Random	None	*Mortality_adults,* *Impact_on_GOF,* *Impact_on_Baltic,* *Occurrence_of_birds,* *Exposure_to_oil*	Expert 1, Expert 2, Expert 3, Expert 4
Occurence_of_birds	Random	*Time_of_year, GOF, Expert*	*Exposure_to_oil*	0-20, 20-50, 50-80, 80-100
Exposure_to_oil	Random	*Oil_type,* *Time_of_year,* *Occurrence_of_birds,* *Expert*	*Mortality_adults*	0-20, 20-50, 50-80, 80-100
GOF	Random	None	*Occurence_of_birds*	East, West
Mortality_adults	Random	*Exposure_to_oil,* *Expert*	*Impact_on_GOF*	0-20, 20-50, 50-80, 80-100
Impact_on_GOF	Random	*Mortality_adults,* *Expert*	*Impact_on_Baltic*	0-20, 20-50, 50-80, 80-100
Impact_on_Baltic	Random	*Impact_on_GOF,* *Expert*	None	0-20, 20-50, 50-80, 80-100

Appendix 4. The prior distributions of the variables

The common guillemot model

Variable	States	%
Time_of_year	Spring	39
	Summer	28
	Autumn	33
Oil_type	Light	23,3
	Medium	18,9
	Heavy	57,8
Occurrence_of_birds	0-20	37,64
	20-50	12,79
	50-80	12,7
	80-100	39,87
Exposure_to_oil	0-20	23,24
	20-50	20,96
	50-80	22,46
	80-100	33,35
Mortality_adults	0-20	0,73
	20-50	3,58
	50-80	11,25
	80-100	84,44
Mortality_a_final	0-20	58,96
	20-50	17,74
	50-80	20,06
	80-100	3,23
Mortality_offspring	0-20	42,58
	20-50	20,84
	50-80	14,59
	80-100	21,99
Recolonization	0-20	31,67
	20-50	30,38
	50-80	16,6
	80-100	21,36
Recovery	0-20	1,2
	20-50	0,0002
	50-80	5,4
	80-100	93,4

The long-tailed duck model

Variable	States	%
Time_of_year	Spring	39
	Summer	28
	Autumn	33
Oil_type	Light	23,3
	Medium	18,9
	Heavy	57,8
Occurrence_of_birds	0-20	62,46
	20-50	19,3
	50-80	11,99
	80-100	6,25
Exposure_to_oil	0-20	29,28
	20-50	34,5
	50-80	27,16
	80-100	9,06
Mortality_adults	0-20	0,01
	20-50	0,25
	50-80	6,04
	80-100	93,7
Mortality_a_final	0-20	85,76
	20-50	11,5
	50-80	2,56
	80-100	0,18
Impact_on_GOF	0-20	12,5
	20-50	12,5
	50-80	17,5
	80-100	57,5
Impact_on_Baltic	0-20	12,5
	20-50	17,5
	50-80	29,5
	80-100	40,5

Appendix 5. The posterior distributions of the variables

The common guillemot model

Variable	States	%	%
Occurrence_of_birds	Spring	0-20	17,5
		20-50	20
		50-80	20
		80-100	42,5
	Summer	0-20	2,5
		20-50	7,5
		50-80	17,5
		80-100	72,5
	Autumn	0-20	91,25
		20-50	8,75
		50-80	0
		80-100	0

The common guillemot model

Variable	States		%	%
Exposure_to_oil	Spring	Light	0-20	22,25
			20-50	16,4
			50-80	19
			80-100	42,35
		Medium	0-20	13,04
			20-50	17,75
			50-80	22,89
			80-100	46,32
		Heavy	0-20	23,12
			20-50	19,62
			50-80	28,37
			80-100	28,87
	Summer	Light	0-20	25,28
			20-50	8,34
			50-80	22,01
			80-100	44,36
		Medium	0-20	28,33
			20-50	13,04
			50-80	2,29
			80-100	35,34
		Heavy	0-20	1,62
			20-50	8,57
			50-80	34,6
			80-100	55,21
	Autumn	Light	0-20	36,71
			20-50	33,95
			50-80	17,56
			80-100	11,78
		Medium	0-20	27,85
			20-50	33,32
			50-80	22,57
			80-100	16,27
		Heavy	0-20	25,5
			20-50	24,5
			50-80	23,75
			80-100	26,25

The common guillemot model

Variables	States			%
Mortality_adults	Spring	Light	0-20	0,55
			20-50	3,7
			50-80	11,25
			80-100	84,5
		Medium	0-20	0,6
			20-50	3,8
			50-80	11,25
			80-100	84,35
		Heavy	0-20	1,05
			20-50	3,6
			50-80	11,25
			80-100	84,1
	Summer	Light	0-20	1,25
			20-50	4,2
			50-80	11,25
			80-100	83,3
		Medium	0-20	1,5
			20-50	3,95
			50-80	11,25
			80-100	83,3
		Heavy	0-20	1,7
			20-50	4
			50-80	11,25
			80-100	83,05
	Autumn	Light	0-20	0,25
			20-50	3
			50-80	11,25
			80-100	85,5
		Medium	0-20	0,25
			20-50	3
			50-80	11,25
			80-100	85,5
		Heavy	0-20	0,25
			20-50	3
			50-80	11,25
			80-100	85,5

The common guillemot model

Variable	States		%	%
Mortality_a_final	Spring	Light	0-20	43
			20-50	21,53
			50-80	29,87
			80-100	5,6
		Medium	0-20	38,06
			20-50	24,64
			50-80	31,53
			80-100	5,77
		Heavy	0-20	48,77
			20-50	33,8
			50-80	15,94
			80-100	1,49
	Summer	Light	0-20	35,25
			20-50	26,16
			50-80	33,28
			80-100	5,3
		Medium	0-20	40,63
			20-50	29,19
			50-80	26,95
			80-100	3,23
		Heavy	0-20	12,8
			20-50	33,69
			50-80	46,51
			80-100	7
	Autumn	Light	0-20	99,83
			20-50	0,017
			50-80	0
			80-100	0
		Medium	0-20	99,61
			20-50	0,39
			50-80	0
			80-100	0
		Heavy	0-20	99,56
			20-50	0,44
			50-80	0
			80-100	0

The common guillemot model

Variables	States			%
Mortality_offspring	Spring	Light	0-20	42,81
			20-50	13,68
			50-80	10,08
			80-100	33,43
		Medium	0-20	42,04
			20-50	13,81
			50-80	10,57
			80-100	33,58
		Heavy	0-20	39,74
			20-50	25,21
			50-80	18,69
			80-100	16,36
	Summer	Light	0-20	33,32
			20-50	24,25
			50-80	13,59
			80-100	28,84
		Medium	0-20	32,61
			20-50	36,22
			50-80	13,31
			80-100	17,86
		Heavy	0-20	33,58
			20-50	12,41
			50-80	16,39
			80-100	37,62
	Autumn	Light	0-20	50,15
			20-50	17,34
			50-80	19,77
			80-100	12,75
		Medium	0-20	50,16
			20-50	17,33
			50-80	19,77
			80-100	12,75
		Heavy	0-20	50,16
			20-50	17,32
			50-80	19,77
			80-100	12,75

The common guillemot model

Variables	States			%
Recolonization	Spring	Light	0-20	31,31
			20-50	38,14
			50-80	10,91
			80-100	19,64
		Medium	0-20	31,56
			20-50	38,1
			50-80	10,78
			80-100	19,55
		Heavy	0-20	31,93
			20-50	30,82
			50-80	17,69
			80-100	19,56
	Summer	Light	0-20	33,29
			20-50	32,47
			50-80	17,89
			80-100	16,36
		Medium	0-20	33,92
			20-50	25,76
			50-80	24,02
			80-100	16,31
		Heavy	0-20	34,43
			20-50	37,49
			50-80	11,71
			80-100	16,37
	Autumn	Light	0-20	30,01
			20-50	23,75
			50-80	18,5
			80-100	27,74
		Medium	0-20	30,02
			20-50	23,74
			50-80	18,5
			80-100	27,74
		Heavy	0-20	30,02
			20-50	23,74
			50-80	18,5
			80-100	27,74

The common guillemot model

Variables	States			%
Recovery	Spring	Light	0-20	0
			20-50	0
			50-80	7,08
			80-100	92,92
		Medium	0-20	0
			20-50	0
			50-80	7,69
			80-100	92,31
		Heavy	0-20	0
			20-50	0
			50-80	4,92
			80-100	95,08
	Summer	Light	0-20	0
			20-50	0,00064
			50-80	8,8
			80-100	91,2
		Medium	0-20	0
			20-50	0,00078
			50-80	8,26
			80-100	91,74
		Heavy	0-20	0
			20-50	0,0014
			50-80	12,99
			80-100	87,01
	Autumn	Light	0-20	3,63
			20-50	0
			50-80	0,31
			80-100	96,07
		Medium	0-20	3,62
			20-50	0
			50-80	0,31
			80-100	96,07
		Heavy	0-20	3,62
			20-50	0
			50-80	0,31
			80-100	96,07

The common guillemot model

Variable	States	%	%
Occurrence_of_birds	Spring	0-20	36,75
		20-50	17,5
		50-80	12,5
		80-100	6,25
	Summer	0-20	81,25
		20-50	6,25
		50-80	6,25
		80-100	6,25
	Autumn	0-20	45
		20-50	32,5
		50-80	16,25
		80-100	6,25

The long-tailed duck model

Variable	States		%	%
Exposure_to_oil	Spring	Light	0-20	43,5
			20-50	17,12
			50-80	35,62
			80-100	3,75
		Medium	0-20	17,56
			20-50	52,12
			50-80	26,25
			80-100	4,06
		Heavy	0-20	41
			20-50	36,29
			50-80	12,99
			80-100	9,72
	Summer	Light	0-20	33,85
			20-50	15,68
			50-80	40,68
			80-100	9,79
		Medium	0-20	32,19
			20-50	26,25
			50-80	31,25
			80-100	10,31
		Heavy	0-20	56,25
			20-50	10,42
			50-80	17,36
			80-100	15,97
	Autumn	Light	0-20	30,75
			20-50	44,25
			50-80	12,5
			80-100	12,5
		Medium	0-20	29,88
			20-50	32,62
			50-80	25
			80-100	12,5
		Heavy	0-20	28,25
			20-50	20,88
			50-80	25,87
			80-100	25

The long-tailed duck model

Variable	States		%	%
Mortality	Spring	Light	0-20	0
			20-50	0,25
			50-80	6,06
			80-100	93,69
		Medium	0-20	0
			20-50	0,25
			50-80	6,13
			80-100	93,62
		Heavy	0-20	0
			20-50	0,25
			50-80	6,19
			80-100	93,56
	Summer	Light	0-20	0
			20-50	0,25
			50-80	6
			80-100	93,75
		Medium	0-20	0
			20-50	0,25
			50-80	6
			80-100	93,75
		Heavy	0-20	0
			20-50	0,25
			50-80	6
			80-100	93,75
	Autumn	Light	0-20	0
			20-50	0,25
			50-80	6
			80-100	93,75
		Medium	0-20	0
			20-50	0,25
			50-80	6
			80-100	93,75
		Heavy	0-20	0
			20-50	0,25
			50-80	6,09
			80-100	93,66

The long-tailed duck model

Variable	States		%	%
Mortality_a_final	Spring	Light	0-20	91,42
			20-50	7,03
			50-80	1,46
			80-100	0,09
		Medium	0-20	85,78
			20-50	12,2
			50-80	1,9
			80-100	0,12
		Heavy	0-20	83,96
			20-50	13,19
			50-80	2,62
			80-100	0,23
	Summer	Light	0-20	88,72
			20-50	8
			50-80	3,04
			80-100	0,24
		Medium	0-20	88,05
			20-50	8,23
			50-80	3,45
			80-100	0,27
		Heavy	0-20	87,25
			20-50	8,24
			50-80	4,14
			80-100	0,38
	Autumn	Light	0-20	86,78
			20-50	11,32
			50-80	1,75
			80-100	0,15
		Medium	0-20	81,62
			20-50	15,44
			50-80	2,79
			80-100	0,15
		Heavy	0-20	73,74
			20-50	20,79
			50-80	5,02
			80-100	0,45

The long-tailed duck model

Variable	States		%	%
Impact_on_GOF	Spring	Light	0-20	12,5
			20-50	12,5
			50-80	17,5
			80-100	57,5
		Medium	0-20	12,5
			20-50	12,5
			50-80	17,5
			80-100	57,5
		Heavy	0-20	12,5
			20-50	12,5
			50-80	17,5
			80-100	57,5
	Summer	Light	0-20	12,5
			20-50	12,5
			50-80	17,5
			80-100	57,5
		Medium	0-20	12,5
			20-50	12,5
			50-80	17,5
			80-100	57,5
		Heavy	0-20	12,5
			20-50	12,5
			50-80	17,5
			80-100	57,5
	Autumn	Light	0-20	12,5
			20-50	12,5
			50-80	17,5
			80-100	57,5
		Medium	0-20	12,5
			20-50	12,5
			50-80	17,5
			80-100	57,5
		Heavy	0-20	12,5
			20-50	12,5
			50-80	17,5
			80-100	57,5

The long-tailed duck model

Variable	States		%	%
Impact_on_Baltic	Spring	Light	0-20	12,5
			20-50	17,5
			50-80	29,5
			80-100	40,5
		Medium	0-20	12,5
			20-50	17,5
			50-80	29,5
			80-100	40,5
		Heavy	0-20	12,5
			20-50	17,5
			50-80	29,5
			80-100	40,5
	Summer	Light	0-20	12,5
			20-50	17,5
			50-80	29,5
			80-100	40,5
		Medium	0-20	12,5
			20-50	17,5
			50-80	29,5
			80-100	40,5
		Heavy	0-20	12,5
			20-50	17,5
			50-80	29,5
			80-100	40,5
	Autumn	Light	0-20	12,5
			20-50	17,5
			50-80	29,5
			80-100	40,5
		Medium	0-20	12,5
			20-50	17,5
			50-80	29,5
			80-100	40,5
		Heavy	0-20	12,5
			20-50	17,5
			50-80	29,5
			80-100	40,5

Appendix 6. Code for the population model of the common guillemot

Estimation part: describes population dynamics

```
model<-"
model{

for(t in 1:T){

Nestsc[t]~dbin(prc,Nests[t
Nests[t]<-round((Recruits[t]+A[t]+Immigs[t])/2 )

Eggs[t]<-round(Clutch*Nests[t])
Fledglings[t]<-round(segg[t]*Eggs[t])
pegg[t]<-alpha*exp(-alpha*Eggs[t]/(K*exp(1)))
segg[t]~dbeta(aegg[t],begg[t])
aegg[t]<-pegg[t]*(Eggs[t]+1)+0.1
begg[t]<-(1-pegg[t])*(Eggs[t]+1)+0.1

Y1[t+1]<-round(sfled[t]*Fledglings[t])
sfled[t]<-Afled[t]/(Afled[t]+Bfled[t])
Afled[t]~dgamma(afled[t],Fledglings[t])
Bfled[t]~dgamma(bfled[t],Fledglings[t])
afled[t]<-pfled*(Fledglings[t]+1)+0.1
bfled[t]<-(1-pfled)*(Fledglings[t]+1)+0.1

Y2[t+1]<-round(sY1[t]*Y1[t])
sY1[t]<-AY1[t]/(AY1[t]+BY1[t])
AY1[t]~dgamma(aY1[t],e1[t])
BY1[t]~dgamma(bY1[t],e1[t])
e1[t]<-Y1[t]+1
aY1[t]<-pY1*(Y1[t]+1)+0.1
bY1[t]<-(1-pY1)*(Y1[t]+1)+0.1

Y3[t+1]<-round(sY2[t]*Y2[t])
sY2[t]<-AY2[t]/(AY2[t]+BY2[t])
AY2[t]~dgamma(aY2[t],e2[t])
BY2[t]~dgamma(bY2[t],e2[t])
e2[t]<-Y2[t]+1
aY2[t]<-pY2*(Y2[t]+1)+0.1
bY2[t]<-(1-pY2)*(Y2[t]+1)+0.1

Y4[t+1]<-round(sY3[t]*Y3[t])
sY3[t]<-AY3[t]/(AY3[t]+BY3[t])
AY3[t]~dgamma(aY3[t],e3[t])
BY3[t]~dgamma(bY3[t],e3[t])
e3[t]<-Y3[t]+1
aY3[t]<-pY3*(Y3[t]+1)+0.1
bY3[t]<-(1-pY3)*(Y3[t]+1)+0.1

Recruits[t+1]<-round(sY4[t]*Y4[t])
sY4[t]<-AY4[t]/(AY4[t]+BY4[t])
AY4[t]~dgamma(aY4[t],e4[t])
BY4[t]~dgamma(bY4[t],e4[t])
e4[t]<-Y4[t]+1
aY4[t]<-pY4*(Y4[t]+1)+0.1
bY4[t]<-(1-pY4)*(Y4[t]+1)+0.1

Immigs[t]~dpois(8

muA[t+1]<-(pA*A[t]+precr*Recruits[t]+pimmig*Immigs[t])
```

```
A[t+1]~dpois(muA[t+1])

sA[t]<-AA[t]/(AA[t]+BA[t])
AA[t]~dgamma(aA[t],eA[t])
BA[t]~dgamma(bA[t],eA[t])
eA[t]<-A[t]+1
aA[t]<-pA*eA[t]+0.1
bA[t]<-(1-pA)*eA[t]+0.1

srecr[t]<-Arecr[t]/(Arecr[t]+Brecr[t])
Arecr[t]~dgamma(arecr[t],er[t])
Brecr[t]~dgamma(brecr[t],er[t])
er[t]<-Recruits[t]+1
arecr[t]<-precr*er[t]+0.1
brecr[t]<-(1-precr)*er[t]+0.1

simmig[t]<-Aimmig[t]/(Aimmig[t]+Bimmig[t])
Aimmig[t]~dgamma(aimmig[t],eimmig[t])
Bimmig[t]~dgamma(bimmig[t],eimmig[t])
eimmig[t]<-Immigs[t]+1
aimmig[t]<-pimmig*eimmig[1]+0.1
bimmig[t]<-(1-pimmig)*eimmig[1]+0.1

Ntot[t]<-Y1[t]+Y2[t]+Y3[t]+Y4[t]+Recruits[t]+A[t]+Immigs[t]
}

K~dnorm(muK,tauK)T(0,)
muK<-70
tauK<-1/pow(5,2)

logit(alpha)<-zalpha
zalpha~dnorm(mualpha,taualpha)
mualpha<-0.95
taualpha<-1/pow(0.10,2)

logit(pfledu)<-lpfled
lpfled~dnorm(Mlpfled,Tlpfled)
Mlpfled<-(logit(pfled975)+logit(pfled025))/2
Tlpfled<-1/pow((logit(pfled975)-logit(pfled025))/(2*1.96),2)
pfled975<-0.4
pfled025<-0.2

pYu[5]<-pfledu
pYu[1]~dbeta(3,7)
pYu[2]~dbeta(4,6)
pYu[3]~dbeta(5,5)
pYu[6]~dbeta(6,4)
pYu[4]~dbeta(9,1)
pYr[1:6]<-sort(pYu
pY1<-pYr[2]
pY2<-pYr[3]
pY3<-pYr[4]
pY4<-pYr[5]
pA<-pYr[6]

precr<-pA
pimmig<-pA

Clutch<-0.70
prc<-0.95
```

```
A[1]<-A1
Recruits[1]<-Recruits1
Y1[1]<-Y11
Y2[1]<-Y21
Y3[1]<-Y31
Y4[1]<-Y41
}
"
data<-list(Recruits1=10, A1=72, Y11=0, Y21=4, Y31=6, Y41=8, Recolons1=0,
)

Post<-
cbind(v[,"A[54]"],v[,"Recruits[54]"],v[,"Y1[54]"],v[,"Y2[54]"],v[,"Y3[54]
"],v[,"Y4[54]"],v[,"pYr[1]"],v[,"alpha"],v[,"K"],v[,"pY1"],v[,"pY2"],v[,"
pY3"],v[,"pY4"],v[,"pA"])
v[1:10,"A"]
A[1:10,]
```

Prediction part: scenario with oil spill

```
require(rjags)

model<-"
model{
for (t in T+1:a+10){

Nests[t]<-(Recruits[t]+A[t]+Immigs[t])/2

Eggs[t]<-Clutch*Nests[t]

Fledglings[t]<-segg[t]*Eggs[t]

pegg[t]<-alpha*exp(-alpha*Eggs[t]/(K*exp(1)))

segg[t]~dbeta(aegg[t],begg[t])
aegg[t]<-pegg[t]*Eggs[t]+0.1
begg[t]<-(1-pegg[t])*Eggs[t]+0.1

Y1[t+1]<-sfled[t]*Fledglings[t]
sfled[t]~dbeta(afled[t],bfled[t])
afled[t]<-pfled*Fledglings[t]+0.1
bfled[t]<-(1-pfled)*Fledglings[t]+0.1

Y2[t+1]<-sY1[t]*Y1[t]
sY1[t]~dbeta(aY1[t],bY1[t])
aY1[t]<-pY1*Y1[t]+0.1
bY1[t]<-(1-pY1)*Y1[t]+0.1

Y3[t+1]<-sY2[t]*Y2[t]
sY2[t]~dbeta(aY2[t],bY2[t])
aY2[t]<-pY2*Y2[t]+0.1
bY2[t]<-(1-pY2)*Y2[t]+0.1

Y4[t+1]<-sY3[t]*Y3[t]
sY3[t]~dbeta(aY3[t],bY3[t])
aY3[t]<-pY3*Y3[t]+0.1
bY3[t]<-(1-pY3)*Y3[t]+0.1

Recruits[t+1]<-sY4[t]*Y4[t]
sY4[t]~dbeta(aY4[t],bY4[t])
aY4[t]<-pY4*Y4[t]+0.1
bY4[t]<-(1-pY4)*Y4[t]+0.1

Immigs[t]~dpois(20)

A[t+1]<-(sA[t]*A[t]+srecr[t]*Recruits[t]+simmig[t]*Immigs[t])

sA[t]~dbeta(aA[t],bA[t])
aA[t]<-pA*A[t]+0.1
bA[t]<-(1-pA)*A[t]+0.1

srecr[t]~dbeta(arecr[t],brecr[t])
arecr[t]<-precr*Recruits[t]+0.1
brecr[t]<-(1-precr)*Recruits[t]+0.1

simmig[t]~dbeta(aimmig[t],bimmig[t])
aimmig[t]<-pimmig*Immigs[1]+0.1
bimmig[t]<-(1-pimmig)*Immigs[1]+0.1
```

```
Ntot[t]<-Y1[t]+Y2[t]+Y3[t]+Y4[t]+Recruits[t]+A[t]+Immigs[t]

Nestso[t]<-(Recruitso[t]+Ao[t]+Immigso[t]+Recolons[t])/2

Eggso[t]<-Clutch*Nestso[t]*(1-Mor[propmory]*Oilinge[season,t])

Fledglingso[t]<-seggo[t]*Eggso[t]*(1-Mor[propmory]*Oilingf[season,t])

peggo[t]<-alpha*exp(-alpha*Eggso[t]/(K*exp(1)))
seggo[t]~dbeta(aeggo[t],beggo[t])
aeggo[t]<-peggo[t]*Eggso[t]+0.1
beggo[t]<-(1-peggo[t])*Eggso[t]+0.1

Y1o[t+1]<-sfledo[t]*Fledglingso[t]
sfledo[t]~dbeta(afledo[t],bfledo[t])
afledo[t]<-pfled*Fledglingso[t]+0.1
bfledo[t]<-(1-pfled)*Fledglingso[t]+0.1

Y2o[t+1]<-sY1o[t]*Y1o[t]*(1-Mor[propmor]*Oiling[season, t])
sY1o[t]~dbeta(aY1o[t],bY1o[t])
aY1o[t]<-pY1*Y1o[t]+0.1
bY1o[t]<-(1-pY1)*Y1o[t]+0.1

Y3o[t+1]<-sY2o[t]*Y2o[t]*(1-Mor[propmor]*Oiling[season, t])
sY2o[t]~dbeta(aY2o[t],bY2o[t])
aY2o[t]<-pY2*Y2o[t]+0.1
bY2o[t]<-(1-pY2)*Y2o[t]+0.1

Y4o[t+1]<-sY3o[t]*Y3o[t]*(1-Mor[propmor]*Oiling[season,t])
sY3o[t]~dbeta(aY3o[t],bY3o[t])
aY3o[t]<-pY3*Y3o[t]+0.1
bY3o[t]<-(1-pY3)*Y3o[t]+0.1

Recruitso[t+1]<-sY4o[t]*Y4o[t]*(1-Mor[propmor]*Oiling[season,t])
sY4o[t]~dbeta(aY4o[t],bY4o[t])
aY4o[t]<-pY4*Y4o[t]+0.1
bY4o[t]<-(1-pY4)*Y4o[t]+0.1

Recolons[t+1]<-
Recolon[proprec]*(Ao[t]+Recruitso[t]+Immigso[t])*Mor[propmor]*Oiling[seas
on,t]*oil[t]

Immigso[t]~dpois(20)

Ao[t+1]<-(sA[t]*Ao[t]+srecr[t]*Recruitso[t]+simmig[t]*Immigso[t])*(1-
Mor[propmor]*Oiling[season,t])+Recolons[t+1]

sAo[t]~dbeta(aAo[t],bAo[t])
aAo[t]<-pA*Ao[t]+0.1
bAo[t]<-(1-pA)*Ao[t]+0.1

srecro[t]~dbeta(arecro[t],brecro[t])
arecro[t]<-precr*Recruitso[t]+0.1
brecro[t]<-(1-precr)*Recruitso[t]+0.1

simmigo[t]~dbeta(aimmigo[t],bimmigo[t])
aimmigo[t]<-pimmig*Immigso[t]+0.1
bimmigo[t]<-(1-pimmig)*Immigso[t]+0.1

Ntoto[t]<-
Y1o[t]+Y2o[t]+Y3o[t]+Y4o[t]+Recruitso[t]+Ao[t]+Immigso[t]+Recolons[t]
```

```
Oilinge[1,t]<-oil[t]*1
Oilinge[2,t]<-oil[t]*0
Oilinge[3,t]<-oil[t]*0

Oilingf[1,t]<-oil[t]*0
Oilingf[2,t]<-oil[t]*1
Oilingf[3,t]<-oil[t]*0

Oiling[1,t]<-oil[t]*1
Oiling[2,t]<-oil[t]*1
Oiling[3,t]<-oil[t]*0

oil[t]<-equals(t,a)
}
Ao[T+1]<-A[T+1]
Recruitso[T+1]<-Recruits[T+1]
Y1o[T+1]<-Y1[T+1]
Y2o[T+1]<-Y2[T+1]
Y3o[T+1]<-Y3[T+1]
Y4o[T+1]<-Y4[T+1]
Recolons[T+1]<-Recolons1

A[1]<-Post[m,1]
Recruits[1]<-Post[m,2]
Y1[1]<-Post[m,3]
Y2[1]<-Post[m,4]
Y3[1]<-Post[m,5]
Y4[1]<-Post[m,6]


m~dcat(pm[1:1000])
for(i in 1:1000){
pm[i]<-1/1000
}

Ratio<-Ntoto[a+10]/Ntot[a+10]

Prob020<-step(0.20-Ratio)*step(Ratio-0)
Prob2050<-step(0.50-Ratio)*step(Ratio-0.20)
Prob5080<-step(0.80-Ratio)*step(Ratio-0.50)
Prob80100<-step(Ratio-0.80)

Mor[1]~dunif(0,0.20)
Mor[2]~dunif(0.20,0.50)
Mor[3]~dunif(0.50,0.80)
Mor[4]~dunif(0.80,1)

Recolon[1]~dunif(0,0.20)
Recolon[2]~dunif(0.20,0.50)
Recolon[3]~dunif(0.50,0.80)
Recolon[4]~dunif(0.80,1)

K<-Post[m,9]

alpha<-Post[m,8]

pfled<-Post[m,7]

pY1<-Post[m,10]
pY2<-Post[m,11]
```

```
pY3<-Post[m,12]
pY4<-Post[m,13]
pA<-Post[m,14]
precr<-pA
pimmig<-pA

Clutch<-0.70
prc<-0.95
}
"
)
```