National Environmental Research Institute
Ministry of the Environment · Denmark

Potential environmental impacts of oil spills in Greenland

An assessment of information status and research needs

NERI Technical Report, No. 415

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Anders Mosbech (ed.)

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Abstract: This report analyses information status and research needs in relation to potential environmental impacts of oil spills (offshore and onshore) in Greenland. The report assesses potential effects and potential mitigation and monitoring measures. Information gaps are identified and a number of recommendations are presented.

Keywords: Oil spill, oil degradation, oil spill impacts, Greenland

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Contents

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Forord

Denne redegørelse kortlægger status og behov for forsknings og videnopbygning i forbindelse med miljøeffekter af oliespild i Grønland.

Formålet med redegørelsen er at tilvejebringe et overblik over eksisterende viden og vidensmiljøer i Danmark/ Grønland samt at identificere og vurdere behov for yderligere forskning og videnopbygning, der er relevant i relation til miljøeffekter af oliespild i Grønland - offshore og onshore. Dette omfatter vurdering af mulige effekter, vurdering af metoder til begrænsning af effekter og vurdering af metoder til overvågning. Redegørelsen fokuserer på effekter der hidrører fra en spildsituation og ikke effekter der hidrører fra en generel driftsituation i forbindelse med efterforskningsboringer, produktion og transport af olie. Redegørelsen omfatter heller ikke kortlægning af metoder til opsamling af olie i det akutte beredskab.

Redegørelsen er blevet til på opfordring af det rådgivende udvalg for Arktis, med henblik på at danne baggrund for prioritering og koordinering af projektforslag for Miljøstyrelsen og Det rådgivende udvalg for Arktis.

Redegørelsen er udarbejdet af forskere på DMU, GEUS og RUC. Alle bidrag har i første udkast været rundsendt til alle bidragsydere. Der har været afholdt et møde og alle deltagere har haft lejlighed til at kommentere de indkomne bidrag. Af hensyn til engelsksprogede bidragydere, samt muligheden for at præsentere resultatet for en bredere kreds, blev det besluttet at lave redegørelsen på engelsk.

Følgende har deltaget i projektet: Anders Mosbech, redaktør (DMU), Hanne K. Petersen (DMU), Hap Pritchard (DMU), Carsten S. Jacobsen (GEUS), Beate Strandberg (DMU), Ole Andersen (RUC), Gary Banta (RUC), Anders Giessing (RUC), David Boertmann (DMU) og Peter Aastrup (DMU).

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Redegørelsen er finansieret med støtte fra Miljøstyrelsen via miljøbistandsprogrammet Dancea - Danish Cooperation for Environment in the Arctic. Redegørelsens resultater og konklusioner er forfatternes egne og afspejler ikke nødvendigvis Miljøstyrelsens holdninger.

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Sammenfatning

Kortlægning af status og behov for forsknings og videnopbygning i forbindelse med miljøeffekter af oliespild i Grønland

I redegørelsen gives en oversigt over den nuværende relevante viden og der peges på behov for yderligere videnopbygning dels vedr. nedbrydning af olie, dels vedr. effekter på mikroorganismer, planter, invertebrater, fisk, fugle og pattedyr. De relevante fagmiljøer beskrives kort. Deltagerne i projektet har ikke fortaget en overordnet prioritering mellem de forskellige fagområder.

Indledning

Viden om effekter af oliespild i denne sammenhæng kommer fra toksikologiske undersøgelser og nedbrydningseksperimenter samt undersøgelser af effekterne efter spild i naturen. Denne viden kan sammen med viden om bestande og økosystemer anvendes til at: a) vurdere de mulige effekter af et oliespild, b) planlægge risikofyldte aktiviteter så effekterne af et spild minimeres og c) planlægge beredskab og oprydning efter et spild.

Spredning, nedbrydning og effekter af oliespild er meget afhængig af olietype og naturtype. Oliespild i havet kan påvirke store områder og levende ressourcer langt fra spildstedet, mens spild på land oftest kan begrænses til små områder.

Bestandseffekter især på højere trofiske niveauer

Olie er giftig for næsten alle organismer, men i et økologisk perspektiv er det vigtige hvordan bestande bliver påvirket. En arts individer kan have en høj individuel følsomhed overfor olie, samtidig med at bestanden kan have en lav følsomhed overfor olie. Det er tilfældet hvis bestanden er spredt over et stort område og har en stor formeringsevne. Et enkelt oliespild vil kun ramme en lille del af bestanden og med en stor formeringsevne vil bestanden hurtigt kunne kompensere for et tab af individer. Dette er tilfældet for mange arter på de lavere trofiske niveauer og væsentlige bestandseffekter er derfor en større risiko på de højere trofiske niveauer, især hvor en stor del af en bestands individer forekommer i et begrænset område og den naturlige levealder er høj (dvs. formeringshastigheden er lav).

Når mulige effekter af et oliespild ses i et økologisk perspektiv er der behov for at se påvirkningerne fra et oliespild sammen med andre påvirkninger som effekter af bundtrawl på bunddyr og effekter af jagt på fugle og pattedyr.

Generel viden om olienedbrydning og effekter, og områdespecifik viden om bestande og økologi

Den relevante viden om miljøeffekter af oliespild i Grønland består dels af generel viden om olies spredning og nedbrydning i forskellige miljøer, og olies effekter på forskellige levende organismer dels af områdespecifik viden fra Grønland om forekomsten og dynamikken i de bestande og økosystemer der kan blive påvirket at oliespildet. Selvom der stadig er huller i vores generelle viden om oliespild i Arktis så har forskning i olieefterforskningsområder især i Alaska, Canada og Norge givet væsentlig viden, der er relevant for de grønlandske forhold. For at kunne anvende denne viden i Grønland er det imidlertid nødvendigt med områdespecifik viden om særligt følsomme områder og om bestandsforholdende for de arter der kan blive påvirket.

Det er i den sammenhæng vigtigt at have Grønlands størrelse og klimatiske og biologiske mangfoldighed for øje og fokusere på de områder hvor der vil være risiko for oliespild i de kommende år. Det er på nuværende tidspunkt hensigtsmæssigt at samle viden fra de grønlandske havområder med olieinteresser, mens lokal viden fra landområderne, hvor et oliespild ikke vil spredes over så stort et område, med fordel kan afvente at der er lokaliseret områder med planlagte aktiviteter hvor oliespild vil blive en reel risiko.

I det følgende refereres rapportens vigtigste anbefalinger og identificerede mangler i videngrundlaget for hhv. vandmiljøet og landmiljøet.

Atlas over områder der er særligt følsomme over for oliespild

Det anbefales at der i områder hvor der er risiko for oliespild udarbejdes en samlet oversigt over de ressourcer der er følsomme over for oliespild (oil spill sensitivity map). En sådan kortlægning kan bruges til på forhånd at planlægge risikobetonede aktiviteter og til at vurdere hvor der primært skal sættes ind mod et oliespild, hvis det er nødvendigt at prioritere indsatsen.

Langsigtet monitering efter et spild

De høje koncentrationer af olie der opstår ved spild i naturen kan påvirke alle organismer indtil olien er fortyndet eller nedbrudt. De lave temperaturer, mørke og is samt begrænset infrastruktur gør at man generelt må forvente at effekterne af et oliespild varer længere i Grønland end på lavere breddegrader. Det anbefales derfor generelt at der udvikles en langsigtet moniteringsplan til at overvåge oliekoncentrationer og biologiske effekter i miljøet i tilfælde af et oliespild (kapitel 1 m.fl.).

Vandmiljøet

Opsamling, fysisk nedbrydning og spredning

Det anbefales at opsamling af olie benyttes som den primære bekæmpelsesmetode. Når den olie det ikke er muligt at opsamle spredes og opblandes vil toksiciteten formindskes, overfladen forøges og den fysiske og biologiske nedbrydning vil gå hurtigere. Den biologiske nedbrydning kan kun forventes at have en begrænset effekt så længe olien findes i høje koncentrationer med lille overflade i forhold til volumen (kapitel 2).

Biologisk nedbrydning

Der mangler viden om potentialet for biologisk nedbrydning af olie i det grønlandske vandmiljø, herunder hvordan mikrobielle populationer påvirkes, effekter af glacialt silt (finkornede mineralske partikler) i vandet og om nedbrydningen kan fremmes ved tilsætning af kvælstofgødning uden væsentlige negative effekter af gødningen på miljøet (kapitel 2 og 3).

Strandenge

Strandenge er en sårbar vegetationstype der bør kortlægges i områder hvor der er risiko for marine oliespild (kapitel 4).

Effekter på hvirvelløse dyr af bundtrawl

Ved et oliespild kan der være en betydelig dødelighed blandt bunddyrene og ved genindvandringen vil opportunistiske arter dominere i starten. Der mangler generelt viden den økologiske struktur og om de mulige økologiske nøglearter blandt bunddyrene.

Bunddyrene i mange områder er imidlertid udsat for en massiv påvirkning fra bundtrawl og viden om denne væsentlige påvirkning vurderes at være nødvendig for at kunne forudsige og vurdere effekterne af oliespild på bunddyrene (kapitel 5).

Bunddyrenes opblanding af sedimentet

Der mangler viden om bunddyrenes betydning for opblanding af sedimentet (bioturbation) i lavvandede områder i Arktis. Opblandingen har betydning for nedbrydning af olie, og opblandingen kan blive påvirket hvis artssammensætningen af bunddyrene ændrer sig efter et oliespild (kapitel 5).

Gydeområder for lodde og stenbidder

Lodde (ammassat) og stenbider der gyder i strandzonen og på lavt vand er særligt udsat for at blive påvirket af et oliespild. Det anbefales at den eksisterende kortlægning af gydeområder udvides og forbedres (kapitel 6).

Ørredelve

Fjeldørred kan blive påvirket af et oliespild både i gydeområderne i ferskvand og i marine fouageringsområder nær elvudløb. I dele af udbredelsesområdet mangler der viden om de vigtige områder for fjeldørred (kapitel 6).

PAH i fisk

Der er fundet uventet høje PAH koncentrationer i enkelte analyser af ulke fra Grønland. Det anbefales at der laves yderligere analyser for at beskrive baggrundsniveauet af PAH i fisk (og rejer) i Grønland.

Fugle: langtidsstudier af nøglearter

Havfuglebestande er særligt udsatte for at blive påvirket af marine oliespild, selvom sunde bestande har en vis robusthed overfor enkeltstående katastrofer. Der er behov for yderligere kortlægning af “hot spots for havfugle” og især er der behov for fokus på nøglearter der er under pres, små bestande og truede (nedadgående) bestande. Risikoen for påvirkning fra oliespild skal ses i sammenhæng med påvirkningen fra bl.a. jagt. En vigtig beskyttelse mod langsigtede effekter af oliespild kan opnås ved på forhånd at sikre sunde bestande af arter der er vigtige i Grønland og kan blive alvorligt ramt af et spild (kapitel 7). Det drejer sig primært om arterne: ederfugl, kongeederfugl, strømand og polarlomvie samt i anden række lunde og søkonge, havlit, toppet skallesluger og lysbuget knortegås.

Landgangspladser for spættet sæl

Spættet sæl er den eneste sæl der går på land i Vestgrønland. På landgangspladserne er den særligt udsat for at få olie på sig ved et oliespild. Da bestanden er lille, og har været faldende, vil det være væsentligt at få kortlagt de aktive landgangspladser, så de kan sikres særlig beskyttelse (kapitel 8).

Landmiljøet

Gødning af oliespild

Ved et oliespild på land er fysisk opsamling evt. kombineret med naturlig nedbrydning in situ den mest oplagte behandling. Der er imidlertid en begrænset viden om potentialet for biologisk nedbrydning af olie i det grønlandske landmiljø. Der mangler viden om mulighederne for at fremme den naturlige nedbrydning ved tilsætning af kvælstofgødning samt om de sekundære skadevirkninger ved at gødningen spredes i miljøet (kapitel 2 og 3).

Vegetationskortlægning i olieefterforskningsområder

Selvom udstrækningen af et oliespild på land vil være begrænset sammenlignet med et marint spild vil effekterne på især tørre vegetationstyper kunne vare årtier. Det er derfor vigtigt at kortlægge særligt sårbare og vigtige vegetationstyper i områder med olieefterforskning, således at risikoen for skader i disse områder kan minimeres (kapitel 4).

Oliespild på land i Grønland forventes kun at kunne give relativt små lokale effekter på bestande af landpattedyr og landfugle (kapitel 7 og 8).

Siulequt

Nalunaarusiami matumani Kalaallit Nunaanni uuliaarluertoqartillugu avatangiisinut sunniutaasartut pillugit ilimatusarnerup paasissutissanillu katersuinerup sumut killissimanera pisariaqassusaalu nassuiarneqarput.

Nalunaarusiap siunertaraa Qallunaat Nunaanni / Kalaallit Nunaanni ilisimasat ilimasatusarfiillu ingerlanneqartut nalornisaallisarnissaat kiisalu Kalaallit Nunaanni - imaani nunamilu - uuliaarluernerit avatangiisinut sunniutaannut atatillugu sunik annertunerusumik ilisimatusarnissap paasissutissarsiornerullu pisariaqarnerisa qulaajarneqarnissaat nalilersorneqarnissaallu. Tamatumunnga ilaapput sunniutaasinnaasunik nalilersuineq, sunniutaasunik akiueriaatsinik nalilersuineq kiisalu upalungaarsimanermi periaatsinik nalilersuineq. Nalunaarusiami uuliaarluertoqartillugu sunniutaasartut pingaarnerusutut sammineqarput nalinginnarlu uuliamik qillerinermi, qalluinermi assartuinermilu sunniutaasartut ilanngunneqarsimanatik. Nalunaarusiami aamma uuliaarluertoqartillugu pilertortumik saliinissaq eqqarsaatigalugu upalungaarsimanermut atatillugu uuliamik qallueriaatsit atorneqartartut ilanngunneqarsimanngillat.

Nalunaarusiaq Avatangiisinut Aqutsisoqarfik (Miljøstyrelsen) aammalu Nunani Issittuni siunnersuisoqatigiinni (Det rådgivende udvalg for Arktis) suliniutissatut siunnersuusiat tulleriiaarneqarnissaat aqunneqarnissaallu siunertaralu Nunani Issittuni siunnersuisoqatigiit inassuteqarnerat / kaammattuinerat tunngavigalugu pilersinneqarsimavoq.

Nalunaarusiaq DMU-mi, GEUS-imi RUC-imilu ilisimatuunit suliarineqarsimavoq. Nalunaarusiami allaaserisat allanneqaqqaaramik tamarmik suleqataasunut tamanut nassiunneqarsimapput. Tamatuma kingorna allaaserinnittut akornanni ataatsimiittoqarsimavoq tamarmillu allaaserisanut uparuateqarsinnaasimallutik. Allaaserinnittut tuluttut oqaasillit kiisalu nalunaarusiap inernerata siammasinnerusumut nittarsarnissaa pissutigalugit nalunaarusiap tuluttut suliarineqarnissaa aalajangerneqarsimavoq.

Misissuinermi inuit maku peqataasimapput: Anders Mosbech, aaqqissuisoq (DMU), Hanne K. Petersen (DMU), Hap Pritchard (DMU), Carsten S. Jacobsen (GEUS), Beate Strandberg (DMU), Ole Andersen (RUC), Gary Banta (RUC), Anders Giessing (RUC), David Boertmann (DMU) og Peter Aastrup (DMU).

Nalunaarusiaq Avatangiisinut Aqutsisoqarfimmit avatangiisinut sulianut atatillugu aningaasaateqarfik Dancea - Danish Cooperation for Environment in the Arctic aqqutigalugu aningaasaliiffigineqarsimavoq. Nalunaarusiami angusat naliliinerillu allaaserinnittut namminneq akisussaaffigaat Avatangiisinullu Aqutsisoqarfiup isumaanut naleqquttuusariaqaratik.

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Eqikkarnera

Kalaallit Nunaanni uuliaarluertoqartillugu avatangiisinut sunniutaasartunik ilisimatusarnerup paasissutissanillu katersuinerup sumut killissimaneranik pisariaqassusaanillu nalilersuineq.

Nalunaarusiami ullumikkut ilisimasat pingaaruteqartut nalunaarsorneqarsimapput taassumalu saniatigut annertunerusumik ilisimatusarfigineqartariaqartut tikkuartorneqarlutik, tassa uuliap arrortarneranut, uumasuaqqanut, naasunut, uumasunut qimerloqanngitsunut, aalisakkanut, timmissanut uumasunullu miluumasunut tunngasut. Avatangiisinut atatillugu ilisimatusarfiit pingaaruteqartut naatsumik aamma allaaserineqarput. Suliami peqataasut akornanni ilisimatusarfinnik assigiinngitsunik pingaarnerutitsiniarluni tulleriiaarisoqarsimanngilaq.

Aallaqqaasiut

Uuliaarluernermut atatillugu sunniutaasartunik ilisimasat uumasunut toqunassusaannik misissuisarnernit arrortarneranillu misileraanernit kiisalu pinngortitami uuliaarluernerup kingorna sunniutaasartunik misissuisarnernit tunngaveqarput. Ilisimasat tamakku uumasunik pinngortitamillu pissutsinik ilisimasat ilanngullugit makununnga atorneqarsinnaapput: a) uuliaarluernerup sunniutaasinnaanik nalilersuinermi, b) suliat uuliaarluernermut atatillugu navianarsinnaasut pilersaarusiornerinut taamaalilluni uuliaarluernerit annikillisarneqarsinnaammata aammalu c) uuliaarluernermi upalungaarsimanissamut atatillugu kingornalu saliinissami pilersaarusiornermi.

Uuliap suunera pinngortitamilu pissutsit uuliaarluernerup siaruaattarneranut, arrortarneranut sunniutaanullu apeqqutaasartorujussuupput. Imaani uuliaarluernerup piffiit annertoorujussuit uumasullu ungasissorujussuarmiittut sunnersinnaavai, nunamili uuliaarluernerni amerlanertigut piffiit annikinnerit sunnerneqarsinnaasarlutik.

Uumasuni nerisareqatigiinni uumasunut qaffasinnerusunut sunniutaasartut

Uulia uumasunut tamarluinnangajannut toqunartuuvoq, uumasulli pinngortitarlu ataatsimut isigalugit pingaaruteqartoq tassaavoq uumasut qanoq sunnerneqartarnerat. Uumasuni ataatsimoortuni uumasut ataasiakkaat uuliamut malussarissorujussuusinnaapput, ataatsimulli isigalugit uuliamut malussarissusaat annertuvallaarani. Taamaatut ittarpoq uumasut siammasissumiitsut akornanni amerlasoorsuanngorlutillu kinguaassiorsinnaagaangata. Uuliaarluerneq ataaseq uumasunik ikittuinnarnik sunniisussaavoq kinguaassiuullaqqinnerallu pissutaalluni uumasut nalaanneqartut pilertortumik amerliartorsinnaasarlutik. Tamanna uumasuni assigiinngitsuni nerisareqatigiinni appasinnerusuni atuuppoq taamaattumillu uumasunut nerisareqatigiinnut qaffasinnerusumiittunut navianarnerusarpoq, ingammik uumasut ataasiakkaat piffimmi annertunngitsumiikkaangata uumasullu inunertussusaat qaffasikkaangat (tassa kinguaassiorsinnaanerat arriikkaangat).

Uumasut pinngortitallu akornanni pissutsit tunngavigalugit uuliaarluernerup kingunerisinnaasai nalilersussagaanni uuliaarluernerup kinguneri immap naqqani uumasut kilisanneqarnerisa kiisalu timmissat uumasullu miluumasut piniagaanerinut atatillugu sunniutaat peqatigalugit nalilersorneqartariaqarput.

Uuliap arrortarneranik sunniutaanillu nalinginnaq ilisamasat, kiisalu pinngortitap uumasullu pissusaannik immikkut ilisimasat

Kalaallit Nunaanni uuliaarluertoqartillugu avatangiisinut sunniutaasinnaasunut atatillugu ilisimasat pingaaruteqartut avatangiisini assigiinngitsuni uuliap siaruartarneranut arrortarneranullu nalinginnaq ilisimasanit, uuliap uumasunut assigiinngitsunut sunniutaanit kiisalu Kalaallit Nunaanni piffinni ataasiakkaani uumasunit pinngortitamillu uuliaarluernermit sunnerneqarsinnaasunik pissutsinik aallaaveqarput. Nunani issittuni uuliaarluernermut atatillugu nalinginnaq ilisimasavut suli amigaraluartut, ingammik Alaskami, Canadami Norgemilu uuliasiorfinni ilisimatusarnerit Kalaallit Nunaanni pissutsinut pingaaruteqartunik annertuumik paasissutissarsiffiusimapput. Ilisimasalli tamakku Kalaallit Nunaanni atussagaanni piffiit ataasiakkaat sunnertiasut uumasullu assigiinngitsut sunnerneqarsinnaasut paasissutissarsiffigisariaqarput.

Tassunga atatillugu Kalaallit Nunaata angissusaa, silaannaanut tunngasut aammalu uumasorpassuaqarnera isigisariaqarpoq kiisalu ukiuni aggersuni piffiit uuliaarluernermik nalaanneqarsinnaasut qitiutillugit. Maannakkut Kalaallit Nunaata imartai uulisiornissaq eqqarsaatigalugu soqutigineqartut paasisassarsiorfigissallugit pissusissamisuussaaq, nunamili piffinni ataasiakkaani uuliaarluertoqartillugu siaruarujussuarfigineqartussaanngitsuni ilisimasat aatsaat uuliasiorfiginiarneqalerpata, taamatullu uuliaarluernermik nalaanneqarsinnaalerpata, paasisassarsiorfigineqarnissaat utaqqisinneqarsinnaavoq.

Ataani nalunaarusiami unnersuutit pingaarnersaat imaani nunamilu avatangiisinut paasissutissat amigaataasut allaaserineqarput.

Piiffit uuliaarluernermik immikkut sunnertiasut nalunaarsorneqarnissaat

Siunnersuutigineqarpoq piiffinni uuliaarluernermik nalaanneqarsinnaasuni uumasut uuliaarluernermut sunnertiasut pillugit ataatsimut nalunaarsuisoqassasoq (oil spill sensitivity map). Taamatut nalunaarsuinermi suliat navianartutut isigineqartut siumut pilersaarusiorneqarsinnaapput uuliaarluertoqartillugulu tulleriiaarinissaq pisariaqalissagaluarput suut siulliunneqartussatut nalilersuinermut atorneqarsinnaalluni.

Uuliaarluernerup kingorna sivisumik misissuineq

Pinngortitami uuliaarluertoqartillugu uuliap kinertorujussuup imerpallarnissani arrornissaaluunniit tikillugu uumasunik tamanik sunniisinnaasarpoq. Silaannaap nillernera, qaamanikittarnera sikoqarnera kisalu pilersuinerup attaveqarnerullu killeqarnera nunanut kujasinnerusunut naleqqiullugu Kalaallit Nunaanni uuliaarluernerup sunniutai ataatsimut isigalugit sivisunerusarnissaat ilimagisariaqarpoq. Taamaattumik siunnersuutigisariaqarpoq uuliaarluertoqartillugu nalinginnaq piffissap sivisunerusup ingerlanerani uuliap kinissusianik pinngortitamullu sunniutaanik misissuisarnissaq inerisartariaqarpoq (kapitali 1 allallu).

Imaani avatangiisit

Uuliap katersorneqartarnera, arrortarnera siaruartarneralu

Inassutigisariaqarpoq uuliaarluernermut akiuinermi uuliamik qalluineq imaluunniit katersuineq aallaqqaataanit atortariaqartoq. Uulia katersorneqarsinnaangitsoq siaruaraangami toqunassusaa millisarpoq, kiisalu qaavata annertussusaa allisarluni uumasullu arrorterinerat sukkanerulersarluni. Uumasut arrorterinerat uulia imaani annertoorujussuutillugu killilimmik sunniuteqarnissaat ilimagisariaqarpoq (kapitali 2).

Uumassut arrorterinerat

Kalaallit Nunaata imartaani uumasut uuliamik arrortitsisinnaassusaannik ilisimasat amigaataapput, soorlu imaani uumasuaqqat qanoq sunnerneqartarnersut, sioraaqqat sermersuup aannermini assartorsimasai qanoq sunnerneqartarnersut kiisalu naggorissaatit annertuvallaanngitsumik avatangiisinut akornutaanatik uuliap sukkanerusumik arroriartorneranut iluaqutaasinnaanersut (kapitali 2 aamma 3).

Sissap narsaamarnge

Sissap narsaamarngisa naasui sunnertiasuupput taamaattumillu sumi imaani uuliaarluertoqarsinnaanera taakkunnga atatillugu nunap assiliortariaqarpoq (kapitali 4).

Immap naqqani kilisattarnerup uumasunut qimerloqanngitsunut sunniutai

Uuliaarluertoqartillugu immap naqqani uumasut akornanni toqusoqangaatsiartarpoq uumasunikkiartuleqqinneranilu uumasut uumaniallaqqinnerpaat aallaaqqaammut amerlanerulersarlutik. Pinngortitap uumasullu pissusaannik ilisimasat ataatsimut isigalugit amigaataapput kiisalu immap naqqani uumasut pingaarnerit pillugit ilisimasat amigarlutik.

Immap naqqani uumasut piffinni arlaqaqisuni immap naqqani kilisannermik peqquteqartumik annertuumik sunnerneqarsimapput, tamatuminngalu ilisimasaqarneq immap naqqani uumasunik uuliaarluernerup sunniutaanik siumut eqqoriaasinnaaneq naliliisinnaanerlu pisariaqartutut isigineqarput (kapitali 5).

Immap naqqani uumasut kinnernik akoorinerat

Nunani Issittuni imaani ikkattuni kinnerit akoorneqarnerannut (bioturbation) atatillugu immap naqqani uumasut qanoq pingaaruteqartiginerannik paasissutissanik amigaateqarpoq. Kinnerit akoorneqarnerat uuliap arrortarneranut pingaaruteqarpoq tamannalu uuliaarluernerup kingorna immap naqqani uumasoqatigiit allanngornerisigut sunnerneqarsinnaasarpoq (kapitali 5).

Ammassaat nipisaallu suffisarfii

Ammassaat nipisaallu sissap sinaani suffisarput immamilu ikkattumi uuliaarluernermit sunnertiasuararsuullutik. Siunnersuutigineqarpoq ullumikkut suffisarfinnik nalunaarsuineq ingerlanneqareersoq annertusineqassasoq pitsanngorsarneqarlunilu (kapitali 6).

Eqaloqarfiit

Eqaluk immami tarajoqanngitsumi suffisarfinni imaanilu kuup akuani neriniartarfiusuni uuliaarluernermit sunnerneqarsinnaapput. Eqaloqarfiit pingaartut ilaai paasissutissanik amigaateqarfiupput (kapitali 6).

Aalisakkani PAH (Polycykliske Aromatiske Hydrocarboner) - uuliami akuutissat toqunartut

Kalaallit Nunaanni kanassuni misissorneqarsimasuni ataasiakkaani ilimagineqanngitsunik annertuumik PAH-nik akulinnik siumuisoqarsimavoq. Kalaallit Nunaanni aalisakkat (kinguppaallu) PAH-mik akoqassusaat paasiniarlugu misissueqqinnissaq siunnersuutigineqarpoq.

Timmissat: timmissat pingaarnerit sivisuumik misissorneqarnerat

Timmissat imarmiut imaani uuliaarluertoqartillugu sunnertiasuararsuupput, timmissalli ataatsimoortut peqqissut ajutoornernut ataasiakkaanut sunneruminaatsuullutik. Suli imarmiunik timmiaqarfissuit annertunerusumik nalunaarsorneqarnissaat pisariaqarpoq ingammillu timmissat pingaarnerit navianartorsiortinneqartut, timmissat amerlavallaanngitsut kiisalu timmissat ikiliartortut qitiutinneqartariaqarlutik. Uuliaarluertoqartillugu sunnerneqarsinnaanerat soorlulu piniagaanerat ilanngullugu ataatsimut isigisariaqarput. Piffissaq sivisunerusoq isigalugu uuliaarluernermut akiuussutissatut pingaaruteqartut ilagaat Kalaallit Nunaanni timmissat pingaaruteqartut uuliaarluernermillu nalaanneqarujussuarsinnaasut peqqissuutinniarnissaat (kapitali 7). Timmissat pingaarnerusutut naatsorsuussaasut tassaapput: miteq siorartooq, miteq siorakitsoq, toornaviarsuk appalu kisalu pingaarnerit tulliisut qilanngaq, appaliarsuk, alleq, paaq kiisalu nerlernaq.

Qasigissat nunnittarfii

Qasigiaq tassaavoq Kitaani puisit nunnittartut kisiartaat. Nunnittarfimminni uuliaarluertoqartillugu uuliatersinnaanera annertoorujussuuvoq. Qasigissallu amerlassusaat killeqarmat appariartorsimallunilu pingaartorujussuuvoq nunnittarfiit suli atorneqartartut nalunaarsussallugit, tamatumuuna immikkut illersorsinnaaniarlugit (kapitali 8).

Nunami avatangiisit

Uuliaarluernernik naggorissaaneq

Nunami uuliaarluertoqartillugu uuliamik qalluineq ilaatigullu uuliap nammineq arroriartornera ilanngullugu akiuineq pitsaanerpaasarpoq. Kalaallit Nunaannili nunami uumasut uuliamik arrortitsisinnaassusaat annikitsuinnarmik ilisimasaqarfigineqarpoq. Naggorissaatinik akoorineq atorlugu uuliap nammineq arroriartortarnerata sukkatsisarsinnaanera naggorissaatillu avatangiisinut siaruarterneqarnerisa akornutaasinnaaneranik paasissutissat amigaataapput (kapitali 2 aamma 3).

Uuliasiorfiusut naasoqasusaanik nalunaarsuineq

Nunami uuliaarluerneq imaani uuliaarluernermut sanilliullugu siaruarsinnaassusaa annikinnerugaluartoq nunaminertat masarsuunngitsut eqqarsaatiginerullugit sunniutai ukiuni qulikkuutaartuni sivisussuseqarsinnaasarput. Taamaattumik piffiit uuliasiorfiusut sunnertiasut ingammik naasoqassusaannik nalunaarsuinissaq pingaaruteqarpoq, taamaalilluni nunaminertat tamakku ajoquserneqarsinnaanerat millisinneqarsinnaammat (kapitali 4).

Kalaallit Nunaanni nunami uuliaarluertoqartillugu uuliaarluernerup eqqannguani nunaminertat uumasuinik timmiaanillu annikitsuinarmik akornusiisarnissaq ilimagineqarpoq (kapitali 7 aamma 8).

Extended summary and recommendations

Introduction

The high concentration of oil in accidental spills represents a serious environmental threat, until the oil is diluted and/or degraded. Low temperature, ice and lack of infrastructure will generally make the impact of oil spills in the Arctic longer lasting than at lower latitudes. The spreading, fate and impact of oil spilled in different habitats differ, with the marine spill having the potential to impact large areas and resources far away from the spill site, while terrestrial spill are generally confined to limited areas.

Oil is toxic to almost all organisms. The toxic effect depends on the composition and concentration of the oil, and the sensitivity of the species affected. A species may have a high individual sensitivity and a low population sensitivity, if individuals are evenly and/or widely distributed and have a high reproductive capacity. This is the case for many species at lower trophic levels. Population impacts are therefore more likely at the higher trophic levels, where many species occur in significant concentrations and have a lower reproduction rate.

Due to the diversity of oil types, habitats and the importance of weather conditions for the fate of the oil, impact predictions can only be in general terms. However, from toxicological tests and impact studies after oil spill events, a body of general knowledge exists. This information can be used to assess the potential impact of oil spills in different environments, as well as minimising potential impacts through planning of activities to avoid the most sensitive areas and periods and planning of oil spill clean up.

The relevant knowledge for dealing with environmental impacts of oil spills in Greenland consists of general knowledge on the fate in different habitats, effects of oil on different animal groups (especially in the Arctic), and area (site) specific information from Greenland on the dynamics of ecosystems and populations likely to be impacted from an oil spill. Although there still are a number of general information gaps for oil spills in the Arctic, research especially in Alaska, Canada and Norway have provided important information of relevance to Greenlandic conditions. However in order to fully apply this knowledge area-specific information from Greenland on sensitive areas and on population dynamics is needed. Some part of this information can be gathered from marine areas of hydrocarbon interest at this stage of hydrocarbon exploration, while information from the terrestrial environment generally will benefit from a more targeted approach, when explorative oil drilling sites on land have been planned.

It is important to realise the size and climatic and biological diversity of Greenland and focus on information needs most relevant for the areas where oil activities are likely in the near future. Research should focus on dynamics of ecological systems where impacts are likely to occur, and the interconnectedness of human impacts should be recognised.

The major conclusions regarding critical information gaps and research needs for dealing with environmental impacts of oil spills in Greenland is given below for the marine, freshwater and terrestrial habitats respectively. The authors have not prioritised recommendations across disciplines. The technology used for oil spill containment and cleanup in the acute spill situation is not assessed in this report.

Recommendation: Oil spill sensitivity mapping

In areas where there is a risk of oil spills it is recommended to develop an integrated oil spill sensitivity map as a tool to plan preparedness and response to an oil spill. The objective is to produce an integrated overview of resources vulnerable to oil spills, for example biological resources and fishing and hunting areas, and options for protection and oil spill combat in different areas.

Recommendation: Long term monitoring of oil pollution

In Greenland, it is very likely that an oil spill will lead to long term contamination of certain environments. As a result, one should develop strategies for long term monitoring programs to assess oil concentrations and effects in the environment. This would consist primarily of performing chemical analyses on oil composition and monitoring of oil induced stress on biota (chapter 1 a.o.).

Marine and freshwater environment

Fate, degradation and impact on microbial communities

We know that the fate of oil in cold environments is generally controlled by physical forces (dissolution, dispersion, volatilisation and hardening) and biological processes (biodegradation, bioturbation, bioaccumulation). Chemical processes, such as photolysis, can also affect the oil fate but they are generally unimportant in cold environments. The most important fate processes are those related to a) Physical effects such as coating of plants and animals or engulfing oil directly into the gut, b) Acute toxicity from low molecular weight alkanes and aromatics, and c) Chronic toxicity from exposure to PAHs.

The fate of oil in most environments, including cold environments, is a function of the time to reduce physical effects of the oil and to eliminate acute and chronic toxicity. We know that by far the biggest factor, in this regard, is the ratio of the surface area covered by the oil to the volume of the oil in a particular contaminated area. In general, the higher the ratio value, the more effective the fate process will become and the faster oil weathering will occur. This ratio varies enormously depending on the environmental conditions, weather, and the ultimate " resting place" of the oil. In this respect, cold environments are different only in that they are likely to have more severe storm activity, lower average temperatures and more ice and snow. Temperature affect viscosity, evaporation and density of certain oils, but it is also important from the standpoint of biological activities.

We know that in most environments, including cold water environments, approximately 70-90% of oil spilled will eventually disappear through a variety of fate processes. The residual may be of no further environmental consequence from the standpoint of acute or chronic toxicity. It takes months to years (2-4) to reach this end point. Not included in this time frame is oil that becomes sequestered, for example deep in sediments or in rock crevices, in which the surface area to oil volume ratio is very low. Oil in these situations will often have a chemical composition similar to the spilled oil (virtually no weathering), but the trapped nature of this oil generally means little dissolution of hydrocarbons and minimal direct exposure to biota, thus keeping it from being a major environmental problem. However, it can also cause a long-term low-dose pollution. In cold environments, sequestered oil will be common due to the geophysical complexity and inaccessibility of the shorelines. Where it does become sequestered, weathering will be very slow due to the constant low temperature conditions.

Finally, a significant fraction of oil consists of a complex array of hydrocarbons that are of high molecular weight, very insoluble and very slow to degrade. This fraction can be as high as 30%. Even under conditions where weathering processes are prominent, this fraction will likely change little in composition over extended periods. Under these conditions, the residual either hardens into an asphalt-like material, remaining in the contaminated area or it becomes particulate in consistency, eventually breaking apart and dispersed by the physical action of waves and currents.

Recommendation: Physical removal

We recommend biodegradation options only to be considered as a follow up to the physical removal phase because removal of bulk oil and spreading residual oil over greater surface areas will greatly increase the short term effects of weathering and biodegradation.

Information gap: The potential biodegradation response and the effect of nitrogen fertilisers and glacial till

It is important to have an assessment of the potential biodegradation response to spilled oil in Greenland habitats prior to any spillage events. The level of knowledge is limited on how oil spill affect microbial populations and in particular if any treatment techniques, that can be expected brought into use, will have strong influence on the resilience of microbial communities. It is therefore recommended that an integrated study is being performed assessing both the oil degradation ability on selected coastal areas in Greenland, as well as assessing the diversity of the microbial populations in the particular environmental sample.

To gather this information, we recommend that microcosm studies at relevant temperatures are conducted using samples of water, interand subtidal sediments, and beach material from Greenland, to test for the ability of the indigenous microbial populations to degrade hydrocarbons. We have little doubt that hydrocarbon degradation activities will be present in the samples, but it is important to have some perspective on how responsive these populations will be.

In the coastal environments of Greenland, the physical forces associated with the severe storms will in certain areas quite likely " pound" glacial till into the oil, effectively increasing surface area. As temperatures rise in the summer, this physical change of the oil will possibly increase toxicity, however, also accelerated degradation can be expected and there will almost certainly be nitrogen limitation. We recommend that microcosm studies also are conducted to mimic this infusion of glacial till and to validate the possibility of enhanced degradation using nitrogen fertilisers. Secondary impacts of adding nitrogen fertilisers should be considered as well.

Information gap: Efficiency and impact of physical/chemical cleanup strategies

In coastal areas containment of an oil spill or clean up of the spilled oil will possibly involve the use of dispersants, ignition, speciality products, or perhaps combinations of all three. We recommend that an up to date evaluation of these options and their related products is done prior to planning oil spill response in relation to exploratory drilling, and regularly during an oil production phase. There will be no time to do so at the time of a spill and authorities are likely to be inundated by companies with products to sell at the time of a spill.

Vegetation

Most of the knowledge of ecological effects on aquatic vegetation originates from assessment outside the Arctic climate zone or from laboratory studies with species that are not dominant within the Arctic. Generally, the results point out only limited effects. However, sensitivity studies with relevant species and *in situ* studies are needed to get a better indication of effects in Arctic aquatic environments.

Information gap: Mapping of salt marshes

Some ecologically important Arctic ecosystems, like salt marshes and meadows, are expected to be sensitive to oil spills and we recommend the occurrence of these habitats to be mapped.

Invertebrates

Information gap: Ecosystem structure and keystone species

After an oil spill subsequent mortality occurs and in soft bottom habitats, infaunal species like polychaetes, bivalves and amphipods are particularly affected. On rocky shores the most significant impacts are experienced by mobile fauna such as echinoderms, crabs, gastropods, and amphipods, which are covered by the oil. If the oil and the ensuring mousse are especially thick it will also smother mussels and barnacles. In both cases opportunistic species typically soon invade the polluted habitat and proliferate. However, predicting the effect of an oil spill around Greenland will require better knowledge of ecosystem structure and identification of potential keystone species.

A confounding factor in predicting the effect of oil spills in Greenland is the intense fishery for shrimp and scallops along the coast of Greenland. Shrimps are fished either by small trawlers along the coast and in the fjords or by bigger ocean going vessels. In either case shrimp is taken with trawl dragging heavy gear along the bottom altering the seafloor habitat. Understanding the extent of these impacts, and their effects on populations of living marine resources, is needed not only in order to assess impacts of accidental oil spills, but also to properly manage current and future levels of fishing effort and fishing power

Information gap: Preimpact studies at undisturbed reference sites

Because of a lack of reference sites, where use of mobile fishing gear is prohibited, no empirical studies have yet been conducted on a scale that could demonstrate population level effects of habitat-management options. In the event of a major oil spill in an area that is heavily fished by bottom trawl it would be nearly impossible to evaluate the effect of the oil on the benthic invertebrate communities alone due to lack of knowledge of the undisturbed environment. Therefore, future assessments of the impacts of oil spills or other accidental environmental disturbances could benefit from pre-impact studies that provide objective criteria for selection of matched pairs of sites, thereby supporting the assumption of equality in the absence of the disturbance.

Information gap: Studies of bioturbation

Oil contamination from drilling in wetland and intertidal areas will negatively impact many of the invertebrate animals present. However, as the opportunists begin to dominate this may affect bioturbation, a process that may assist in the more rapid degradation and dispersal of the oil. Greenland waters will likely have a unique community composition in this respect and thus it is necessary to research the bioturbating communities in these environments and see if there is a different processing regime than that studied in more temperate areas.

Fish

Oil can affect fish in many ways. Fish readily take up oil components into their tissues after exposure to oil in water, food or sediment. Oil may cause a number of physiological and histopathological effects depending on the concentration and composition of the oil. Indicators of oil exposure in fish include increased concentrations of hydrocarbon metabolites in bile and increased monooxygenase activity in the liver tissue. Oil components are unlikely to bioaccumulate to high concentrations in fish tissue because fish are able to metabolise and excrete these contaminants.

Even though the effects of exposure to the water soluble fraction of crude oil varies with species developmental stage and temperature, the effects will normally be negligible at the concentration ranges found after accidental oil spills in open water. However, fish eggs and larvae could be exposed to harmful concentrations of these components in polar areas as a result of the use of dispersants (because of the low evaporation rate which increases aquatic exposure) or in coastal areas.

Although concentrations of oil that are lethal to adult fish rarely build up in the open sea following an oil spill, sublethal oil concentrations may stress fish, especially during long term exposure.

Recommendation: Plan to handle fish tainting

The development of an atypical flavour - tainting - in fish tissue is caused by natural spoilage or by assimilation of contaminants. Oil spills may affect the fisheries by tainting the fish, making the fish unmarketable. Acute oil spills will usually taint fish before they have accumulated oil concentrations that are toxic to humans. However, a lesson learned from the Exxon Valdez spill in 1989 was that it should be part of a (national) oil spill contingency plan to be prepared to handle human health concerns in relation to contaminated seafood, especially in areas with subsistence fishing.

Information gap: Mapping of spawning areas

Concerning general knowledge gaps, the importance of long-term subletal effects caused either by individuals damaged during a spill or chronic oil pollution (e.g. from leaks from oil incorporated in the sediment) needs further clarification. However, for impact assessments and sensitivity mapping in Greenland population specific information on spawning concentrations and larval concentrations is more needed for species where eggs and/or larvae are very concentrated near the shoreline, the surface or at the sea bottom at shallow water.

There is no doubt that local spawning stocks of capelin and lumpsucker, which spawn in the intertidal zone or just below, could be impacted by an oil spill. It is unclear how separate these spawning stocks are. Knowledge of the spawning areas is a prerequisite for protection. Spawning areas have been mapped in most of Southwest Greenland based on local knowledge, but research is needed to supplement the local knowledge as well as covering the rest of Greenland.

The spawning areas for fjord stocks of cod (pelagic eggs) and Greenland cod (demersal eggs) may to a lesser extent be impacted by an oil spill. The spawning is less concentrated and in deeper waters where the pelagic and demersal eggs are less likely to come into contact with oil.

For offshore spawners it is based on the present knowledge not likely that an oil spill would impact a significant proportion of eggs and larvae. Given the generally sparse sampling effort and the large range of variation, this conclusion is partly based on general oceanographic information on how concentrated eggs and larvae are likely to be. However, improved data from Southwest Greenland will be available from the REKPRO project on shrimp recruitment carried out by The Greenland Institute of Natural Resources and collaborators.

Information gap: Mapping of Arctic char rivers

Oil at the outlet of Arctic char rivers could impair the spawning migration as well as the feeding of the young chars often gathering at the outlet. And concerning fresh water oil could certainly impact the char spawning areas at the river and lake bottom. There is for some areas good knowledge of the rivers with migrating Arctic char, there are however also large data gaps which should be filled before oil activities in the area.

Information gap: PAH baseline

A few chemical analyses of PAH in sculpin liver from Greenland have shown unexpected high levels. The reason for this is unknown. We need a better description of baseline levels of PAH in fish.

Birds

Seabirds are vulnerable to oil spills in several ways. Primarily, oil soaks into the plumage and destroys insulation and buoyancy causing hypothermia, starvation and drowning. The oil destroys the water repellency of feathers by disrupting the precise orderly arrangement of feather barbules and barbicelles. Arctic seabirds are especially vulnerable to the destruction of the insulating capacity of the plumage because they live in cold water. Furthermore, spilled oil will keep its sticky and feather-destructive properties for a longer period in cold water.

The bird populations, which are believed to be most seriously affected by acute oil spills, are those with a low reproductive capacity and corresponding high average lifespan

Major oil spills do have the potential to deplete bird populations and single seabird colonies may be deserted. However, experiences from spills indicate some resiliency of seabird populations to single catastrophic events. It is unlikely that an oil spill can wipe out a seabird population unless other factors, such as hunting and by-catch in gillnets hamper the recovery of the population, or the population is small and has a very restricted distribution.

Looking at marine oil activities the most important possibilities for minimising the potential effect of a large oil spill is to plan risky activities, so the most important areas and periods are avoided, and to improve the status for populations (and subpopulations and colonies) which face the risk of a large oil spill. Special consideration should be given to key species (species of particular importance), and small declining populations and threatened populations.

Information gap: Seabird hot spots

There is still work to be done before the seabird hotspots in the seas around Greenland are mapped with reasonable certainty. Particular information gaps: offshore areas in general, and particularly the Open Water Area during winter, Avanersuaq and East Greenland.

Information gap: Long-term studies of key species at risk

There is a need for focused long-term studies of species susceptible to serious impacts, to improve the understanding of resilience, and thus the predictive ability and the potential for population supportive measures.

Key species with populations which could be significantly impacted by marine oil spills and have or maybe have populations under stress are primarily Brünnich’s guillemot, eider, king eider and harlequin duck, and secondly little auk, puffin, red-breasted merganser, long-tailed duck and light-bellied brent goose.

Development of methods to scare seabirds away from oil slicks would also be valuable.

Marine mammals

Whales and adult seals are not particularly vulnerable to oiling, mainly because they do not rely on their fur for insulation, but on a well developed blubber layer. Moreover, marine mammals may be able to avoid oil on the surface at least in ice-free waters. Seal pups are more vulnerable to oiling because they are dependent on their natal fur for insulation. Walrus are more vulnerable to oil spills than other seals because they are gregarious, usually stay in pack ice and they have benthic feeding habits.

If an oil spill is caught in leads and cracks in the ice, seals and whales may be forced to breathe air with toxic petroleum vapours. Whether the vapours can be sufficiently concentrated to harm marine mammals is not known. White whales (beluga), narwhals, bowhead whales, ringed seals, walrus and bearded seals in particular are at risk as their primary habitat is ice-covered waters.

In contrast to the other marine mammals, individual polar bears are very sensitive to oil spills. Oiling may disrupt the insulation created by the fur, on which polar bears rely in contrast to the seals and whales, and they may ingest oil from the fur when grooming.

Information gap: Harbour seal haul-out sites

The knowledge on temporal and spatial occurrence of marine mammals in Greenland is generally sufficient and adequate for oil spill sensitivity mapping and response. Particular gaps are related to harbour seal haul outs, whether they still are occupied or not, and to the exposure to and inhalation effects of petroleum vapours on marine mammal living in ice covered waters. In Avanersuaq and North East Greenland potential impacts on polar bear at the population level should also be considered.

Terrestrial environment

Fate, degradation and impact on soil microbial populations

Since inland spills are likely to be absorbed into the soil or the ice and snow, the most straightforward remediation is to physically remove the contaminated material. Aside from the complex question of the environmental impacts that this removal will have, and equally important aspect is the disposal of the contaminated materials. Transportation over large landmasses may not be acceptable depending on the time of the year and thus on site treatment must be considered. Depending on the concentration of the oil spill and the vulnerability of the area, the in-situ treatment may be either based on natural attenuation or the construction of a specially designed containment facility. Installation of such a facility can be quite complex and procedures need to be developed into site specific contingency plans, but often oil spills can be treated in situ by the controlled addition of fertiliser.

If a minor spill occurs in an area where sensitive species and groundwater contamination problems are not found, the option of not removing the spilled oil can be considered. But site specific research is needed to determine the optimal treatment procedure and to minimise contamination of runoff water with oil or nutrients during the summer melt. Oil and nutrients can be readily transported in streams to remote locations and the corresponding potential environmental impacts need to be assessed.

Information gap: Biodegradation potential

To assess the option of not removing the spilled oil research is needed to assess the biodegradation potential in these areas, since this will be the only major fate process affecting the oil. Microcosm experiments need to be performed to asses for the most balanced treatment technologies, at the same time stimulating the specific microbial communities without leading to high leaching of the added nutrients. In addition, oil can be readily transported in streams during summer melts to remote locations, especially to freshwater lakes. We have very little information on the biodegradation of oil in these environments and research is needed to determine at what rate degradation can occur in the different times of year. The most serious consideration is the potential nitrogen limitation that will occur if there is significant degradation. Adding nitrogen fertiliser is most likely needed but we need to know the response of the microbial communities to avoid or minimise secondary impacts, which could be more damaging than the oil itself.

It is therefore recommended that an integrated study is being performed assessing both the oil degradation ability on selected terrestrial areas in Greenland, as well as assessing the impact of fertiliser treatment on the microbial populations in the particular environmental sample.

Vegetation

Generally, effects on Arctic terrestrial vegetation from oil spill including both experimental applications and accidentally spills are better documented than effects on aquatic vegetation. These studies have documented large and lasting effects especially in dry habitats where recovery were not completed after 30 years. Cumulative impacts from persistent toxic compounds and increased sensitivity to other stresses like frost have been noted but experimental studies are lacking.

Information gap: Vegetation mapping

Sensitive vegetation and biologically important habitats need to be mapped in areas with oil exploration in order to protect these areas as far as possible.

Terrestrial birds and mammals

Despite the limited amount of relevant literature it is concluded that no important knowledge gaps exist relating to the Greenland situation. Terrestrial oil spills will only affect relatively small areas and it will be relatively easy to prevent terrestrial mammals to get in contact with oil spills. It is unlikely that terrestrial bird populations will get significantly impacted, as they are generally rather dispersed compared to the size of a terrestrial oil spill. However, local effects may occur. It is concluded that terrestrial oil spills in Greenland most likely only will have minor effects on the population levels of caribou, muskox and terrestrial birds.

1 Introduction

Oil exploration, production and transportation at sea presents a risk of accidental oil spills.

Oil exploration in the Arctic may present serious environmental hazards if a major oil spill occurs, particularly if the oil spill coincides with the occurrence of concentrations of ecologically important and vulnerable species in the ice or at the coast. However, because the impact of a spill depends on numerous more or less unpredictable events, which interact in a complex fashion, a high degree of uncertainty in assessing the potential impact of an oil spill is inevitable.

The ocean is stressed by a myriad of chemicals of anthropogenic origin, oil being one. The major sources of anthropogenic oil and oil derived compounds are chronic ones, such as tanker operations, sewage outfalls, urban runoff, and atmospheric outfall. In the 1980’s it was estimated that an average of 3.3 million metric tons of oil enter the ocean each year (Steering Committee for the Petroleum in the Marine Environment, 1985 National Research Council, Washington DC, p. 82). 45% of this input is believed to enter the ocean as a result transportation related activities with at least 22% intentionally released as a function of normal tanker operational discharges. Only 12% enters directly from tanker accidents. Another 36% come from runoff and municipal and industrial wastes including oil refineries and 8% is believed to be from natural sources such as oil seeps. Atmospheric outfall and offshore oil production account for the remainder of the annual input.

Nevertheless, accidental spills constitute a significant environmental threat because they imply a high oil concentration, even though the impacts will mainly be local or regional.

The natural degradation of oil in the Arctic will generally be slow due to low temperatures and the possibilities of recovery and the harsh climatic conditions and lack of infrastructure can hamper cleanup. Furthermore, if oil is spilled in broken ice, it will tend to pool in the open leads, and wind may keep it in the ice edge area. The leads and ice edges are utilised by high concentrations of birds and mammals during their northward migrations in spring.

Oil is toxic to almost all organisms. The toxic effect depends on the composition and concentration of the oil, and the sensitivity of the species affected. A species may have a high individual sensitivity and low population sensitivity if individuals are evenly or widely distributed and have a high reproductive capacity. This is the case for many species in lower trophic levels.

In order to assess and mitigate impacts of offshore oil activities in the Arctic region, knowledge of biological communities and major trophic structures within these communities is essential. Basic physical parameters, including predominant current patterns, should also be known, and it is important to know the natural variability of both the biological and physical system. Unique habitats and habitats especially susceptible to exploration and development activities must be identified. Special consideration needs to be given to rare or endangered species and the seasonal occurrence of migratory species. Socio-economic and cultural important biological resources must also be identified.

2 Fate and degradation of oil

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2.1 Introduction

We know that the fate of oil in cold environments is generally controlled by physical forces (dissolution, dispersion, volatilization and hardening) and biological processes (biodegradation, bioturbation, bioaccumulation) (Maregsin and Schinner 1999). Chemical processes, such as photolysis, can also affect the oil fate but they are generally unimportant in cold environments (Delille et al. 1998) and will not be considered here. We know that the most relevant fate processes are those that reduce problems associated with a.) physical effects such as coating of plants and animals or engulfing oil directly into the gut, b.) acute toxicity from low molecular weight alkanes and aromatics, and c.) chronic toxicity from exposure to PAHs. The fate of oil in most environments, including cold environments, is, therefore, a function of time required to reduce physical effects of the oil and to eliminate acute and chronic toxicity. We know that by far the biggest factor, in this regard, is the ratio of the surface area covered by the oil to the volume of the oil in a particular contaminated area (Short and Heintz 1997). In general, the higher the ratio value, the more effective fate process will become and the faster oil weathering will occur. This ratio varies enormously depending on the environmental conditions, weather, and the ultimate "resting place" of the oil. In this respect, cold environments are different only in that they are likely to have more storm activity, lower average temperatures, and ice. However, these three aspects are of great importance, as they significantly effect surface to volume ratios and consequently oil fate. That is, storm activities will accelerate the creation water in oil emulsions, temperature can greatly increase the density of oil, and ice will trap and transport oil in unpredictable ways.

Fate clearly depends on some acceptable end point. We know that in most environments, including cold water environments, approximately 70-90% of oil spilled will eventually disappear through a variety of fate processes. The residual may be of no further environmental consequence from the standpoint of acute or chronic toxicity. It generally takes months to years (2-4) to reach this end point. Not included in this time frame is oil that becomes sequestered, for example deep in sediments or in rock crevices, in which the surface area to oil volume ratio is very low. Oil in these situations will often have a chemical composition similar to the spilled oil (virtually no weathering), but the trapped nature of this oil greatly limits dissolution of hydrocarbons and minimizes direct exposure to biota. However, this oil does represent a potential chronic source of pollution and it should therefore be monitored if reasonable. Any evidence for long term chronic effects will always be confounded by oil exposure from sources other than the spill of concern. In cold environments, sequestered oil will be common due to both the geophysical complexity and inaccessibility of the shorelines, and the presence and formation of ice. Where it does become sequestered, weathering will be very slow due to the constant low temperature conditions.

Finally, a significant fraction of oil consists of a complex array of hydrocarbons that are high molecular weight, very insoluble and very slow to degrade. This fraction can be as high as 30%. Even under conditions where weathering processes are prominent, this fraction will likely change little in composition over extended periods. Under these conditions, the residual either hardens into an asphalt-like material, remaining in the contaminated area or it becomes particulate in consistency, eventually breaking apart and becoming dispersed by the physical action of waves and currents.

2.2 Physical factors

The importance of physical fate processes will be dictated by each of the major habitats potentially affected by oil; that is, open ocean, intertidal zones, shoreline and terrestrial.

Open Ocean Areas

In the open ocean, physical forces are the most prominent fate processes. Movement of spilled oil on the water surface can be rapid and controlled by wind and current. The oil slick will spread and begin to break up into patches. In cold water however, surface tension spreading is considerably slower than warm water due to a higher viscosity of the oil. Equilibrium thickness of oil in cold waters can approach millimeters rather than micrometers typical of warmer waters. In addition, the presence of ice will reduce spreading. Generally, wave action causes the oil to become emulsified and this increases its density and reduces its surface flow characteristics. As the oil adsorbs water, it becomes heavier than water and sinks. Wave action, of course, will be less important in areas receiving ice floes or freezing over.

Depending on the weather conditions, then, considerable portions of the oil will sink. We have little definitive information on the fate of the oil once sinking occurs, but we assume that it becomes widely dispersed and eventually settles on to the ocean floor. Oil can also adsorb to marine detritus which will then effectively disperse it in the water column, but this requires 10-100 mg/l particulate concentrations to have a significant effect (Lee and Page 1997). These concentrations would be common in areas where rivers would enter coastal areas, particularly if this involved glacial till.

Clearly, the longer the oil remains on the water's surface, the greater the loss of toxic alkanes and aromatic hydrocarbons will be due to volatilization. Generally alkanes up to C-12 will quickly evaporate, as will 1- and 2-ring aromatic hydrocarbons. However, where high oil film thickness of spreading oil is maintained, i.e., colder waters, evaporation will be considerably reduced (Singsaas et al. 1994).

Unique to cold water environments is the effect of ice. Oil can adhere to ice or be trapped in freshly formed ice and then transported over large distances due to movement of the ice. The behavior of oil in ice-infested waters is a complex phenomenon that is influenced by many different factors. For example, particulate ice can increase equilibrium spreading thickness by 2-4 fold (El-Tahan and Venkatesh 1994). Oil can also be emulsified by "pumping" of the oil between colliding ice floes (Singsaas et al. 1994). The shear forces involved can rapidly saturate the oil with water droplets. Cold-enhanced viscosity of the oil and entrapment by the ice will reduce spreading and sinking of the emulsified oil.

Estimates from a number of oil spills suggests that 1-13% of the oil will contaminate subtidal sediments in the vicinity of heavily oiled shorelines (Lee and Page 1997) but concentrations of hydrocarbons are generally low due to dispersion and dilution. The conditions necessary to produce high concentrations of hydrocarbons in the subtidal sediments requires large amounts oil in semi-enclosed areas along with high particulate matter concentrations to aid in the dispersion and sinking of the oil, conditions that relatively rare. The clay-oil flocs (emulsions) can also be spread out over significant areas and diluted by mixing with non-contaminated sediment. In some cases, oil may move into the subtidal area from the intertidal areas, but this occurs on a time frame of months (Qwens et al. 1987; Short et al. 1996). Clean up activities can also create emulsions and cause them to move into subtidal areas, as has been circumstantially observed from several oil spill clean up operations (*Amoco Cadiz*, Page et al. 1989; *Exxon Valdez,* Sale and Short 1995; O'Clair et al. 1996). There are reported cases where weather conditions physically forced oil into subtidal areas, even with middle distillate fuel oils where rapid evaporation of the hydrocarbons would normally prevent large contamination of the sediments (Ho et al. 1999; Saunders et al. 1980).

Weather conditions and shoreline topography will dramatically determine the effectiveness of engineered solutions for removing the oil. We know that in calm areas such as embayments and coves, floating booms can effectively contain the oil, often allowing considerable amounts of oil to be skimmed off the surface. Skimming becomes more problematical as the viscous water-in-oil emulsions form. To prevent oil from coming ashore, chemical dispersants (mixtures of solvents and detergents) can be applied. This requires turbulence to mix the oil with the dispersant and to produce the desired emulsification. Timeliness of application is critical and often the dispersant is unavailable in sufficient quantities to be used and/or the aerial application equipment is not available. Dispersants themselves can also be toxic to marine life (Burridge and Shir 1995; Singer et al. 1998), although this is not as much of a factor as it once was due to the design of more environmentally compatible dispersants. However, dispersed oil droplets are considered more toxic to marine organisms (Epstein et al. 2000). Thus dispersant use is best applied in areas with high dilution capacity. In general, as the oil approaches the intertidal areas, the toxicological possibilities increase and thus response planners must address environmental "trade offs" which are not as significant in scenarios further offshore (Aurand et al. 1999).

There have also been attempts to burn the oil on the water surface. Igniting the oil is always difficult, as is maintaining the fire long enough to remove significant quantities of the oil. However, estimates show that as much as 85% of the oil set afire will be removed with no significant enrichment of PAHs in the residues (Garrett et al. 2000; Smith and Proffitt 1999). Burning oil in place can be enhanced by low water temperatures, ice and snow, as these conditions maintain the oil at thicknesses that would support combustion (Guenette and Wighus 1996). Thickness, of course, will also depend on oil type, degree of evaporation, and the amount of emulsification. Otherwise, booms are required to keep the oil contained for optimal burning and there are a variety of commercial products that are available for this purpose (Allen 1999). Emulsions are increasingly difficult to ignite with increasing water content and evaporation.

There have been a variety of chemical additions proposed to change the physical characteristics of the oil and aid in its collection. A recent study, for example, has proposed using silicone based materials to solidify oil as an aid to physically collecting it (Pelletier and Srion 1999). A solution of polyoxyehtylenic surfactants, alkyl alcohols, and alkylchlorosilanes in light hydrocarbon solvent reacts on contact with water producing silicone polymer reaction products that " encapsulate" the oil. The polymer material can be recovered from the collected oil and recycled. However, the approach is probably only feasible on small patches of floating oil in relatively calm areas. Finally, it is well known that the additions of particulate material such as clay minerals to floating oil, causes the oil rapidly break up and become dispersed in the water column. This can be undesirable ecologically, in some circumstances, but there is also evidence that the oil associated with the particles has a much greater surface area to promote eventual biodegradation of the hydrocarbons (Weise et al. 1999).

Intertidal areas

In the intertidal areas, oil commonly sinks to the sediment, often covering wide areas depending on the weather conditions. In protected areas, wave action and currents will have little physical effect on the oil. In more exposed areas, the oil will spread over larger areas of the sediment bed. The mixing of the oil with sediment particles creates a situation where little further physical weathering will occur. Any physical cleanup is problematic since it may ultimately cause more harm than the oil itself.

Shoreline areas

Contamination of shoreline areas with spilled oil has received the most attention simply because it is more accessible than open ocean and intertidal areas. Oil tends to become distributed over sandy beaches and the surfaces of cobble and rocks. In general this means that wave and tidal action will have prominent physical effects, removing dissolvable components and loose oil, as well as " pounding" particulate material into the oil, changing its physical consistency and making it more easily dislodged. During vigorous winter storm conditions, physical removal of oil from shorelines may be quite rapid and extensive. Again, the surfaced area to which oil is exposed is very important. On sandy beaches oil can penetrate to as much as 1-2 meters in depth, depending on the amount of oil initially present. Oil below 0.25-0.50 meters will likely be unaffected by physical forces and little weathering can be expected. Oil that is above that depth and not removed initially, will likely weather into asphalt. Oil that penetrates into rock crevices will behave much in the same manner. Oil that contaminates marsh areas where vegetation is present, will likely remain a long time. These areas are often very protected from the physical action of waves and tides. Oil will penetrate deeply into the sediment of these areas and coat the surfaces of vegetation. In the latter case, this can enhanced further by weathering, particularly volatilization and the dissolution of soluble aromatic hydrocarbons. Physical dissolution of oil in these environments will be slow and minimal.

Again ice can be a significant factor affecting the distribution of oil in shoreline areas. Ice formation can trap the oil holding in shoreline areas for longer periods or moving it in large masses to new areas. In the latter case, this may be out to sea, which can be both good and bad. Theoretically, oil-trapped ice could be physically removed from the water taking the oil with it, but this may be operationally very complex. Ice will also moderate the effect of wave action during storms, reducing emulsification and spreading.

Inland areas

The fate of oil spilled on inland areas will be particularly problematic in cold environments because of snow and permafrost. On the other hand, land spills can be easily contained by constructing containment areas (dikes, impoundments, and physical barriers) around the spill areas and virtually preventing further spread. Accessibility to the spill areas by vehicles and earth moving equipment is generally quite high. The fate of oil from a physical standpoint will be primarily through evaporation. The lighter the oil, the more impact evaporation will have. Diesel oil applied to alpine soils in flask microcosm studies lost about 16-23% by evaporation in 20 days at 10°C in sterile controls (Margesin and Schinner 1997a). In a related study using pan microcosms, 30% of the diesel fuel evaporated after 155 days (Margesin and Schinner 1997b). Rates will of course be slower at freezing temperatures and with heavier oil, the later tending to be come more dense in cold temperatures. During summer months, snow melts and rain can potentially disperse oil laterally and horizontally. Oil can be essentially sequestered, often with little weathering, during the winter months due to snow and ice and then released during melts, almost as if was freshly spilled. The oil contaminated areas will, consequently, become a potentially long term source of oil slicks in the run off waters.

2.3 Biological factors

Biological factors that affect oil fate include biodegradation, bioaccumulation and bioturbation. The involvement of these factors will be very dependent on the type and number of species involved, the type of oil spilled, the physical conditions of the oil, and the environmental situation where the oil is located. We know from the standpoint of microorganisms, that hydrocarbon degraders are found in all cold water environments and in most cases they are cold adapted, showing optimal degradation from 15-20°C, but with significant activity at 10°C (Margesin and Schinner 1999). Most importantly these hydrocarbon degraders become enriched when oil is present, often becoming 1-10% of the total population. Each of these factors will be considered relative to the major habitats; open ocean, intertidal zones, shoreline and terrestrial.

Open ocean situations

In open ocean situations there is little time, especially with the more turbulent conditions often associated with cold environments, for biological activity to play much of a role in the fate of the oil except for the coating of birds and sea mammals and uptake by pelagic animals. There have been a few studies showing engulfment of oil particles but this is mainly a toxicological problem rather than a fate consideration. However, the sequestering of this oil in fecal material can act as a mechanism for enhanced settling of the oil (Clark and MacLeod 1977). Despite the ubiquitous presence of hydrocarbon degrading microorganisms in open ocean water, which in itself represents a cold environment (average temperature 4°C), their response to the presence of oil will be on the order of days to weeks, which is generally not enough time to have any significant effect on the oil. In addition, concentrations of nitrogen are likely to be quite low and thus degradation will be come limited quite quickly. Degradation will generally be slow enough such that oxygen does not become limiting. But as the oil weathers, it will form into particulate material that will sink and be distributed throughout the water column by currents. This particulate form can be colonized by oil degrading microorganisms, either from surface or subsurface microbial communities, and slow degradation will take place, even at considerable depths. Degradation rates, again, will likely be severely limited by nitrogen availability but they will not be insignificant and the degradation may eventually reduce the oil mass. Since this is a very difficult process to study, this fate component is largely deducted from inference.

With freshly spilled oil, lower molecular weight aromatic hydrocarbons (toluene, xylenes, benzenes, and naphthalenes) could be quite abundant and they will quickly dissolve into the water and be dispersed. Microorganisms that can degrade these aromatic hydrocarbons at low concentrations are known and their activities will likely remove most of the hydrocarbons from the water column (Roberston and Button, 1989; Geiselbrecht et al., 1998).

Attempts to introduce hydrocarbon degrading bacteria to oil floating on the sea surface (bioaugmentation) have been generally unsuccessful (Swannell et al. 1996). Logistics of application are very complex; large quantities of the organisms must be available in the first days to weeks of the spill and application at sea is easily adversely affected by weather conditions. In most cases, the inert carriers used with the microorganisms will have more initial effect on the oil, such as dispersal and sinking than the microorganisms themselves. Some have argued that the initiation of degradation of the dispersed oil carrying microorganisms will occur more quickly, thus giving the natural degraders a “head start” once they take over. However, nitrogen limitation will again be a prominent factor. Overall, there is no way to test the success of this approach.

We know little about the fate of the oil once it settles to the ocean bottom or into subtidal sediments, with or without microorganisms attached. Studies on subtidal sediments have shown that natural degradation will occur slowly (Lee and Page 1997; Ho et al. 1999) but whether this is helped by bioaugmentation is not known. In addition, in those sediments were oil occurs, increases in the number and mineralization activity of hydrocarbon degraders does occur. Again, these environments are mainly cold water habitats. In intertidal areas, oil can be found in low concentrations associated with the flocculent or nephloid layer (interface of the sediment bed and the overlying water), conditions that would greatly favor biodegradation. But this source of oil can be taken up by invertebrates and fish, as evidenced by hydrocarbon metabolites in their tissues (Collier et al. 1996). The entrance of hydrocarbons into the subtidal microbial communities can be inferred if there is an increase in hydrocarbon mineralization in sample taken from these areas (Braddock et al. 1995, Sugai et al. 1997). We know that PAHs in oil found in the subtidal zone will weather by the initial loss of the alkylated naphthalenes, probably through a combination of dissolution and biodegradation, and in some areas erosional transport of sediments away from the site (Ho et al. 1999). A 100 fold reduction in the ratio of the alkylated naphthalenes to the alkylated phenanthrenes and anthracenes (the naphthalenes being more susceptible to dissolution and biodegradation) occurred over 270 days. Concomitant decrease in the C-17/pristane and C-18 phytane ratios, indicated active biodegradation of the alkanes. Water temperatures during the initial part of the study were less than 10°C and there was no sign that increasing temperatures in the springtime affected the decay rate of the alkanes. Thus degradation in subtidal will probably occur in cold environments of Greenland.

Intertidal areas

In intertidal areas, particularly in protected bays and coves, the milder physical effects of tidal action and current could potentially allow greater time for natural biodegradation and bioaugmentation of the floating oil. However, many of the problems associated with open oceans would also apply here. Natural degradation will again be too slow for much effect and, although bioaugmentation is more operationally feasible, it’s affect may be to initially sink the oil and, in many intertidal areas, this would be quite undesirable. That is, oil that could be potentially recovered physically, such as by skimming, would no longer be available.

Much as in open seawater, intertidal waters are known to have significant populations of hydrocarbon degraders. Studies in the Antarctic have shown that if 200-l water samples are taken from these areas and incubated in containers in shore facilities under ambient conditions with added oil or diesel fuel, enrichments of the hydrocarbon degraders can be obtained and the positive effect of adding fertilizer can be seen (Delille et al. 1998). The interesting aspect of these studies is a comparison of ice-covered system to ice-free system. The presence of the ice clearly kept the number of hydrocarbon degraders about a factor of 10 lower than systems without ice, although a significant enrichment (4 orders of magnitude) occurred nonetheless. Ice reduced the amount of degradation by about 1/3 after sixty days of incubation, compared to ice free systems. Without fertilizer, very little degradation occurred in either treatment. The fertilizer used in this case was a liquid emulsion of oleic acid and urea (commercial name, Inipol EAP 22), which was designed originally for shoreline applications where it would adhere to and perhaps mix with, oil on rock surfaces and on sandy beaches. It’s stimulatory effect in these tanks studies was likely due to the containment of urea within the system, whereas in open sea water situations, the urea would be quickly dispersed away from the oil.

Oil that does reach intertidal sediments becomes rapidly mixed with particulate material and the surface-to-volume ratio increases considerably, thus potentially promoting more degradation. Mixing again is a function of weather conditions. There are two well studied oil spills in which wave action and bad weather conditions physically transported volatile number 2 fuel oil directly into intertidal sediments, with considerable acute toxicological effects (Ho et al. 1999; Sanders et al. 1980).

Because of shallower conditions in intertidal areas, water temperatures can be higher than offshore in the summer months and this will stimulate degradation of the hydrocarbons if nitrogen is available. However, only the top few millimeters of sediment will be aerobic. Although anaerobic degradation of petroleum hydrocarbons has been documented (Kropp et al. 2000), it is probably slower than aerobic degradation. Thus in most intertidal sediments, degradation will likely become oxygen limited. Adding fertilizers will potentially exacerbate the limitation. Thus, there is little one can do to enhance natural degradation in intertidal sediments. Natural degradation, however, will eventually reduce the hydrocarbon concentrations over an extended time period (months to years), but, of course, this will have little impact on the acute toxicological effects of the oil. Physical processing of sediment by certain invertebrate animals (bioturbation), can also have a pronounced effect on aeration of the sediments and degradation of the oil. However, in heavily contaminated areas, these bioturbating organisms may be initially killed and their effects on the oil will depend on recolonization rates (by polychaetes for example).

Many intertidal sediments also contain macrophytic plants. Oil covering the leaf material acts as a means of increasing the surface to volume ratio and, consequently biodegradation. In addition, plant activities can release organic compound and nitrogen that can further stimulate biodegradation.

Shoreline areas

The main biological factor that effects oil contaminated shoreline areas is biodegradation. Oil that covers rocks and stones, and that permeates into sandy beaches, is quickly colonized by hydrocarbon degraders, even in cold water environments (Venosa et al. 1996; Margesin and Schinner 1999; Swannell et al. 1996; Sugai et al. 1997; Pritchard et al. 1992). Tidal waters are responsible for the initial inoculation and they continually bath the oil, bringing oxygen and small amounts of nitrogen. In addition, oxidized degradation products are washed away. Degradation proceeds from the surface of the oil. The thinner the oil coverage, the more quickly it will be degraded. Degradation will remove 5-20% of the oil mass but in the process, the oil changes consistency and begins to physically weather, often leading to complete removal (not degradation) of the oil (Bragg et al. 1994). Where oil exists in pools or thick masses along the shore line areas, reduction in oil concentration will be slow and it is better to physically remove this oil first and use degradation as a finishing step on the remaining oil. Shoreline areas will be much more affected by air temperature, which means that in summer months, increased degradation activity can be expected. In addition, physical reworking of the oil due to wave action in the winter months and input of alternative carbon sources (algal biomass, plant litter, humic materials, etc.) will often positively effect the oil degradation activities (Sugai et al. 1997).

Because of the large amount of carbon available to microorganisms from the oil, significant increases in the number of hydrocarbon degraders will result and but they will become quickly limited by nitrogen availability. This can be overcome by the addition of fertilizer. Many studies have now shown convincingly that fertilizer addition does enhance oil degradation and successful enhancements have been observed in cold environments (Swannell et al. 1996; Margesin and Schinner 1999). The decision to use fertilizer will depend on a variety of factors, including the distribution of the oil in, or on, the shoreline environment and the net environmental benefit relative to other clean up options. Fertilizer addition is generally inexpensive, not man power intensive, and generally free from secondary environmental effects. A variety of fertilizer formulations (briguettes, granules, liquids, etc) are commercially available, each with some quality or trait that assists in keeping the fertilizer associated with the oil as long as possible (i.e., slow release of N and P). Considerable success has occurred with use of oleophilic fertilizers which are designed to, in essence, " dissolve" the nutrients into the oil (Pritchard et al. 1992; Venosa et al. 1996). The amount of fertilizer added is often difficult to estimate but a working range of a C:N ratio of 20-100 is often used (Swannell et al. 1996). The application of fertilizer in cold environments is probably going to be confined to the summer months because weather and ice conditions in the winters will make it logistically unreasonable. Hydrocarbon degradation rates will also be slower in the colder months and thus the potential for nitrogen limitation is lessened.

Adding fertilizer can potentially cause secondary ecological problems, as ammonia is toxic and algal blooms can be stimulated (Hoff 1993). We know that in cases where this has been studied in coastal environments, if controlled amounts of fertilizer are used, no blooms or toxicity will result. In fact, using fucoid brown macroalgae as a monitor, fertilization reduced oil toxicity (No. 2 fuel oil) because of enhanced bioremediation of the oil (Wrabel and Peckol 2000). However, few studies on the effects of fertilizer additions have been conducted in Arctic and Antarctic environments and secondary environmental effects could be more pronounced.

Inland Areas

For terrestrial spills, biodegradation of the oil would be a significant fate process and likely complemented by losses of hydrocarbons from volatilization and photolysis. There is little question that the ubiquitous presence of hydrocarbon degrading microorganisms in soil extends into cold terrestrial environments. Investigations have been made in the Arctic, Antarctica, and high altitude alpine areas (Margesin and Schinner 1999). Hydrocarbon-degrading microorganisms in these environments have clearly adapted to cold conditions, functioning as well as, and in some cases better, at 10°C as they do at 20°C. Optimal growth temperature for these psychrophilic organisms is between 10-15°, and although they will grow below 10°, rates are considerably reduced. This means that oil degradation will be extended over a period of 10's of years rather than months to a few years.

There have been a few studies of microbial oil degradation in Antarctic soils and hydrocarbon degraders are known to be present in these soils and they are enriched in oil contaminated soil (Aislabie et al. 1998; Wardell 1995; Tumeo and Wolk 1994; Delille 2000). These organism survive the freezing temperatures of winter and become active in the summer months, where temperatures can reach 20°C. Isolates from Antarctic soils have been shown to degraded alkane, methyl benzenes, and methyl naphthalenes (Kerry 1993; Aislabie et al. 1998). Aromatic degraders tended to be *Pseudomonas* and *Sphingomonas*, where as, alkane degraders were mainly *Mycobacteria*. Mineralization of hexadecane and naphthalene has also been observed (Aislabie et al. 1998). Similar studies have been performed in the arctic environments of northern Canada and considerable oil degradation capability was present in these soils, with the microbial communities being enriched in the presence of oil and stimulated by the addition of nitrogen (Westlake et al. 1974: Westlake et al. 1978). Nitrogen generally enhances degradation in contaminated areas (Kerry 1993; Aislabie et al. 1998). Phosphorous should not be limiting. Studies have also shown that alpine soils, and even glaciers, contain hydrocarbon degraders and this may be relevant to some areas in Greenland, since the alpine soils reach >10°C only in the summer months. Margersin and Schinner (1998) evaluated 20 different alpine soils and glaciers and found that both polluted and unpolluted samples contained hydrocarbon degraders and a substantial ability to degrade diesel fuel at 4 and 10°C . Clearly, bioremediation is a reasonable option as a clean up technology (Wardell 1995; Aislabie et al. 1998).

There has been one study of freshwater systems in Arctic environments. Enrichments of hydrocarbon degraders following gasoline spillage in Barrow Alaska showed that a degradative capability was present in waters where temperatures were between 0 and 5° C (Horowitz and Atlas 1977). Interestingly, almost 20 years later, these enrichments were still apparent, suggesting that the contamination was still present (Braddock and McCarthy 1996).

2.4 Important knowledge gaps

Open Ocean Areas

In open ocean areas, the significant knowledge gaps will be in a.) the effects of floating ice on oil distribution and physical clean up activities, b.) the physical and biological fate of oil that contaminates subtidal sediments and whether biodegradation will be significant, and c.) the environmental problems associated with the use cleanup technologies such as dispersant use and in situ burning and the problems of assuring the efficacy of new chemical treatments and commercial products.

Intertidal Areas

In the intertidal areas, more knowledge is needed regarding a.) the potential for biodegradation primarily by establishing that hydrocarbon degraders are present an that they will be enriched under typical local environmental conditions when oil is present, b.) the degree to which oxygen and nitrogen availability limit biodegradation and the mechanisms and time scale for re-supply of oxygen and nitrogen, and c.) the effectiveness of fertilizer addition in stimulating biodegradation of the oil, especially in regard to C:N ratios required, and the potential that the fertilizer might cause secondary environmental effects.

Shoreline areas

Since oil spilled at sea will likely move ashore at some point, knowledge must be gained in these areas to complement that obtained for open ocean areas. The knowledge gaps in the shoreline areas for biodegradation potential are the same as those for the intertidal areas, except that the influence of beach material (sand, gravel, rocks, ice) must be studied separately in order to develop some predictive capabilities. Since fertilizer application will be very realistic in these areas, experience with different types of fertilizers and their application methods must be increased. Likewise, the potential for secondary environmental effects will be significant and these effects should be characterized and assessed relative to local ecosystems and relevant environmental policies. There is also little information on how ice movement, or ice formation, effects oil distribution on shorelines and how if affects biodegradation.

2.5 Existing relevant research groups

R. Swannell - AEA Technology, Oxford, England.
R. Margesin - Innsbruck Univ., Innsbruck,Austria.
D. Delille - Observatore Oceanologique de Banyuls, Banyuls, France.
R. Prince - Exxon, Clinton NJ, USA.
J. Braddock - University of Alaska Fairbanks, Fairbanks AK, USA.
I. Singssas - SINTEF Group, Tronheim, Norway.
A. Venosa - USA Environmental Protection Agency, Cincinnati, Ohio.
K. Lee - Fisheries and Oceans Canada, Quebec, Canada.

2.6 Conclusions and recommendations

Physical Factors- As we have stated above, in coastal areas containment of an oil spill or clean up of the spilled oil will likely involve the use of either dispersants, ignition, specialty products, or perhaps combinations of all three. We recommend that an ongoing program be set up to evaluate these options and their related products, as there will be no time to do so at the time of the spill and local authorities are likely to be inundated by companies with products to sell at the time of a spill. One has to make some initial political/regulatory decisions as to which of these approaches is environmentally acceptable for Greenland waters (that is, dispersing oil at sea may not be tolerated) and it is hoped that the decisions will be made in collaboration with scientists as well as with commercial and industrial interests. Once decisions have been made, then available products need to be evaluated and tested for effectiveness in cold water environments and under the weather conditions considered typical of the exposed areas. Many products that are effective in temperate waters conditions will not work in arctic waters, in many cases because of the presence of ice and severe weather conditions, both of which may dramatically disrupt application methods. This information needs to be at hand prior to any spill. In addition, products are continually being developed and refined and thus a program should be set up to keep track of these developments and then perform appropriate tests for effectiveness and potential adverse environments effects.

Since inland spills are likely to be absorbed into the soil or the ice and snow, the best remediation is to physically remove the contaminated material. Aside from the complex question of the environmental impacts that this removal will have, and equally important aspect is the disposal of the contaminated materials. Transportation over large landmasses may not be acceptable depending on the time of the year and thus on site disposal in a specially designed containment facility must be considered. Installation of such a facility can be quite complex. Protocols and procedures need to be research and developed into contingency plans.

In remote areas, the absence of exposure to environmentally sensitive species and the absence of groundwater contamination problems, allows one the option of not removing the spilled oil. But research is needed to determine the potential for contaminating runoff water during the summer melt. Oil can be readily transported in streams to remote locations and the corresponding potential environmental impacts need to be assessed. In addition, methods for containment need to be addressed and these need to be certified for these types of environments.

Biological Factors- It is important to have an assessment of the potential biodegradation response to spilled oil in Greenland habitats prior to any spillage events. This information will help convince authorities that degradation, both natural and engineered (bioremediation), will be a significant clean up tool following the initial efforts to physically remove spilled oil. We recommend that degradation options only be considered as a follow up to the physical removal phase because removal of bulk oil and spreading residual oil over greater surface areas will greatly increase the short term effects of biodegradation. To gather this information, we recommend that microcosm studies be conducted using samples of water, inter- and subtidal sediments, beach material, and terrestrial soil from Greenland, to test for the ability of the indigenous microbial populations to degrade hydrocarbons. We have little doubt that hydrocarbon degradation activities will be present in the samples, but it is important to have some perspective on how responsive these populations will be. Thus microcosm studies should be conducted to simulate the environmental conditions where each of the samples was taken and oil should be added to the microcosms in a manner that will mimic the likely distribution of the oil in the samples. We assume that there will be a lag before degradation occurs because of the time required for the hydrocarbon degraders to become enriched within the populations will take days to weeks. The length of this lag will give an approximate idea of how rapidly the microbial populations in the different Greenland environments will respond, and thus help in cleanup decisions. Tests should be run at 4, 10 and 15 °C to get the minimum and maximum responses. Degradation at temperatures around 4 °C will almost certainly occur but only at slow rates and therefore the contribution to clean up may be much longer term (years). Once degradation is apparent, duplicate systems should be spiked with nitrogen fertilizer. This assumes that nitrogen will become limiting once degradation commences and it will verify that nitrogen addition will stimulate further oil degradation. It is not necessary to test for the effects of different types of oil, since we know that degradation can occur, we can extrapolate from previous studies in Arctic and temperate systems the effect of oil type. In addition, the pattern of hydrocarbon degradation is likely to be very consistent between Arctic and temperate environments and thus the literature can be used to obtain appropriate information.

In the coastal environments of Greenland, the physical forces associated with the severe winter storms will quite likely " pound" glacial till into the oil, effectively increasing surface area considerably. As temperatures rise in the summer, accelerated degradation can be expected and nitrogen will almost certainly have to be added. We recommend that microcosm studies also are conducted to mimic this infusion of glacial till and to validate the possibility of enhanced degradation.

Assuming that the addition of fertilizer to stimulate oil degradation will be contemplated at some time, investigations into the type of fertilizer to be used, should be conducted. There is a high probability that an oleophilic fertilizer will be of high interest, since these materials are simple to apply in remote areas, documented to be effective even in arctic conditions, and they are least likely to be washed away from the oil. Therefore microcosm studies should be conducted with the oleophilic fertilizer of choice, to assure oneself that it will work in Greenland waters. That is, no efficacy testing needs to be conducted at the time of the spill. The microcosms can also be used to screen for the most effective fertilizer. Some information can also be obtained on the amount of fertilizer to add, but this is often confounded by the realities of application methods in the field. That is, covering the oiled areas as best possible using the minimum amount you can, will probably be the practical method. Oleophilic fertilizers can also have side effects, such as ammonia toxicity and a potential of dispersing the oil off of environmental material into the surrounding waters. Assessments should therefore be conducted to prepare for the eventual use of the fertilizer and that may include toxicity testing with appropriate regional species and physical-chemical studies. The resulting information should be reviewed by regulatory authorities to make sure they are " on board" .

In the Greenland environment, it is very likely that an oil spill will lead to long term contamination of certain environments, just simply due to the effect of winter conditions. As a result, one should develop strategies for long term monitoring programs to assess oil weathering. This would consist primarily of performing chemical analyses on oil composition using GCMS methods.

Oil contamination from drilling in wetland and intertidal areas will negatively impact many of the invertebrate animals present. However, as the opportunists begin to dominate and it is not clear if this will affect bioturbation, a process that may assist in the more rapid degradation and dispersal of the oil. Greenland waters will likely have a unique community composition in this respect and thus it is necessary to research the bioturbating communities in these environments and see if there is a different processing regime than that studied in more temperate areas.

In remote areas, the absence of exposure to environmentally sensitive species and the absence of groundwater contamination problems, allows one the option of not removing the spilled oil. Consequently research is needed to assess the biodegradation potential in these areas, since this will be the only major fate process affecting the oil. Microcosm experiments need to be performed as described above. In addition, oil can be readily transported in streams during summer melts to remote locations, especially to freshwater lakes. We have very little information on the biodegradation of oil in these environments and research is needed to determine if degradation can occur in the summer months (we are assuming that freshwater environments will be completely frozen over in the winter). The most serious consideration is the potential nitrogen limitation that will occur if there is significant degradation. Adding nitrogen fertilizer is possible but we have little idea of secondary impacts, which could be more damaging than the oil itself.

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3 Effect on microbial populations

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3.1 Introduction

Prokaryotes dominate many arctic environments and play major roles in food chains, biogeochemical cycles and the mineralisation of pollutants such as oil spills. Further prokaryotes can have beneficial or detrimental effects on other groups of organisms including vegetation, invertebrates and fish. The changes of microbial communities in aquatic environments must thus be considered with great care, since general changes in important groups of microorganisms might be followed by changes in the higher populations.

3.2 Impact on aquatic and shoreline microbial populations in general

However, the impact of oil spills on microbial populations in arctic aquatic environment is closely related to the fate and degradation of oil compounds, since microbial populations is the major players in oil degradation. Microbial activity leading to the degradation of oil spills will consequently lead to changes in the composition of the microbial populations, the more successful the degradation the more drastic changes can be expected. In general successful bioremediation of hydrocarbon contamination includes the stimulation of the microbial populations by optimising nitrogen (N) and phosphorus (P) supply ratio conditions, these changes is generally believed to stimulate hydrocarbon degrading biomass and the changes will further influence composition of the microbial communities (Smith et al. 1998). A number of studies have examined biodegradation of hydrocarbons in Arctic environments for a relatively recent review see Swannell et al. (1996), but these studies have not been addressing the changes in microbial populations.

With the appearance of the newer molecular methods to describe changes in microbial populations a more robust determination of microbial diversity has been launched, for review see Johnsen et al. (2001). A study of changes in microbial populations after an experimental oil spill on a rocky beach in Delaware USA (Macnaughton et al. 1999) has demonstrated a community shift from primarily eukayotic biomass to gram-negative bacterial biomass with time. These results were obtained using the phospholipid fatty acid (PLFA) analysis, and more detailed analysis of populations changes within the prokaryotic biomass were based on 16S rDNA PCR-denaturing gradient gel electrophoresis (DGGE). The DGGE analysis revealed that at the untreated control plot a simple, dynamic dominant population structure were found throughout the experiment. In contrast this banding pattern disappeared in oil contaminated samples, indicating that the structure and diversity of the dominant bacterial populations changed drastically. The oil spill stimulated growth of gram negative bacteria within the group of alfa-Proteobacteria, and these changes were found to remain.

In a study describing the microbial ecology changes following the 1997-tanker accident in the Japan Sea the microbial populations have also been analysed using DGGE. In this study no control plot analysis could be used to compare the oily samples, but the same general group of bacteria (alfa-Proteobacteria) were found to dominate the contaminated watersamples (Kasai et al. 2001). The group further found that the bacteria present in the oil paste samples belonged to types related to hydrocarbon degraders, exemplified by strains related to *Sphingomonas subarctica* (Kasai et al. 2001).

Impact on aquatic and shoreline microbial population in arctic or Antarctic

To our knowledge no studies on oil effects on diversity of microbial populations has been recorded in the Arctic or Antarctic environments. In connection with the Exxon Waldres oil spill studies on microbial populations were undertaken using only total counts of cultivable heterotroph microorganisms and count of cultivable oil degrading microorganisms (Lindstrom et al. 1991). They found that total numbers of bacteria did not shown any changes and that a slight increase was observed on the numbers of oil degrading microorganisms. However today this is not that surprising since the total numbers of bacteria are fairly stable irrespective of most stresses

The response in general microbial activity was however investigated in connection with the Bahia Paraiso grounding near Palmer Station, Antarctica in 1989 in which 6800 hectolitres of diesel fuel were released (Karl 1992). This study found that the acute effect on the metabolic activities of sedimentary microorganisms were negligible even at seawater saturation concentrations with the fuel. On a long-term (120 days) diesel fuel exposure trial a significant decrease was reported in total ATP from sedimentary microorganisms, while contradictory no or only a slight effect was seen on metabolic activity and production. Karl (1992) further reports those sedimentary organisms in contrast to planktonic microbial communities showed positive response to increased temperatures and Karl speculated that this might influence the reported low rate (0.13 - 0.21 pmol g^{-1} sediment dry weight day^{-1}) of diesel fuel degradation in a positive way.

Knowledge gaps

Studies of the diversity of microbial populations including immediate response and long time resilience following an oil spills in arctic environment is missing on a worldwide scale. The study of microbial ecology in these environments has mainly been focussing on the ability of the micro-organisms to degrade oil compounds, however specifically searching, such research carried out in water bodies and shoreline around Greenland is practically non existing.

The role of microbial populations in degradation of oil spills in arctic waterbodies and shoreline will be important in the assessment of possible long term consequences following the strong turbation of the microbial communities that will follow an accidental oil spill in these areas.

The level of knowledge is limited on how oil spill affect microbial populations and in particular if any treatment techniques, that can be expected brought into use, will have strong influence on the resilience of microbial communities. It is therefore recommended that an integrated study is being performed assessing both the oil degradation ability on selected coastal areas in Greenland, as well as assessing the diversity of the microbial populations in the particular environmental sample.

Research groups and knowledge centres

No research is carried out on how oils spills affect microbial populations in Greenland. The research group of Professor Vigdis Torsvik in Bergen has been working on an EU-founded project on microbial ecology in arctic environments. In the framework of the NorFa system Prof. Torsvik is currently heading an application for travel grants to stimulate the discussion on consequences of pollution on Arctic microbial populations, the application involves scientist from Sweden, Norway, Finland and Denmark. GEUS with Carsten Suhr Jacobsen participates in this application.

Research coordinator Parmely Pritchard at DMU MIBI has a background as scientific coordinator on the US-EPA task force on the Exxon Valdes oil spill in Alaska. Concerning general microbial ecology of the open waters in the arctic waters around Greenland Dr. Mathias Middelboe from University of Copenhagen has recently performed extensive measurements of general microbial ecology.

3.3 Impact on terrestrial microbial populations

Bioavailability of oil compounds differs considerably with soil composition. Depending on the type of oil up to more than 99% of the compounds might be sorbed to the soil particles especially to the organic parts of the soil. This low bioavailability will indeed reduce the acute impact of the oil on soil living organisms. However the high sorption/low bioavailability will increase the exposure time.

Microbial populations are typically affected in various ways during the spilling of oil compounds on soil. Of primer interest is the impact on the populations of oil-degrading microorganisms. By comparing contaminated and non-contaminated soils several authors have shown that the microbial populations in contaminated soil has a higher number of mobile genetic elements - as plasmids - then non contaminated soils (Campbell et al. 1995). These plasmids often carry resistance genes or genes, which - if they are expressed - are responsible for degradation of the organic contaminant. Looking at changes among cultivable microorganisms the numbers of specific oil-degrading microorganisms will increase while the total numbers of microorganisms typically not alter (Andersen et al. 2001). While the total numbers of cultivable bacteria as measured on 1/10 TSA or other general media not increase above the background level, selected species of bacteria increase more than others groups. One example on this is the *Pseudomonas* sp. bacteria, which have been found to increase in oil-contaminated soils (Andersen et al. 2001). In general we will probably never know exactly which groups of cultivable microorganisms that will increase after exposure to oil compounds, however among those bacteria that are known to be stimulated by contamination with fast growing bacteria like *Pseudomonas* sp.

As reported in the section on impact on aquatic environment the assessment of diversity changes among microbial populations in contaminated environment has in the recent years received powerful tools (Johnsen et al. 2001). One such example is the analysis of genes that encode enzymes responsible for key steps in the degradation of oil compounds. Guo et al. (1997) found increasing levels of these genes in soil treated with gasoline. Guo et al. (1997) worked on experimental spills and found the threshold level to be it to be lower than 0.5 mg g^{-1}. The increase in genes coding for gasoline degradation is transient.

Only very few studies have described general changes the microbial populations. In one such study it was found that the total number of cultivable bacteria in the soil was unaffected by oil contamination but diversity of the bacterial community as measured by DGGE analysis revealed a decreasing diversity after exposure to hydrocarbon (Duate et al. 2001).

A decreased microbial diversity could disrupt ecosystem dynamics leading to a less robust organic matter mineralisation, however Nyman (1999) reports on a stimulatory effect of crude oil and several additives on microbial activity in two fresh marsh soils. The activity in several plots did increase after addition of crude oil and nutrients to the soil leading to a higher level of remineralisation of soil organic matter. That simultaneous addition of oil and nutrients gives a stimulation of microbial activity is in accordance with previous findings, as discussed in the application of the resource-ratio theory to hydrocarbon biodegradation (Smith et al. 1998).

Impact on terrestrial microbial population in Arctic or Antarctic

Compared to other terrestrial environments the microbial biomass in many arctic ecosystems contains high amount of nutrients compared to the pools in the plant biomass. This is due to the large nutrient-containing organic deposits in the soil and low plant biomass (Jonasson et al. 1999). In case fertiliser containing N and P is spread on arctic soils the microbial biomass will only increase the pool of microbial N if an easy assessable source for C is available.

The hydrocarbon can serve as such a carbon source since all of 18 soils tested from the arctic part of Canada prowed ability to mineralise hydrocarbons if supplied with nitrogen and phosphor nutrients (Mohn & Stewart, 2000).

Microbial activity in a jet-fuel contaminated soil in Alaska was found to be stimulated by the addition of nitrogen to the spill site. The jet fuel spill was 25 years old and nitrogen was found to be the major limiting nutrient in the system, but the best stimulation of microbial activity was found with the addition of both nitrogen and phosphor (Braddock et al. 1997). The addition of different levels of nutrients (i.e. 100, 200 and 300 ppm N, with additional 45% P) showed the highest stimulation of the microbial activity occurred with the lowest addition of nutrients. The authors suggest that an understanding of nutrient effects at a specific site is essential for successful bioremediation (Braddock et al. 1997).

A polyphasic microbial community analysis of the community structure in two northern Canadian soils contaminated with petroleum hydrocarbons was performed using both culture dependent (BIOLOG GN) as well as direct DNA based techniques (DGGE clone sequencing) (Juck et al. 2000). The analysis revealed that the microbial diversity were more differing from site to site than the change in diversity that were recorded between the contaminated and non-contaminated samples. In the contaminated samples the predominant bacteria that was found belonged to the high G-C grampositive *Actinomycetes* sp. (Juck et al. 2000).

The microbial communities involved in the degradation of contaminants in arctic soils have been shown to be adapted to the degradation at low temperatures. By comparing the mineralisation of biphenyl at 30° and 7°C, this compound was mineralised equally effective by arctic soil microbial communities, while poly chlorinated biphenyls were much lesser degraded at the lower temperature (Mohn et al. 1997).

Knowledge gaps

In contrast to aquatic and shoreline environments studies of the diversity of microbial populations including immediate response and long time resilience following oil spill in terrestrial arctic environment has been performed in Canadian samples. However the study of microbial ecology in these environments has mainly been focussing on the ability of the microorganisms to degrade oil compounds.

Specifically searching, such research carried out in terrestrial environments in around Greenland is practically non-existing. The composition of the microbial communities in relation to distribution and activity of genes coding for oil degradation needs to be described in order to understand these natural soils ability to degrade oil spills. Further it is not known to what extend the microbial populations will respond to the addition of fertilisers in order to balance the degradation of the spilled oil with the minimal input of inorganic fertilisers in the vulnerable environments.

Like in the aquatic and shoreline environments the role of microbial populations in degradation of oil spills in arctic terrestrial environment will be important in the assessment of possible long term consequences following the strong impact on the microbial communities that will follow an accidental oil spill in these areas.

It is therefore recommended that an integrated study is being performed assessing both the oil degradation ability on selected terrestrial areas in Greenland, as well as assessing the diversity of the microbial populations in the particular environmental sample.

Research groups and knowledge centres

No research is carried out on how oils spills affect microbial populations in Greenland. The research group of Professor Vigdis Torsvik in Bergen has been working on an EU-founded project on microbial ecology in arctic environments. A collaborative group on consequences of pollution on Arctic microbial populations is being established between Prof. Torsvik (Bergen Norway); K. Lindström (Helsinki, Finland), B. Matiasson (Lund, Sweden), C.S. Jacobsen (Copenhagen, Denmark). The understanding of microbial and plant interactions in arctic soils are currently studied by the group at Department of Plant Ecology, University of Copenhagen (Anders Michelsen and Sven Jonassen).

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4 Impact on vegetation

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4.1 Effects in coastal and marine ecosystems

The pelagic ecosystems

Direct documentation of effects of oil spills on the marine primary producers i.e. the phytoplankton is very sparse. From studies at lower latitudes, it can be concluded that the damages of oil spills to phytoplankton are likely to be limited both in extent and in time. The relatively low concentrations of toxic oil compounds found in the productive surface layers of the water after an oil spill have in some cases stimulated rather than hampered the primary production (Gordon and Prouse 1973, Johansson 1980) and the major negative effects documented in laboratory studies (see reviews by e.g. Vandermeulen and Ahren 1976, O'Brien and Dixon 1976, Johnson 1977) have not been verified in *in situ* studies.

The special features of the Arctic seas, however, may increase the sensitivity to oil spills. The Arctic pelagic ecosystem is characterised by few species occurring at high densities and biomasses during the short production season. The production sequence along the ice edge starts in the north with modest phytoplankton prebloom under the ice followed by an intensive surface bloom along the edge of the melting ice, and finally a postbloom of deeper layers of water during the summer. The most important ice edge bloom algae are diatoms, whereas flagellates dominate during the summer. Laboratory studies have shown a species specific response to toxic oil compounds (Mahoney and Haskins 1980, Daling and Davenport 1982, Dahl et al. 1983) but sensitivity studies with dominating Arctic species are lacking. And even the indirect effect from shading by the oil slick may be critical to the Arctic ecosystems if it happens during the very short bloom period. Moreover, the strong lipid transfer by the food chain from phytoplankton to higher trophic levels often referred to as the 'lipid wave' (e.g. Falk-Petersen et al.1990) may increase toxicity of the strongly lipophilic oil compounds.

Benthic communities

Contrary to the rapidly reduced concentrations of open waters, the coastal communities may be exposed to heavy and lasting contamination from oil stranding. Due to frequent ice scouring the polar intertidal zones are generally poor and transitory by nature. The effects of stranded oil to such areas may be regarded as just another instance of the recurring natural disturbances. The toxicity and persistence of the oil may, however, prolong the 'barren' period and prevent or reduce the potential for recolonization. The investigations of the massive contamination of Arctic coastal areas after the Exxon Valdez crude oil spill in Alaska showed survivors of a few species mainly seaweeds on the most heavily impacted shores and a strong recovery potential of the shoreline communities through recruitment from nearby unaffected sites. Two years after the spill most oiled shores appeared healthy and recovered to the pre-spill community (e.g. Stocker et al. 1992, Dean et al. 1996, van Tamelen and Stekoll 1996).

However, biologically rich Arctic salt mashes may be found at protected sites and such areas may be expected to be much more sensitive to contamination (Baker 1971, 1979). Therefore, it seems important to map the occurrence of such sensitive areas.

Conclusion and recommendations

Most of the knowledge of ecological effects on aquatic vegetation originates from assessment outside the Arctic climate zone or from laboratory studies with species that are not dominant within the Arctic. Generally, the results point out only limited effects. However, sensitive studies with relevant species and *in situ* studies are needed to get a better indication of effects in Arctic aquatic environments.

Some ecologically important Arctic ecosystems, like salt marshes and meadows, are expected to be sensitive to oil spills and the occurrence of these habitats need to be mapped.

4.2 Effects in freshwater ecosystem

Published assessments of the ecological effects of oil spills in Arctic freshwater ecosystems are still limited. Experiments by Snow and Scott (1975) and Helleburst et al. (1975) indicate that the direct toxic effects on microphytes (algae) are limited but secondary effects resulting in both increased and reduced primary production are reported (Robertson 1998). The effects on freshwater macrophyte communities may, however, be widespread and severe but most experiences originate from cold temperate regions. Some studies have shown that perennial plants, including growth forms such as emergent, surface floating and submerged plants, are more tolerant to and recover more rapidly from oil pollution than annuals (Burk 1977). Moreover, the effects are less severe in running water like rivers compared to more stationary water e.g. lakes and ponds (Baca et al. 1985). Barsdate et al. (1980) found that experimental application of oil to tundra pond vegetation resulted in limited damages when only stems were contaminated but more severe and lasting damages when leaves were contaminated.

4.3 Impact on vegetation in the terrestrial environment

Reported damage of oil to terrestrial vegetation varies considerably from one spill to another.

Resistance and toxicity:

Wein and Bliss (1973) found that all actively growing plant tissues were destroyed in Arctic wetland plant communities. Mosses were eliminated almost entirely, whereas sedges recovered rapidly. Similar results were found by Freedman and Hutchinson (1976).

Many observations indicate that refined oil products are potentially more toxic to plant cover than crude oil (McCown et al. 1972, Lawson et al. 1978, Walker et al. 1978). This was also demonstrated in an experimental application of crude and diesel oil to different plant communities including wet marsh, grassland, and three types of dwarf shrub heath at Mesters Vig in Northeast Greenland (Holt 1987). The spills were seen to have an immediate effect. During the first week after the treatment the vegetation started to show damage by turning yellow and brown, losing chlorophyll or abscissing leaves. Species with xeromorphic leaves generally reacted more slowly to the application than species with orthophyllous leaves. Forbs showed the greatest susceptibility in all sites. Graminoids showed some resistance at the mesic sites but were killed at the dry sites. The shrub least susceptible was Salix arctica. Lichens appeared to be killed by diesel oil at all sites. Wet and mesic conditions seem to favour resistance (or decrease exposure?) compared to dry or xeric sites. The total vegetative cover decreased most drastically in the driest sites where oil could penetrate to the roots.

Sensitivity of the plant species to oil pollution to some extent is related to the type of root system they possesses (Johnson et al. 1980). Generally, a vertical rooting strategy versus a shallow minimises the amount of biomass that is in contact with the oil. Arctic plant communities are thought to have a ‘root biased’ physiognomic structure (sensu Pickett and White 1985) which in turn determines the resistance and the resilience of the system. Plants with shallow, sparsely developed root systems are expected to be more vulnerable (Klokk 1986) than those having a well-developed stock root (Baker 1979). Deneke et al. (1975) report examples of species with stock roots being sensitive to oil, presumably because they are incapable of regrowth by root ramification to uncontaminated soil. The lower rate of immediate killing for plant species growing at waterlogged soil could be due to the protection of the below-ground biomass by the water. Hutchinson et al. (1976) also found that survival is often a result of stage organs being located underground and away from the toxic hydrocarbons, which are largely surface contaminants at waterlogged soils. Several observations show that oil exposure limited to aboveground parts, such as in a spray spill, may result in severe but generally short-lasting damages because resprouting from protected plant parts can occur (Wein and Bliss 1973, Freedman and Hutchinson 1976, Walker et al. 1978, Johsnon et al. 1980). Much longer-term impacts may occur if the oil penetrates the soil and resides in the root zone.

Cumulative injuries were noted in a few species e.g. some shrubs during the following season after application (Holt 1987). This may be due both to persistent toxic compounds or increased sensitivity to other stresses like frost or lack of water. Johnson et al. (1980) also noted slow killing and described three main frames for injuries: immediate, occurring during the season of application, and cumulative, occurring after the season of application. McCown et al. (1972) concluded that when soil is contaminated with oil at sublethal levels, plant deterioration will continue to increase over at least two successive seasons due to increased sensitivity to stress during winter.

Wein and Bliss (1973) found a highly significant difference in resistance with season of application.

These effects are often due to declines in plant nitrogen content, reduced viable root biomass, and changes in mychorrhizal structure (Linkins et al. 1985). Increased root biomass and other functional changes in the root system have been reported as adaptations to long-term oil exposure (Linkins et al. 1985).

Recovery and invasion:

The ability among different plant communities to recover from crude and diesel oil spills seems to be determined by several interacting factors: 1) the sensitivity of the species to toxic effects, 2) moisture conditions at the site, 3) exposure to secondary stress such as desiccation, frost or snow abrasion, and 4) the duration of the latent toxicity. Generally, the environmental impact on Arctic organisms and ecosystems is similar to those observed within other climatic zones, the bioavailability of toxic substances and biological recovery following damages, however, are expected to be different. The recovery time increases with increasing degree of latitude. This has also been demonstrated within the Arctic when going from low Arctic to high Arctic ecosystems (Forbes et al. 2001).

Short-term recovery

The species diversity of vascular plants was reduced significantly the year after oil spills, particularly in plots treated with diesel oil. The total vegetative cover decreased most drastically in the driest sites where the oil could penetrate to the roots. Mosses and shrubs showed a better short-term recovery than forbs. Mosses showed better recovery in the mesic and wet sites than in the drier sites. On a few occasions tissues earlier coated with oil showed ability to recover during the first growing season. Within three years shrubs and herbs that have been exposed to diesel oil spills showed virtually no sign of recovery. Graminoids showed slight recovery in all mesic and wet plots. Mosses recovered to some extent in all plots although recovery was poor at the dry sites.

Long-term recovery

Plots treated with crude oil generally showed a better or nearly equal recovery compared to plots treated with diesel oil eleven years after application (Bay and Strandberg 1994, Bay 1997).

A combination of oil toxicity and altered edaphic factors most probably affects plant regrowth and seedling establishment after oil spills. According to references given by Linkins et al. (1984) the residence time of toxic oil fractions in tundra soils may be very long, up to 30 years. Long-term decline or lack of revegetation after oil spills is believed to be caused by oil-associated changes in edaphic factors influencing plant regrowth (Everett 1978).

Revegetation studies along the Trans-Alaskan-Pipeline have shown that tundra recovery after oil spill may be enhanced (Brendel 1985). Heavy application of fertilizers with high nitrogen and phosphorous content combined with soil tilling gave good establishment of sown grasses. Soil content of oil appeared to be reduced significantly through fertilization and aeration.

Conclusion and recommendations

Generally, effects on Arctic terrestrial vegetation from oil spill including both experimental applications and accidentally spills are better documented than effects on aquatic vegetation. These studies have documented large and lasting effects especially in dry habitats where recovery were not completed after 30 years. Sensitive and biologically important habitats need to be mapped. Cumulative impacts from persistent toxic compounds and increased sensitivity to other stresses like frost have been noted but experimental studies are lacking.

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5 Impact on invertebrates

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5.1 Introduction

Accidental oil spills in the marine coastal environment often result in coating of the shoreline with oil, leading to immediate and readily detectable impacts to the biota. Impacts of spilled oil are less obvious to nearshore subtidal invertebrate populations and habitats because these are out of sight. "Even though invertebrate communities are predictable recipients of spilled oil, and often suffer at least as much as birds and mammals, the "cuter" furry and feathered animals typically occupy most of the 30 sec video bits dedicated to media coverage of spectacular oil spills" (Suchanek 1993). Adding to the lacking public perception and legislative attention to marine invertebrates is the fact that despite decades of research there is still insufficient information to evaluate population and community level changes in invertebrate assemblages in order to determine and predict adverse long term effects of an oil spill. Another major factor impeding scientific progress is the difficulty associated with the pollution (i.e. effect) measurement. Often little pre-spill data exist on invertebrate community structure and dynamics as well as the chemical composition of the site in question. This makes it difficult to document and predict long term changes in population levels or shifting relationships between different species.

This chapter provides a general overview on impacts of oil spills on marine invertebrate communities and populations with as much attention as possible given to arctic conditions in the limited space available. For excellent reviews on the effect of oil spills in general see Clark (Ed.) (1982a, b), Suchanek (1993), Lee & Page (1997), and (Danovaro 2000). Further information on effects can be found in reports from some of the major oil spills during the last three decades (Sanders et al. 1981, Elmgren et al. 1983, Ho et al. 1999, Jewett et al. 1999b, Gesteira & Dauvin 2000, Peterson et al., 2001).

5.2 Oil spills in marine habitats

The fate of an oil spill is complicated and depends on such factors as chemical composition of the oil, sea state, wind speed, temperature, the geology of the sea floor and shore line, and biological activity at the site of the accident. Crude oil in the coastal environment typically breaks into three major components; a volatile component, a floating component, a sinking component (Suchanek 1993). On a short time scale (days to weeks) the lower molecular weight components of the oil tend to evaporate or dissolve and/or becomes photochemically degraded. This volatile component usually constitutes 20-50% by volume (sometimes even as much as 100%) depending on the type of oil. If the sea surface is calm an oil spill initially forms a slick which is subjected to physical processes such as advection and turbulence. Advection aids in dispersal of the oil and turbulence can form emulsions of the floating component often termed ‘chocolate mousse’ which eventually turns into tar balls. This mousse is the fraction that typically affects seabirds, marine mammals and which is eventually transported on shore by currents and wind. The oily mousse reduces the insulative and flotation function of fur and feathers for vertebrates, but it also suffocates invertebrates. The floating nature of this fraction together with the limited mobility of most shoreline invertebrates, means that intertidal communities are especially vulnerable. Studies on oil spills indicate that the mousse affects most taxa indiscriminately and that most organisms covered by such oil are typically killed on a time scale of days to weeks after the spill. The loss of low molecular weight components due to evaporation increases the density of the remaining material so that it sinks rapidly in normal seawater (Kolpack et al. 1978). Nearshore subtidal zones, and especially soft sediment environments in protected bays which are settling areas often serve as reservoirs of oil that persists for long periods of time (Page et al. 1995). The sinking component of oil degrades slowly and may severely impact subtidal communities over long periods of time causing changes in population densities or shifting interspecies relationships. Such changes have the potential to influence important biogeochemical and ecosystem processes. Although oil undergoes abiotic degradation processes and degradation by indigenous marine bacteria these processes are usually only fast enough to reduce the less toxic aliphatic oil fraction and therefore do not reduce the impacts of oil in the environment (Cerniglia & Heitkamp, 1985; Cerniglia, 1991). Thus the residence time and spatial distribution of sunken oil is controlled primarily by the rate of burial by burrowing organisms, sediment accumulation and hydrodynamic regime of the site in question and is a complex issue which lies beyond the scope of this review.

Some general features on the impact of the spills on macrobenthic species and communities have resulted in a few key observations: (i) Species sensitive to hydrocarbons, especially crustaceans and amphipods, disappear rapidly and show very high initial mortality rates, (ii) the initial observed impact is correlated with the importance of the sensitive species in natural conditions. (iii) in some cases non-sensitive species or opportunistic species, especially polychaetes which thrive after an increase in organic matter, show important increases of abundance 1-3 years after the stress, and (iv) both positive and negative effects on population dynamics of affected species after an oil spill generally exceeds 10 years (Gesteira & Dauvin 2000).

The first major mechanism of impact of an oil spill for most invertebrates is by physical factors. Physical smothering with oil of benthic and to some extent pelagic invertebrates prevents respiration and reduces mobility and creates excess weight and shearing forces on mobile species eventually causing the animal to die. Many organisms resists desiccation during low tide by closing up their shell or outer protection, e.g. mussels and barnacles, and they may survive short-term oil smothering the same way. Still they will be suffocated by thick layers of oil. Mobile organisms such as crustaceans may escape by seeking deeper waters, but escape reactions can also cause animals to get stuck in oil (Bonsdorff & Nelson, 1981). In general crustaceans, and in particular amphipods, have shown to be sensitive to oil spills (Sanders et al. 1980; Elmgren et al. 1983; Kingston et al. 1995). Mortality as an impact has an obvious effect at the population level.

Reported effects on subtidal benthic communities differ strongly from one oil spill to another. After the B.I.O.S. experimental oil spill no apparent short-term effects on infauna community structure were revealed (Cross & Thomsom 1987). Slight effects on some few species were detected on a longer term from oil transported down with particles (Cross et al. 1987). Elmgren et al. (1983) observed a reduction of the benthic amphipods genus *Pontoporeia* and the polychaete *Harmothoe sarsi* to less than 5% of pre-spill biomass after the Tsesis oil spill in 1977. Recolonization of affected species was evident in the first years after the spill but full recovery was estimated to take more than 10 years. On the other hand pollution from an oil spill in the North Sea off the Norfolk coast of England did not appear to exert lethal effects on the fish and intertidal organisms, except for cases of complete smothering by oil. Although the levels of hydrocarbons in flesh from mussels and other intertidal fauna remained high months after the oil spill, growth of the organisms continued under the polluted conditions (Blackman & Law 1980). Anderson et al. (1978) observed no substantial inhibition of recruitment by benthic organisms at 5000-6000 ppm oil in a field experiment and Kingston et al. (1995) reported that no significant changes in benthic community structure, as characterized by species richness, individual abundance, and diversity could be related to the areas of seabed affected by the Braer oil spill at Garth’s Ness, southern Shetlands in 1993. The authors argued that the major factors determining the distribution of species in the affected areas appeared to be primarily related to the nature of the sediments, and not the degree of oil contamination. However, the levels of petroleum hydrocarbons in the most heavily contaminated sediments were sufficiently high to have eliminated sensitive groups such as the Amphipoda and encourage opportunistic species associated with oil pollution (i.e. polychaetes), but the overall number of species involved and their abundances were too low to significantly affect community structure (Kingston et al. 1995). If the sensitive species within a community are those who contribute significantly to structuring and maintaining community interactions, then elimination of those species will have the greatest effect on the community as a whole and vice versa. Following the Exxon Valdez oil spill in 1989 the number of taxa within a heavily oiled fjordic embayment in western Prince William Sound, Alaska, dropped from 24 to 6 from 1989 to 1990 (Jewett et al., 1996). By 1991, hydrocarbon concentrations were greatly reduced and the benthic community had recovered to include 32 taxa. These data suggest a possible adverse impact of oiling in 1989 and 1990, followed by recovery. However, sampling in fall 1993 again showed a greatly impoverished community (4 taxa), concomitant with low hydrocarbon concentrations in sediment and depleted dissolved oxygen in bottom water (Jewett et al., 1996). These data suggest that although the Exxon Valdez oil spill may have been, in part, responsible for the initial mortality and the impoverished infaunal community in the years subsequent to the spill, reductions of benthic infauna can occur as a result of natural hypoxia-anoxia.

Generally, refined products will produce more toxic effects than crude oil and the relative toxicity of oil is directly correlated with the proportion of polycyclic aromatic hydrocarbons (PAH) (Neff et al. 2000). There is plentiful data which clearly indicate bioaccumulation of various PAH in aquatic plants, molluscs, crustaceans, echinoderms, annelids, and fish (Neff 1979, Varanasi 1989). Uptake of PAHs by aquatic organisms from the water column, from sediment, and from their diet varies widely among organisms and among individual PAH compounds. Bioaccumulation is generally positively correlated with physical/chemical properties of PAH such as molecular weight and octanol/water partitioning coefficients. The degree to which an organism will bioaccumulate a PAH can therefore roughly be predicted from knowing the PAH's physical/chemical properties.

Toxic effects of PAH exposure to invertebrates occur at all levels of organization altering cell function, reproduction, physiology and behavior of individuals as well as affecting the community structure (Rubinstein et al. 1980, Mageau et al. 1987, Albers 1995, Sibly 1996; Reish & Gerlinger 1997). PAH may have immediate lethal consequences for the individual with the obvious direct influence on population structure. LC_{50} values for amphipod crustaceans when exposed to the PAH fluoranthene, for example, are in the range of 15 to 50 µg fluoranthene L^{-1} interstitial water (Swartz et al. 1990). Studies of both acute and chronic oil toxicity to polychaetes indicate that the water-soluble fraction of refined oils is more toxic than crude oils as measured by survival, growth and reproduction (Reish & Gerlinger 1997). However, growth and reproduction rates may also be significantly affected even when pollutants have no direct effect on survival as a result of an effective detoxification system, because the energy used for detoxification is not available for growth and reproduction (Sibly 1996). Exposure to organic contaminants like oil is known to induce behavioral changes such decreased feeding rates and reduction in animal burrowing activity. High concentrations of crude oil can completely stop sediment reworking by deposit feeding polychaete *Arenicola marina* and may cause the polychaete to leave its burrow, and lower concentrations can reduce the rate of fecal cast production (Prouse & Gordon 1976). A significant impact of the PAHs pyrene and phenanthrene on the feeding activity by the freshwater oligochaete *Limnodrilus hoffmeisteri* was observed with daily egestion rates decreasing with increasing PAH concentration (Lotufo & Fleeger 1996). Kielty et al. (1988) determined that a long term exposure to endrin significantly reduced reworking rates of *L. hoffmeisteri* at concentrations two orders of magnitude lower than the 96-h LC50. Gilbert et al. (1994) reported that the sediment reworking activity of deposit feeding polychaete *Nereis diversicolor* was significantly reduced in the presence of Arabia light crude oil.

Impact on Arctic marine invertebrate communities

Arctic marine invertebrate communities face special types of problems associated with stresses like an oil spill. Atlas et al. (1978, 1979) reported studies on the fate and effects of crude and refined oils in Arctic ecosystems. Major conclusions of the study was that though microbial populations respond rapidly to an introduction of hydrocarbons into the environment by an increase of the number of hydrocarbon utilizing bacteria and a decrease in infaunal species diversity hydrocarbons will remain in Arctic ecosystems for prolonged periods of time following contamination. Following initial abiotic weathering, biodegradation occurs slowly and fate depends on the particular ecosystem that is contaminated. Hydrocarbon biodegradation in the Arctic is limited mainly by poor availability of nutrients, and, to a lesser extent, by low temperatures. The major difference between petroleum biodegradation in the Arctic and in temperate regions appears to be a reduction in total amounts of oil components in both areas but no alteration in relative percentages of oil components in the Arctic. Seasonal changes in certain physical parameters such as temperature or ice-cover may also influence the impact of an oil spill in Arctic environments. Oil spilled under ice or transported there by currents does not weather appreciably and thus remains toxic for extended periods of time (Percy 1975) and ice coverage can greatly restrict the losses of light hydrocarbons by evaporation. Extruded brine, generated during sea ice formation in nearshore arctic waters, will sink to the bottom and can form a stable bottom boundary layer. This layer can persist for periods of 4-6 months and limited quantities of dissolved hydrocarbons resulting from a spill of crude oil or refined petroleum distillation products during periods of ice growth can be transported as conservative components to the benthos with the sinking brine. Once incorporated into the stable bottom boundary layer, these components are no longer subject to loss by evaporative processes, and they can only be diluted by mixing with unpolluted water masses, a process that proceeds slowly throughout the ice-covered period (Payne et al. 1991). These implications are pertinent to shallow nearshore oil and gas exploration, development, production, and transportation activities in high-latitude marine systems. Oil contamination of Arctic sediments will result in alterations of the benthic community and exhibits differential toxicity to benthic invertebrates. In a study of 39 Alaskan invertebrate and vertebrate species exposed to water soluble fractions of Cook Inlet crude oil and no. 2 fuel oil Rice (1979) concluded that although sensitivity increased from lower invertebrates to higher invertebrates, to fish, sensitivity was better correlated to habitat. Pelagic fish and shrimp were the most sensitive animals to Cook Inlet crude oil. Benthic animals, including fish, crabs, and scallops were moderately tolerant and intertidal animals, including fish, crabs, and starfish, and many mollusks, were the most tolerant to the water-soluble fraction of oil. Most of the intertidal animals were not killed by static oil exposures. Sensitive pelagic animals were not more vulnerable to oil spills than tolerant intertidal forms and oil damaged intertidal environments much more easily and adverse effects persisted longer than in damaged pelagic environments. It appears that arctic invertebrates may be slightly more sensitive to oil contamination than similar species residing in more temperate regions (Rice et al. 1977). Rice et al. (1977) stated however that the observed difference could be a result of greater toxicity of oil at lower temperatures due to persistence of hydrocarbons rather than a measure of sensitivity. From a community level perspective, there are also fewer species in the Arctic food chains and if one taxon is particularly impacted there would likely be few replacement species and thus the community as a whole would be more significantly impacted.

One of the greater oil spills at high latitudes happened in March of 1989 when Exxon Valdez spilled ca. 41 million liters of Alaskan north slope crude oil into Prince Williams Sound, Alaska and affected shoreline communities at least 800 km from the point of origin from the spill. Several studies on the effect on fauna have been conducted in the years following the spill (Dean et al. 1996, Driskell et al. 1996, Hooten & Highsmith 1996, Jewett et al. 1996, Feder & Blanchard, 1998, Jewett et al. 1999a). In areas where oiling occurred, impacts were generally limited to middle and upper intertidal zones. Analyses of mussel samples indicated that by 1990, 16 months after the spill, little of the shoreline oil remained bioavailable to epifauna (Gilfillan et al. 1995). Impacts of the Exxon Valdez oil spill on benthic communities within and adjacent to eelgrass beds in Prince William Sound were assessed based on classification and ordination analyses. Communities of infauna and small epifauna at some oiled sites in 1990 differed from communities at reference sites, and from the same sites in subsequent years. Percent sand and mud and concentration of total chrysenes (PAH analytes indicative of crude oil) all explained significant proportions of the temporal and spatial variation in benthic community structure. Total abundance and biomass of epifauna were generally higher at oiled sites, primarily because of higher densities of epifaunal bivalves. Otherwise, there were few consistent community-wide responses to oil pollution in diversity, richness, total abundance, total biomass, or the abundances of major taxonomic groups (e.g. polychaetes or bivalves) (Jewett et al. 1999a). Jewett et al. (1999a) attributed the lack of a stronger community-wide response to the varying sensitivities of constituent taxa to oil and organic enrichment. Over half of the dominant families differed with respect to abundance at oiled versus reference sites. Most of the taxa, including 9 families of polychaetes, were more abundant at oiled sites. Most of these were stress-tolerant or opportunistic, and their increase was likely due to organic enrichment caused in part by the oil. Negative impacts were most evident in oil-sensitive amphipods where abundances at oiled sites were probably reduced, as a result of oil toxicity. Most of these differences between oiled and reference sites persisted through 1995, 6 yr after the spill. The authors hesitated to conclude that these differences were a result of the spill, because of little prespill knowledge on equality between oiled and reference sites.

At some sites, effects from oiling were compounded by impacts from high-pressure hot-water washing used in shoreline cleanup (Driskell et al. 1996). Total abundance, species richness, species diversity, and abundance of several major taxa (polychaetes, bivalves, and gastropods) were significantly lower in hot-water-washed beaches than in unoiled beaches. Infauna at oiled sites that were not hot-water washed rebounded quickly following the disturbance. Although all study sites showed some degree of recovery by 1992, recovery of infauna at sites that were cleaned still lagged significantly behind the oiled, but not cleaned sites. Assessment of biota and environmental data at 40 m and 100 m depth demonstrated patterns in deep benthic assemblages reflective of oceanographic conditions, as indicated by sediment differences, rather than toxicity related to the Exxon Valdez oil spill (Feder & Blanchard1998). These results agree with conclusions of studies of intertidal and shallow subtidal regions following oil spills that disturbance effects decreases with depth.

In one of the very few spills to occur in sub-Antarctic cold waters densities of marine invertebrates were markedly reduced in the lower tidal and subtidal zones in the vicinity of the wreck of Nella Dan which spilled 270,000 L of oil, mostly light marine diesel into the sea at Macquarie Island, New Zealand. In the upper tidal zones, algal cover and invertebrate abundance were similar at oil-affected and control locations twelve months after the spill (Pople et al. 1990). Again no pre-spill data existed, making it difficult to draw a clear conclusion.

Marine invertebrates in Greenland

A recent assessment of marine invertebrates in Greenland covered species that live from the tidal zone to 500 meters depth not including meiofauna and parasites (see page 95-102 and table 17 in Jensen, 1999). The incomplete list contains 2000 invertebrate species of which crustaceans are the most abundant with approx. 800 species with copepods and krill (Euphausids) being the dominant and important species in the Greenlandic marine ecosystem. Included are also the economically very important species, northern shrimp (*Pandalus borealis*) and the snow crab (*Chionoecetes opilio*). The shrimp is primarily found at 100 to 600 meters depth and its abundance is determined by salinity, water temperature, and the composition of the sea floor. Shrimp is an important food source for several species of cod (Gadidae). Polychaetes, molluscs, and echinoderms are also abundant with 252, 283 and 112 species, respectively, of which the Iceland scallop (*Chlamys islandica*) is fished commercially in Western Greenland. Many polychaetes and molluscs are important food sources for fish, birds and marine mammals. The main food source of the king eider (*Somateria spectabilis*), common eider (*Somateria mollissima*) and walrus (*Odobenus rosmarus*) is molluscs of the families *Mya*, *Cardium*, *Hiatella*, *Astarte*, and *Serripes*, and whales like killer whales (*Orcinus orca*), sperm whale (*Physeter macrocephalus*) and pilot whale (*Globicephala maelaena*) feeds to a large degree on squid the dominant species being *Gonatus fabricii*. The majority of the polychaetes in Greenland are benthic epi- and infaunal species like the lugworm *Arenicola marina*. Some species of cod and narwhal (*Monodon monoceros*) feed to some extent on polychaetes.

In the event of an oil spill in coastal waters around Greenland an immediate reduction in diversity and subsequent increase in abundance of opportunistic species as outlined above is likely to occur. In principle, the ecological effects of oil are similar in tropical, temperate and arctic environments for related or similar biological targets, i.e. species. The important environmental differences between climatic regions are those that affect distribution, composition, and physical state of the oil. In the Arctic, the rate of recovery from oil damage is considered to be slower due to slow growth rates, short reproductive seasons, low generation turnover and high age at maturity. The overall implication is that the effects of oil pollution may be more severe and persistent in Arctic than for corresponding situations in other environments. Predicting the effect of an oil spill around Greenland will require better knowledge of ecosystem structure and identification of potential keystone species which play a key role in ecosystem health.

5.3 Oil spills in terrestrial and freshwater habitats

The fauna of terrestrial and freshwater invertebrates in Greenland is described in Jensen (1999, pages 72-83 and 91-92). Knowledge of the distribution of most terrestrial and freshwater invertebrates in Greenland is sparse due to random and scattered sampling. In general diversity seems to decline from south to north or more precisely from southwest to northeast (Jensen 1999). An oil spill on land will, in general, be more confined than oil spilled in aquatic ecosystems. However, oil spill on land may migrate both laterally and vertically and the rate and extent of oil flow over the surface will depend on a number of factors such as amount and type of oil, plant cover, slope, soil texture and water content (AMAP 1998). Experimental oil spills in freshwater ecosystems have shown that oil spilled in freshwater ecosystems may cause a marked decrease in total abundance and diversity of invertebrates as seen with oil spills in marine ecosystems (AMAP 1998). Again, the effect of the oil will vary greatly among species and effects on ecosystems will differ from one oil spill to another emphasizing the need for knowledge of pre-spill conditions.

5.4 Discussion and recommendations

Initial impact and long-term effects from major spills have been documented in only a few cases. In general, the lasting impacts on invertebrate populations and communities are typically a function of the type and amount of oil spilled, the type of habitat and species impacted, and the type of cleanup techniques used. Suchanek (1993) argued, however, that the following generalizations can be applied to coastal marine invertebrate communities following a major oil spill:

Initially, significant mortality effects all taxa indiscriminately. Subsequent mortality occurs and in soft bottom habitats, infaunal species like polychaetes, bivalves and amphipods are particularly affected. On rocky shores the most significant impacts are experienced by mobile fauna such as echinoderms, crabs, gastropods, and amphipods which are covered by the oil. If the oil and the ensuring mousse is especially thick it will also smother mussels and barnacles. In both cases opportunistic species typically soon invade the polluted habitat and proliferate. In soft bottom habitats population of invading opportunistic species, typically polychaetes like *Capitella* spp., undergo wildly fluctuating boom and burst cycles with a dampening amplitude over time. In rocky environments with grazer populations severely reduced or eliminated, green and brown algae bloom and become the dominant special species until the grazers return. While many ecosystems studies show substantial recovery after only a few years the time scale of complete recovery to pre spill conditions is likely to be measured in decades and long term effects of an oil spill will likely be difficult to separate from natural perturbations. This is especially evident in populations, which show stochastic or unpredictable recruitment patterns under normal conditions. This is often a characteristic of the opportunistic invading species in "natural" situations.

A confounding factor in predicting the effect of an oil spill in Greenland is the intense fishery for shrimp and scallops along the coast of Greenland. Shrimps are fished either by small trawlers along the coast and in the fjords or by bigger ocean going vessels. In either case shrimp is taken with trawl dragging heavy gear along the bottom altering the seafloor habitat. Understanding the extent of these impacts, and their effects on populations of living marine resources, is needed not only in order to assess impacts of accidental oil spills, but also to properly manage current and future levels of fishing effort and fishing power. For example, the entire U.S. side of the Gulf of Maine was impacted annually by mobile fishing gear between 1984 and 1990, based on calculations of area swept by trawl and dredge gear (Auster et al. 1996). Georges Bank was impacted three to nearly four times annually during the same period. Studies at three sites in the Gulf of Maine (off Swans Island, Jeffreys Bank, and Stellwagen Bank) showed that mobile fishing gear reduced the complexity (i.e. physical structure) of benthic habitats. Complexity was reduced by direct removal of biogenic (e.g., sponges, hydrozoans, bryozoans, amphipod tubes, holothurians, shell aggregates) and sedimentary (e.g., sand waves, depressions) structures. Also, removal of organisms that create structures (e.g., crabs, scallops) indirectly reduced complexity. Reductions in habitat complexity may lead to increased predation on juveniles of harvested species and ultimately reduced recruitment to the harvestable stock. Fragile, slow recruiting animals are considered to be most susceptible to disturbance, while the least sensitive species are generally fast growing and have good recruitment. Because of a lack of reference sites, where use of mobile fishing gear is prohibited, no empirical studies have yet been conducted on a scale that could demonstrate population level effects of habitat-management options. In the event of a major oil spill in an area that is heavily fished by bottom trawl it would be nearly impossible to evaluate the effect of the oil on the benthic invertebrate communities alone due to lack of knowledge of the undisturbed environment. Therefore, future assessments of the impacts of oil spills or other accidental environmental disturbances could benefit from pre-impact studies that provide objective criteria for selection of matched pairs of sites, thereby supporting the assumption of equality in the absence of the disturbance.

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6 Impacts of oil spill on fish

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6.1 Introduction

This account covers both marine and freshwater spills, but is focusing on marine oil spills. However the general information on impact is relevant for freshwater oil spills as well and the specific data gaps for fish and fresh water spills is discussed separately.

6.2 Oil toxicity to fish, eggs and larvae

Oil can affect fish in many ways. Fish readily take up oil components into their tissues after exposure to oil in water, food or sediment. Oil may cause a number of physiological and histopathological effects depending on the concentration and composition of the oil. Indicators of oil exposure in fish include increased concentrations of hydrocarbon metabolites in bile and increased monooxygenase activity in the liver tissue. Oil components are unlikely to bioaccumulate to high concentrations in fish tissue because fish are able to metabolise and excrete these contaminants.

In laboratory studies several fish species have been exposed to the water-soluble fraction (WSF) of different crude oils. The WSF of crude oils consists mainly of aromatics and are dominated by benzene, toluene and xylenes (Serigstad 1992). The toxicity to fish appears to be functionally related to the total aromatic hydrocarbon concentration in the WSF (Rice 1985). As a broad generalisation, lethal effects (LC50) among adult fish are found in the range 1 - 10 mg/kg of water soluble aromatics and sublethal effects in the range 0.1 - 1 mg/kg (Rice 1985). Fish eggs and larvae are generally more sensitive than adult fish. Lethal effects (LC50) of water-soluble aromatic hydrocarbons on larvae have been estimated to be in the range 0.1 - 1 mg/kg (Rice 1985). Carls et al. and Heintz et al. (both 1999) found a higher sensitivity of herring and pink salmon embryos during long-term exposure to weathered Exxon Valdez crude oil. Lowest observed effective concentrations (LOECs) were about 1 µg/kg (ppb) total PAH from very weathered oil. Total PAH from less weathered oil was less toxic indicating that toxicity in the very weathered oil was primarily associated with the larger PAHs.

In Norwegian field and laboratory experiments different groups of marine organisms were exposed to the WSF of crude oil (Booman et al. 1995). Organisms were exposed to 10 - 70 µg/kg BTX of WSF for up to 24 hours (BTX stands for benzene, toluene, xylene and ethylbenzene, which constitutes approx. 80% of the WSF of crude oil). These are concentrations and periods of exposure that would be realistic in an offshore oil spill situation. The threshold for effect on oxygen consumption of yolk-sac larvae of cod lies within a concentration range from 20 to 80 µg /kg BTX of WSF. The critical concentration range for effect on larval first feeding would be somewhat higher. Adult Arctic cod (*Boreogadus saida*) react to concentrations between 10 and 25 µg /kg-BTX with an increase in activity and oxygen consumption. Thus, adult fish will be able to detect low concentrations of water-soluble components and try to avoid contaminated areas. Considerable variation was found in sensitivity between species, and sensitivity was also found to be temperature dependent. Cod (*Gadus morhua*) and saithe (*Pollachius virens*) eggs and larvae seem to be particularly sensitive to oil, while herring eggs and larvae are less sensitive, and capelin eggs and larvae are intermediate (Føyn 1992).

Booman et al. (1995) concluded that even though the effects of exposure to the water soluble fraction of crude oil varies with species developmental stage and temperature, the effects will normally be negligible at the concentration ranges found after accidental oil spills in open water. However, fish eggs and larvae could be exposed to harmful concentrations of these components in polar areas as a result of the use of dispersants (because of the low evaporation rate which increases aquatic exposure) (Booman et. al 1995) or in coastal areas.

Although concentrations of oil that are lethal to adult fish rarely build up in the open sea following an oil spill, sublethal oil concentrations may stress fish, especially during long term exposure. The metabolism and excretion of aromatic hydrocarbons in fish can result in the modifications of aromatic hydrocarbons into reactive intermediates, which have been associated with DNA-damage. Chronic exposure to elevated oil concentrations may impose an additional form of stress, which could interact with natural stress factors and result in increased mortality, reduced growth, and susceptibility to parasites and other types of effects, which are difficult to document in nature (National Research Council 1985, Futsæter et al. 1991, Stagg and McIntosh 1996).

6.3 Fish mortality during an oil spill in the open sea

Extensive fish kills after oil spills have not been documented (National Research Council 1985). This is primarily because in the open sea, toxic concentrations are seldom reached in significantly large areas and depths. Furthermore adult fish are mobile and can avoid the oil. Avoidance behaviour has been observed in salmon and cod exposed to oil (Ernst et al. 1989; Serigstad 1992). In coastal areas where oil can be trapped in shallow bays and inlets, toxic concentrations can build up to levels where adult fish kills can occur. However, fish usually avoid oil by swimming away. During the “Braer” spill in Shetland in 1993, a storm dispersed the oil and caused very high oil concentrations in the water column near the coast. After the grounding, the concentration of oil in the water was ‘some hundreds’ of mg/l in the area close to the tanker (The Scottish Office 1993). Ten days after the spill, 4.3 mg/l was measured in a bay within a few kilometres of the wreck. Subsequent monitoring programs found no evidence of major effects on fish populations (Richie & O’Sullivan

1994). Work not yet completed indicates that there may have been some subtle effect on larval growth and on the proportion of sexually mature sandeels in given length classes (Richie & O'Sullivan 1994).

In model work from the Barents Sea (Børresen et al. 1988), the oil concentration in the water column just below the oil spill was estimated at 0.3 mg/kg WSF, with the level decreasing to 0.1 mg/kg WSF at a depth of 5 m. Field experiments on Haltenbanken showed concentrations up to 0.09 mg/kg of Statfjord crude oil at a depth of 1 m 10 hours after the release of the oil. This concentration was reduced to 0.02 mg/kg 170 hours after the release (Serigstad 1992). In the Ekofisk blowout, where c. 12 000 ton crude oil was spilled, aromatic hydrocarbon concentrations in the water column ranged between 0.002 - 0.8 mg/kg, however, most concentrations were less than 0.1 mg/kg (Rice 1985). No extensive fish kill was associated with this spill, which never reached the coast.

Payne (1989) stated before the Exxon Valdez spill that there was no evidence that fish stocks had been affected by oil spills. Many conflicting impact results were published with respect to the Exxon Valdez spill (Wells et al. 1995, Rice et al. 1996). Although no massive fish kills were observed outside sheltered areas following the "Exxon Valdez" spill, several effects which may have had an effect on the population level were documented (Rice et al. 1996). Armstrong et al. (1995) concluded that the bottom fish and crustaceans fisheries remained unimpaired after the spill, as far as could be seen for large natural population fluctuations. There was no significant difference in deep-sea shrimp (*Pandalus borealis*) catch per unit effort (CPUE) between oiled and non-oiled areas (Armstrong et al. 1995). In general, few effects of the "Exxon Valdez" oil spill were detected on bottom fish and crustaceans, despite the hydrocarbon sensitivity of crustacean larvae noted above (Armstrong et al. 1995).

Damage to eggs, larvae and juveniles in coastal habitats may, however, have significantly affected recruitment to some fish populations in Prince Williams Sound. Oiling of intertidal spawning habitat had large effects on reproduction by e.g. pink salmon (intertidal spawner in PWS) and herring (Peterson 2001). There is agreement that a concern for the herring and salmon fishery is justified (Wells et al. 1995), although there are disagreement about the assessment of the possible damage. The total adult return of both hatchery and wild pink salmon to Prince William Sound were at record levels in 1990 (one year after the spill). The return numbers were, however, estimated to be 1.9 million fish fewer than would have appeared without the effect of the spill on the growth on juvenile salmon in 1989 (Geiger et al. 1996, Templin et al. 1996) (See next chapter 6.4. Impacts in coastal environments").

6.4 Impacts in coastal environments

Oil that enters intertidal and subtidal shore zones can have an effect on the benthic fauna. After an experimental oil spill on a sheltered beach on Baffin Island, it was concluded that effects were mainly temporary, and apparently without serious consequences. After a two-year post-spill monitoring period it was further concluded that there was no evidence of large-scale mortality of subtidal benthic biota attributable to the oil spill (Sergy & Blackall 1987). The natural removal of the oil from the shoreline slowed down over time, and after a period of eight years, approximately 5% of the original spill volume remained on the beach in a highly weathered state (Humphrey et al. 1991). After the “Exxon Valdez” oil spill, most surface deposits of oil on the shorelines of Prince William Sound decreased by a factor 10 in one year. Oil in low-energy sediment areas and in areas of subsurface burial, however, was expected to be retained much longer (Wells et al. 1995). Wolfe et al. (1994) estimated that 3 years after the spill approximately 2% of the spilled oil remained on the intertidal shorelines, much of it being highly weathered, biologically inert residues.

Oil that is trapped in an unweathered state and is slowly released into the environment can cause chronic pollution. Research in Prince William Sound after the “Exxon Valdez” oil spill has shown that oil can be trapped in the sediment beneath mussel beds on protected shorelines without being cleaned by wave action (Babcock et al. 1996, Harris et al. 1996). Because the underlying sediment often is anaerobic, oil can remain there in a relatively unweathered state. Oiled mussel beds in Prince William Sound still contained high concentrations of relatively unweathered oil 3 years after the spill. The oil was distributed unevenly within these beds. Concentrations as high as 30 000 - 40 000 µg/g wet weight of total hydrocarbons were found within two metres of concentrations two orders of magnitude less. The “Exxon Valdez” crude oil contains 0.8% total polynuclear aromatic hydrocarbons (TPAH). TPAH in mussels generally averaged 1% or less of the TPAH in the underlying sediment. Contaminated mussel beds are suspected to have caused chronic intoxication of black oystercatcher, Barrows goldeneye and harlequin ducks (*Histrionicus histrionicus*), which feed on the mussels (Rice et al. 1993, Patten 1993a, 1993b, Lance et al. 2001). However this question is disputed, and other scientists estimate that the average oil dosage is well below the ‘no-effect’ level for wildlife feeding on the mussels, and for the mussels themselves (Hartung 1995, Wells et al. 1995).

Toxic concentrations can build up in coastal areas where oil can be trapped in shallow bays and inlets. Adult fish kills have occurred in such spill situations. In Greenland, both the lumpsucker and the capelin which spawn in localised areas just below the shoreline, (intertidal and subtidal) are likely to be quite vulnerable in the spawning period.

If oil is trapped and persists for longer periods of time, the local and stationary fish may suffer from a number of sublethal effects. After the Amoco Cadiz oil spill, estuarine flat fish and mullets suffered fin rot disease, and showed reduced growth, fecundity and recruitment (Conan 1982). A comparison of sculpins from oil free and oil contaminated sites following the “Exxon Valdez” oil spill showed that the prevalence and intensity of parasitism (*Trichodina*) was significantly higher in the oil exposed group (Kahn 1990). In Prince William Sound cutthroat trout (*Oncorhynchus clarki*) and Dolly Varden (*Salvelinus malma*) use nearshore and estuarine areas for feeding during summer. Tagging studies of both species have demonstrated reduced growth in oil contaminated areas; a difference which persisted for two years after the spill in the case of cutthroat trout (Hepler et al. 1996). There was also a tendency for reduced survival during the first year after the spill; however, this difference was not statistically significant. Cutthroat trout and Dolly Varden, which belong to the salmon family, are anadromous, as are Arctic char (*Salvelinus alpinus*) in Greenland.

Lab studies simulating conditions for embryos of Herring and pink salmon in Prince Williams Sound after the spill indicate significant effects (se above and Carls et al. and Heintz et al. 1999). There are however conflicting results on the effects on herring and salmon populations in Prince William Sound, primarily due to large natural fluctuations. Wells et al. (1995) concluded that only continued studies of the fish populations would clarify the true causes of the changes in these fish populations. By comparing oiled and non-oiled areas, Brown et al. (1996) found indications that oil caused increased larval abnormalities in Pacific herring (*Clupea pallasi*). A study of health and condition of Pacific herring from Prince William Sound in 1994, on the other hand, did not reveal any such trends in herring health and condition that could reasonably be attributed to the oil spill in 1989 (Elston et al. 1997).

Pink salmon (*Oncorhynchus gorbuscha*), which spawn in streams in the intertidal zone, had significantly higher egg mortality in oiled compared to non-oiled streams from 1989 through 1993; however, there was no difference after 1993 (Bue et al. 1996). The egg mortality study provides the most compelling evidence of long-term damage to fish from the oil spill (Spies et al. 1996).

6.5 Impact of oil spill induced egg and larvae mortality on fish stocks

Oil spills that coincide with spawning or larval concentrations can cause significant egg and larval mortality, because these are very sensitive and immobile. Most species of fish produce large numbers of eggs, and only a relatively small number reach adulthood due to natural mortality. The importance of oil spill induced mortality compared with the high natural mortality of fish eggs and larvae is disputable. In a consensus statement, Canadian scientists (Longhurst 1982 from Rice 1985) suggest that as much as 50% oil induced mortality among eggs and larvae may have little effect on the fish stock. In contrast, Norwegian scientists (Berge et al. 1978 from Bjørke et al. 1991), state that egg and larvae mortality due to human activities will induce a similar decrease in the yearclass.

American model work simulated the impact of a 10,000 m^3 crude oil spill on George Bank, south of Nova Scotia. The impact on cod was estimated in a worst case simulation. It was estimated that the mean impact was a loss of 0.5% of a year's catch when the simulated oil spill coincided with peak spawning (Reed & French 1989). Norwegian model work simulated a blowout in the Barents Sea (duration 10 days, total spill 24,000 m^3). With respect to cod spawning, a worst case scenario will be a spill occurring in April, which could result in a 10 - 15% reduction of the size of the yearclass. A spill simulated in July gave a reduction of less than 0.5% of the yearclass (Børresen et al. 1988). In a study simulating the potential effects of spilled oil on commercial fisheries in the Bering Sea, Laevastu et al. (1985 quoted in Meyer & Geiselman 1989) concluded that a large blow-out in the eastern Bering Sea would have no measurable effect on offshore fishery resources. This study did not address the potential effects on coastal fishery resources.

6.6 Sea-food tainting and health concern

The development of an atypical flavour - tainting - in fish tissue is caused by natural spoilage or by assimilation of contaminants. Oil spills may affect the fisheries by tainting the fish, making the fish unmarketable. Tainting of fish by oil and the potential effects on human health has been reviewed by GESAMP (1993). Experimental studies show that the minimum concentration of oil components in water that will induce tainting in fish is in the range 0.01- 1.0 mg/l. Tainting therefore occurs at concentrations below those which causes acute effects in adult fish, but similar to those causing acute and sublethal effects in their embryonic and larval life stages. The water-soluble fraction of the oil is the most important in causing tainting. Ernst et al. (1989) has investigated tainting of cod by petroleum hydrocarbons in laboratory experiments. Their study suggests that the risk of tainting of cod and related species due to offshore blowouts is minimal. Even under a chemically dispersed offshore oil slick, fish will rarely encounter oil concentrations sufficiently high to cause tainting. Furthermore, experiments suggest that cod show avoidance behaviour. In the experiments, depuration following tainting generally occurred within 24 hours (Ernst et al. 1989). However, the risk of tainting of fish will be larger in shallow coastal waters, where oil concentrations may build up. When the oil disappears fish depurate the hydrocarbons taken up. In the "Braer" spill, tainting and contamination of fish and shellfish occurred around southern Shetland and a fisheries exclusion zone was established (Richie & O'Sullivan 1994). Contamination in fish samples from the exclusion zone fell rapidly, and three months after the spill, the ban on fishing was lifted. However, one year later, there were still areas with elevated levels of oil in the sediment. Some species of shellfish, which are more exposed to oil in the sediment than fish because of their close association with sediments, still had low levels of contamination present. Fishing of these species remained prohibited.

Acute oil spills will usually taint fish before they have accumulated oil concentrations that are toxic to humans. However, a lesson learned from the "Exxon Valdez" spill in 1989 was that it should be part of a (national) oil spill contingency plan to be prepared to handle human health concerns over contaminated seafood, especially in areas with subsistence fishing (Walker & Field 1991).

The US Food and Drug Administration assessed the long-term health hazard associated with subsistence seafood following the "Exxon Valdez" Oil Spill (Bolger et al. 1996). They focused on polynuclear aromatic hydrocarbons (PAH). Of all the components in crude oil, the PAHs are toxic at the lowest doses. These hydrocarbons are the most likely to be passed through the marine food chain and are well characterised as carcinogens. The ability of fish to metabolise PAHs, make the consumption of fish of considerable less concern as a dietary source of PAHs compared to molluscan bivalves; the marine organisms where PAH bioaccumulation occurs to the greatest extent. Bolger et al. (1996) concluded that the risk of contracting cancer from eating finfish from the spill area was so low that it could not be calculated, and therefore is, for practical purposes, equal to zero. The risk of acquiring cancer from a lifetime of eating mussels collected from even the most heavily impacted site where mussels were sampled in 1989 was extremely low; lower than eating smoked salmon. Furthermore recent samples have demonstrated a significant decrease in PAH levels since the oil spill.

6.7 Closing of fishing areas

The closing of fishing areas during an oil spill, may be necessary because there is a potential for fouling of fishing gear and catches by oil, tar balls and oiled debris. The closing of fishing areas is a complex issue with both health, economic and social implications (Meyer & Geiselman 1989).

6.8 Research groups and knowledge centres

A research group at Alaska Fisheries Science Center (Juneau) and a research group at the Marine Research Institute in Bergen, and collaborators, have been involved in the most significant contributions to the basic knowledge on the impact of oil pollution on marine fish in cold water.

Greenland Institute of Natural Resources is the main centre for fish research in Greenland. NERI (DMU) has done research on lake ecology (including fish) and mapping of coastal spawning areas. The Zoological Museum in Copenhagen has done faunistic research.

6.9 Assessment of knowledge gaps in relation to Greenland

Concerning general knowledge, the importance of long-term subletal effects caused either by individuals damaged during a spill or chronic oil pollution (e.g. from leaks from oil incorporated in the sediment) needs further clarification. However, for impact assessments and sensitivity mapping in Greenland population specific information on spawning concentrations and larval concentrations is more needed for species where eggs and/or larvae are very concentrated near the shoreline, the surface or at the sea bottom at shallow water.

About 150 marine fish species occur regularly in Greenland (Jensen 1999). A summary for species used for consumption and ecological important species, in West Greenland is given in Table 6.1.

Table 6.1. Important fish and large invertebrate species in West Greenland (from Mosbech et al. 1998).

Species	Main habitat	Spawning area	Spawning period	Exploitation
Blue mussel	subtidal, rocky coast			s
Scallop	inshore and on the banks, in area with high current velocity, 20 -60 m depth		July-August	c & s
Deep sea shrimp	mainly offshore, 100 -600 m depth	larvae released at relatively shallow depth (100-200 m), larvae in middle water-column	(July -September) larvae released March to May	important c
Snow crab	coastal waters and fjords, 180-400 m depth		larvae released April-May	c
Atlantic cod		pelagic eggs and larvae in upper water column		
offshore stock	on banks north to 64°N	(former) western slope of banks	March-April,	
Inshore stock	fjords	inner fjords	April-May	c & s
Greenland cod	inshore waters/fjords	inshore/fjords, demersal eggs	February-March	c & s
Polar cod	pelagic	mainly N of 68°N		no
Sand eel	on the banks at depths between 10 and 80 m	on the banks, demersal eggs, larvae in the water column	June-July south of 66°N later in the north	no, important prey item
Wolffish	inshore and offshore waters	hard bottom, one area known outside Maniitsoq, demersal eggs	peaks in September	c & s
Atlantic salmon	offshore and coastal waters	freshwater	-	c & s
Arctic char	coastal waters, fjords	freshwater	August-October, eggs hatch in spring	c & s
Capelin	coastal waters	beach, demersal eggs	April-June	c & s, important prey item
Atlantic halibut	offshore and inshore, deep water	? western slope of banks south of 66°N, pelagic eggs and larvae, deep water	winter	c & s
Greenland halibut	offshore and inshore, deep water	offshore south of 66°N, deep water, pelagic eggs and larvae	spring	important c & s
Redfish	offshore and in fjords, 150-600 m depth	main spawning south-west of Iceland, larvae drifts to West Greenland banks		c & s
Lumpsucker	pelagic	coastal, demersal eggs	May-June -	c & s

Exploitation of the species are categorised as c: commercial and s: subsistence fishery

This section is an assessment of whether there is adequate information to:

1) Identify if there are fish populations at risk, which potentially could be significantly impacted

2) Pinpoint important areas and periods for these species (concentrations, hot spots),

3) Conduct of risk evaluation / impact assessment of oil activities (exploration, production, transport) for decision making

Coastal spawners

There is no doubt that local spawning stocks of Capelin and Lumpsucker, which spawn in the intertidal zone or just below, could be impacted by an oil spill. It is unclear how separate these spawning stocks are. Knowledge of the spawning areas is a prerequisite for protection. Spawning areas have been mapped in most of Southwest Greenland based on local knowledge (Nielsen et al. 2000), but research is needed to supplement the local knowledge as well as covering the rest of Greenland.

The spawning areas for fjord stocks of cod (pelagic eggs) and Greenland cod (demersal eggs) may to a lesser extent be impacted by an oil spill. The spawning is less concentrated and in deeper waters where the pelagic and demersal eggs are less likely to come into contact with oil.

Offshore spawners

For offshore spawners it is based on the present knowledge not likely that an oil spill would impact a significant proportion of eggs and larvae. Given the generally sparse sampling effort and the large range of variation, this conclusion is partly based on general oceanographic information on how concentrated eggs and larvae are likely to be. However, improved data from Southwest Greenland are coming up from the REKPRO project on shrimp recruitment carried out by The Greenland Institute of Natural Resources and collaborators.

PAH baseline

A few chemical analyses of PAH in shorthorn sculpin liver from Greenland have shown unexpected high levels (AMAP Greenland 1997). The reason for this is unknown, PAH levels in fish is in general only considered a problem in connection with oil spills or chronic oil pollution (AMAP 1998). We need a better description of baseline levels of PAH in important fish species in Greenland.

Freshwater

Oil at the outlet of Arctic char rivers could impair the spawning migration as well as the feeding of the young chars often gathering at the outlet. In fresh water oil could certainly impact the char spawning areas at the river and lake bottom. In some areas the rivers with migrating Arctic char have been identified, however, in other areas there are large data gabs which should be filled before oil activities in the area.

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7 The impact of oil spills on bird populations

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Bird vulnerability to oil has often been illustrated to the public as oiled birds washed ashore. However, scientific attention has focused on how additional mortality due to oil spills can affect birds on the population level, which is the significant ecological question. Several reviews of birds and oil pollution have been published in the last 30 years: Bourne (1968), Holmes and Cronshaw (1977), Clark (1984, 1987), Leighton et al. (1985), National Research Council (1985), Dunnet (1987), Hunt (1987), Anker-Nilssen (1987), and Wiens (1995) incorporating experience from the Exxon Valdez oil spill in 1989.

This account covers both marine and freshwater spills, but is focusing on marine oil spills. However the general information on impact is relevant for freshwater oil spills as well and the specific data gaps for birds and fresh water spills is discussed separately.

7.1 The effect of oil on seabirds

Oil coating of the feathers

Seabirds are vulnerable to oil spills in several ways (Fig. 7.1). Primarily, oil soaks into the plumage and destroys insulation and buoyancy causing hypothermia, starvation and drowning (for reviews see Leighton et al. 1985, Anker-Nilssen 1987). The major effect of oil on feathers is alteration of the structure. The oil destroys the water repellency of feathers by disrupting the precise orderly arrangement of feather barbules and barbicelles (Leighton et al. 1985, Mahaffy 1991).

The oiled feathers become matted and waterlogged and the birds loose buoyancy and the insulating properties of the plumage (Stephenson 1997). This causes a stress on the energy metabolism in the bird. In experiments an external dose of 20 g oil on ducks plumage at 0° C was found to increase basal metabolic rate to 186% of the rate of controls (experiments by several authors reviewed in Leighton et al. (1985)). The dose was estimated to be within the range of oiled ducks found in the wild, which was in average 10 g oil/kg body weight for moderately to lightly oiled ducks. For eiders resting on water (instead of standing in air) the thermal stress has been found to be even higher. Jenssen and Ekker (1991) found an almost 400% increase in heat production for eiders resting in water (5.5 ° C) after exposure to 70 ml crude oil. The rate of heat loss exceeded the thermoregulatory capacity and eiders became hypothermic within 70 min. after contamination.

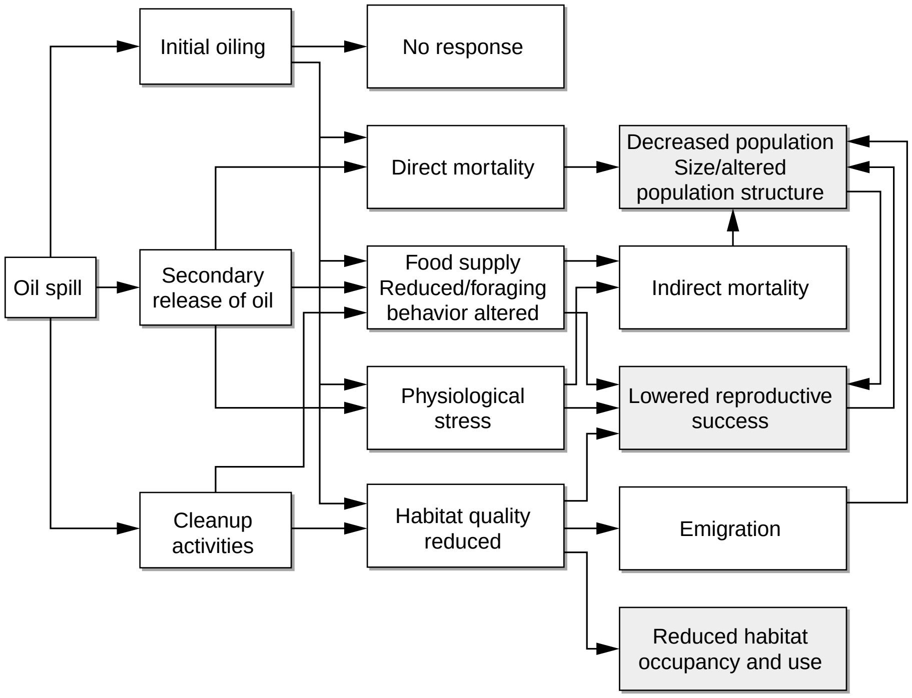

Figure 7.1. A schematic representation of the ways in which an oil spill can influence seabirds. Three primary avenues of effects: population size and structure, reproduction, and habitat occupancy, are highlighted (from Wiens 1995).

Assuming that all the oil an eider encounter on the water surface is absorbed by the plumage, an eider will absorb 70 ml oil by swimming through a 6.7 m stretch of an oil slick with a thickness of 0.1 mm, or through a 670 m stretch of a blue-shine with a thickness of 1 µm.

The experimental studies of Jenssen and Ekker (1991) further indicate that the effect of oil doses are aggravated if birds are allowed to preen oil into a greater part of their plumage, as they do in the wild. Burger (1997) studied the effect of oiling on feeding behaviour of sanderlings (*Calidris alba*) and semipalmated plovers (*Charadrius semipalmatus*) following an oil spill on the Atlantic coast of New Jersey. It was found that time devoted to foraging decreased with the degree of oiling, and oiled birds spend more time preening and standing about than un-oiled birds. This increases the energy stress during the migration. For aquatic feeders the increased energy demand is combined with a reduced ability to feed, due to loss of buoyancy in the water logged plumage.

Birds feeding and resting on the sea surface like alcids could suffer severe impact from even small oil doses (Leighton et al. 1985). Arctic seabirds are especially vulnerable to the destruction of the insulating capacity of the plumage because they live in cold water. Furthermore, spilled oil will keep its sticky and feather-destructive properties for a longer period in cold water.

Toxic effects of oil

Birds ingest oil when they attempt to clean the oiled plumage, and when they feed on oil-contaminated food. Ingestion of oil can cause irritation of the gastro-intestine, damage to liver and kidney function, anaemia and dysfunction of the salt gland (Fry and Lowenstine 1985).

Many toxicological experiments have been conducted, but the literature is somewhat confusing, primarily because oils have different compositions. The different components have different toxic effects, and the various components have not been adequately specified in most experiments. When spilled oil becomes weathered it is generally less toxic, because the most acute toxic components evaporate (Prichard et al. 1997). In spite of the fact that there is no comprehensive understanding of the toxic effect, it is clear that ingested oil can be directly and severely toxic. It may also have more subtle effects at low doses, both acute and chronic, that can significantly affect survival and reproduction (Fry and Lowenstine 1985, Leighton et al. 1985, Peterson 2001, Lance et al. 2001).

External oiling is likely to be responsible for the majority of seabird losses after an oil spill, but long-term effects after intoxication may hamper the reproductive capacity by increasing the proportion of non-breeders in the population (Fry and Lowenstine 1985). There are indications that sub-lethal effects may have reduced reproduction capacity in oiled penguins that have been rehabilitated and released in South Africa (Morant et al. 1981 from Fry and Lowenstine 1985). However, these results from rehabilitated seabirds can not be regarded as generally applicable to oiled seabirds. Field experiments have shown that lightly oiled adult birds may transfer oil to eggs when incubating, thereby diminishing the hatching success (Lewis and Malecki 1984).

Intake with food

After an oil spill the oil gets weathered i.e. the composition shift towards components with low volatility and resistance to light- and bio-degradation. At the same time, the primary pathway of exposure shifts from direct intake (typically related to preening) to indirect intake with the food. Weathered crude oil is generally less toxic than fresh oil. Stubblefield et al. (1995) fed mallard duck (*Anas platyrhynchos*) weathered crude oil (from the Exxon Valdez oil spill) at oral doses or dietary concentrations exceeding those representing maximum likely field exposure from heavily oiled areas. The oil did not significantly affect survival, growth, or reproduction at these concentrations. However, at extremely high concentrations (20 g oil/kg diet) there were significant reductions in mean eggshell thickness and strength. It was assessed based on these results and the toxicological literature that sub-lethal toxic effects of crude oils on wildlife in spills such as the Exxon Valdez appear to be very unlikely (Hartung 1995).

However, relatively un-weathered oil with toxic properties still remained in protected sediments under rock armour and in some mussel beds in Prince Williams Sound several years after the spill (Spies et al. 1996). Spies et al. (1996) concluded that chronic sub-lethal effects most likely attributable to residual oil occurred for several years (in sea otters, and some fish and invertebrates), although hard evidence is missing for bird species. Lance et. al. (2001) from US Fish and Wildlife Service found that 10 years after the spill only 4 out of 17 bird taxa had showed signs of recovery, while 9 taxa showed no recovery and 4 taxa showed signs of being increasingly affected by the spill. He believes that birds are still suffering because food in the intertidal zone and shallow waters near the shore, such as mussels, is still contaminated with oil (see chapter 6.4). In the same period average water temperatures in the area has increased three to four degrees above the historical average. Potential lingering effects of the spill and natural variability appear to be acting in concert in delaying the recovery of the bird populations (Lance et al. 2001).

Seabirds: different lifestyles - different vulnerability

The more time birds spend on the sea-surface the more susceptible they are to be fouled with oil in the case of an oil spill. Both birds that feed at sea throughout the year (alcids, diving ducks, many terns and gulls) and for a part of the year (some ducks, grebes, divers (loons), phalaropes) can be considered sensitive to oil spills.

The behaviour of the seabirds is varied. Species, which spend most of the time swimming or diving, are most vulnerable to oil. Species that spend most of the time airborne, snatching the food from the surface, are less vulnerable. In any case, most species rest on the sea surface now and then.

Large guillemots (*Uria* spp.) and ducks moult their flight feathers after the breeding season and are unable to fly during 2-7 weeks. Large guillemots and most diving ducks spend this flightless period at sea, where they are safe from terrestrial predators. Most ducks gather in flocks during the moulting period, while the large guillemots (*Uria* spp.) undertake a more dispersed swimming migration away from the coast

Birds, which aggregate in small areas on the sea, are more vulnerable than birds, which are dispersed, because a single spill has the potential to affect a significant proportion of the population. High seabird concentrations are found in colonies, moulting and feeding areas, and in leads in the ice during winter and spring. Little is known about whether seabirds deliberately avoid oil slicks; however, evidence strongly suggested that fulmars (*Fulmarus glacialis*) avoided settling on sea surface polluted with heavy oil during a Norwegian experiment (Lorentsen and Anker-Nilssen 1993).

The bird populations, which are believed to be most seriously affected by acute oil spills, are those with a low reproductive capacity and corresponding high average lifespan. This is the strategy adopted by e.g. alcids and fulmars that are typical K-selected species with stable populations (Hudson 1985, Furness and Monaghan 1987, Croxall and Rothery 1991). The size of a seabird breeding population is more sensitive to changes in adult survival than to changes in immature survival or breeding success. This effect is most pronounced in species with high adult survival and low reproductive rate (Croxall and Rothery 1991). However, seabirds like alcids and fulmars with a long life span have delayed maturation. Often pre-breeding and non-breeding individuals ("floaters") in these populations form a pool that act as a buffer from which individuals may be recruited to replace losses from breeding populations (Dunnet 1982). The length of the delayed maturation may in part be determined of available breeding sites (Dunnet 1982).

Population regulation of seabirds

The non-breeding pool can be seen as an adaptation to natural catastrophes. During prolonged periods of severe storms, making foraging difficult, seabird "wrecks" can occur. One wreck estimated to 25 000 birds, mainly guillemots (*Uria aalge*), occurred in the North Sea in February 1994 (Ritchie and O'Sullivan 1994). The largest reported wreck were 100 000 guillemots in the Gulf of Alaska in April 1970 (Bailey and Davenport 1972, Hudson 1985). The extent to which the effect of an extra oil spill mortality will be additive or compensatory depends on whether extra oil spill mortality will be compensated by relaxation of density dependent regulating factors. Seabird are generally believed to be subject to density dependent regulation although currently there is little clear evidence that it occurs (Wooller et al. 1992), and density-independent environmental effects and parasites may be more important than was hitherto recognised (Croxall and Rothery 1991). However, many population-regulating factors are operating. The availability of nest sites in seabird colonies can act as a density dependant factor regulating the breeding populations, especially in a proximate fashion and at a local level. Food availability is considered the factor most likely to limit overall numbers of seabirds (Croxall and Rothery 1991) and this regulation is believed to take place during breeding, where the feeding areas are confined to areas near the colonies (Alerstam and Høgstedt 1982).

Seaducks have a somewhat different strategy for coping with catastrophic events. They have a higher reproductive potential than e.g. alcids, such that adult losses can be more rapidly replaced, but the population size will tend to fluctuate more.

Seabird mortality due to oil spills

It is often difficult to assess bird mortality caused by an oil spill because only a fraction of the dead birds will beach, and not all the beached birds are found (National Research Council 1985). Results from rather well documented oil spills around the world shows, however, that a substantial number of birds can be affected by medium sized oil spills when the circumstances are bad.

Following a relatively small oil spill (c. 600 t) in Skagarak in 1981 c. 45,000 oiled birds were killed or found dead, and it was estimated that 100,000-400,000 birds died (Anker-Nilssen and Røstad 1982). After the Exxon Valdez oil spill (c. 40,000 m^3) in Prince William Sound, c. 36,000 dead birds were found. It was later estimated that between 100,000 and 645,000 birds died because of oiling, based on carcass recovery and modelling of recovery patterns (Ford et al. 1996, Piatt et al. 1990, Piatt and Ford 1996). The best estimate may be about 250,000 birds killed by the spill (Piatt and Ford 1996). English drift experiments with marked seabirds corpses gave recovery rates on the shore between 10% and 60% varying with the distance to the coast and wind speed and direction (RSPB 1979 from Clark 1984).

Extirpation of colonies

The extreme case is: can populations become extinct in oil spill catastrophes? Historical examples show that bird populations in general can recover from very small populations (Ryan and Siegfried 1994). "*Populations as small as several hundred individuals have a very good chance of survival, particularly given monitoring of the populations demographic parameters to give early warning of impending problems*". (Ryan and Siegfried 1994). However, extinction of bird species has occurred mainly due to habitat destruction and hunting (e.g. the former very abundant passenger dove (Bucher 1992) and the great auk (Lyngs

1994)), and seabird colonies have been deserted, with oil pollution as a major factor.

Marginal populations such as puffins at Brittany, at the southern border of their distribution, have been affected. Here a puffin colony crashed due to a combination of natural causes and oil pollution following the Amoco Cadiz wreck at the coast of Brittany (Hope Jones et al. 1978 cited from Clark 1984). This colony was later restocked with puffins from the Faeroe Islands (Duncombe and Reille 1980 cited from Clark 1984). In southern California the guillemot colony on Devil's Slide Rock was extirpated in the 1980's, mainly due to a number of oil spills (Parker et. al 1997). Recently this colony has been recolonized using social attraction techniques (Parker et al. 1997). The disappearances of puffins and guillemots from the English Channel Coast during World War II probably also relates to oil spills as a result of the enormous pollution from sinking and burning ships (Gaston and Jones 1998).

7.2 Predicting of population impacts of oil spills with simulation models

As emphasised by Clark (1984, 1987), only mortality resulting from oil pollution which has an impact on a population or community can be considered as biologically significant. This can be evaluated in nature, where oil spills may have had an impact on bird populations. Alternatively, it can be evaluated by creating models, using estimates of the mortality caused by an oil spill and estimated population parameters. Both strategies have been used and are useful, but they both have their limitations in the present fragmentary understanding of the quantitative dynamics of ecosystems.

A density independent model

Ford et al. (1982) developed simulation and analytical models to estimate the impact of oil spills occurring within feeding areas of colonial seabird populations. The analysis was hampered by the lack of field information on several critical model parameters. The work first of all pointed out features of seabird biology, which merits closer attention, and it gave some general idea of what may happen in an oil spill. In a given scenario, a spill (approximately 620 m^3) occurs during the middle of the breeding season 24 km from an island with very large colonies of guillemots and kittiwakes (St. George, Pribilof Islands). This results in a 68% mortality of adult guillemots and 10% mortality of adult kittiwakes. As a crude first-level estimate, they simulated that it will take 80 years before the guillemot population is back to normal. However, the model used does not account for increased population growth due to decreased competition in the depleted population (density dependence), so the recovery rate will probably be higher.

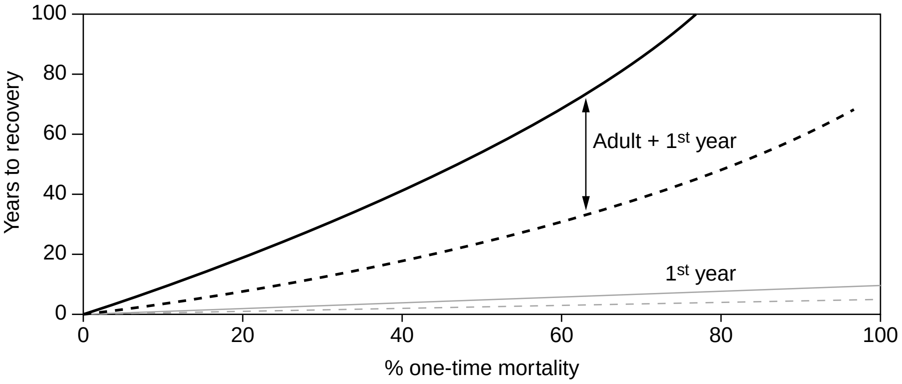

Figure 7.2. Time to recovery of a stable age distribution and the original population size as a function of one-time mortality for adult and first-year guillemot *(Uria aalge)* (full line) and Brünnich's guillemot (*Uria lomvia*) (dashed line) (from Ford et al. 1982).

The most important factor regarding population impact is the adult oil spill mortality, as could be expected for a long-lived K-selected species (Fig. 7.2). A complete breeding failure in one year may have a lesser effect than a 5% one-time die-off of adults (Ford et al. 1982).

Sensitivity analysis showed that the model is extremely sensitive to the foraging distribution of birds around colonies and to variations in the rate at which a population responds to the occurrence of a perturbation by adjusting its foraging distribution (Ford et al. 1982, Hunt 1987).

A density dependent model

Samuels and Ladino (1983) developed a model to determine the effects of hypothetical oil spills on seabird populations in the mid- Atlantic region of the United States. Their model was density dependent in contrast to the model of Ford et. al. (1982). They assumed the number of young produced per breeding bird to be inversely related to the total adult population size. Using life-table data for common terns they found that if 25% of all age classes were killed by an oil spill, the tern population (colony) would require nearly 20 years to recover.

However, the form of density dependence used by Samuels and Ladino is largely speculative. Actually if a colony experience a large mortality and no immigration occurs the reproductive outcome per individual may decrease because of a larger predation.

It is difficult to predict the sensitivity to oil spills (and recovery time) for a seabird population. The restitution or recovery of a seabird population is not only the return of numbers but also of population structure. The population dynamics and foraging ecology of the seabirds are complex and important information for modelling is still lacking (Wiens et al. 1984, Hunt 1987). Because seabirds have a high average lifespan with age-specific survival and fecundity, long-term population studies are needed to give the answers (Wooller et al. 1992). If an oil spill kills all the birds in a colony, the recolonization and population recovery will depend on the size and location of neighbouring colonies (Cairns and Elliot 1987). It will also depend on the extent of movements of seabirds between colonies (metapopulations), on which there is a lack of information (Wooller et al. 1992).

Although we need important information for making realistic models of seabird population responses to oil spills, models can be useful tools. If the basic model concept is correct, modelling, and sensitivity analysis of models, can give valuable knowledge on which information is mostly needed for improving model predictions; and not the least, on the relative sensitivity of different areas, periods and seabird species (Wiens et al. 1984, Hunt 1987, Anker-Nilssen 1988)

7.3 Prediction of population effects, mitigation and management

In conclusion, major oil spills do have the potential to deplete bird populations and single seabird colonies may be deserted. However, experiences from spills indicate a considerable resiliency of seabird populations to single catastrophic events. It is unlikely that an oil spill can wipe out a seabird population unless other factors, such as hunting and by-catch in gillnets hamper the recovery of the population, or the population is small and has a very restricted distribution.

Integrated management

Given the limited possibilities for precise scientific predictions of impacts of large oil spills on seabirds, attention should focus on integrated analysis and management of flyway populations in EIA of new oil activities (Mosbech 1997). The " extra oil spill risk" shall be seen in the context of management of the population. Research focusing on population dynamics and " bottlenecks" can provide important knowledge, which can be used operationally. Information can be used for identification of the most important areas and for supportive measures to populations facing the risk of significant impact from a large oil spill (Fig. 7.3).

Focus on important populations and threatened populations

Looking at marine oil activities the most important possibilities for minimising the potential effect of a large oil spill is to plan risky activities so the most important areas and periods are avoided, and to improve the status for populations (and subpopulations and colonies) which face the risk of a large oil spill. Special consideration should be given to key species (species of particular importance), and small declining populations and threatened populations (redlisted species). The calculation of seabird oil vulnerability indices can be a valuable tool for identifying the most vulnerable areas (King and Sanger 1979, Anker-Nilssen 1988, Williams et al. 1994). See e.g. Anker-Nilssens method described in chapter 4.3. Williams et al. (1994) developed another oil vulnerability index to assess and map the vulnerability of seabirds in the North Sea. However, Williams et al.'s method does not use information on population trends, and thus seems less adequate than Anker-Nilssens to protect the most vulnerable populations. Anker-Nilssens method (1987, et al. 1988) has later been incorporated into a GIS-based analyse tool called SIMPACT (Anker-Nilssen and Kvenild 1996) and used in assessing potential effects on seabirds of petroleum activity in the northern Barents Sea (Isaksen et al. 1998).

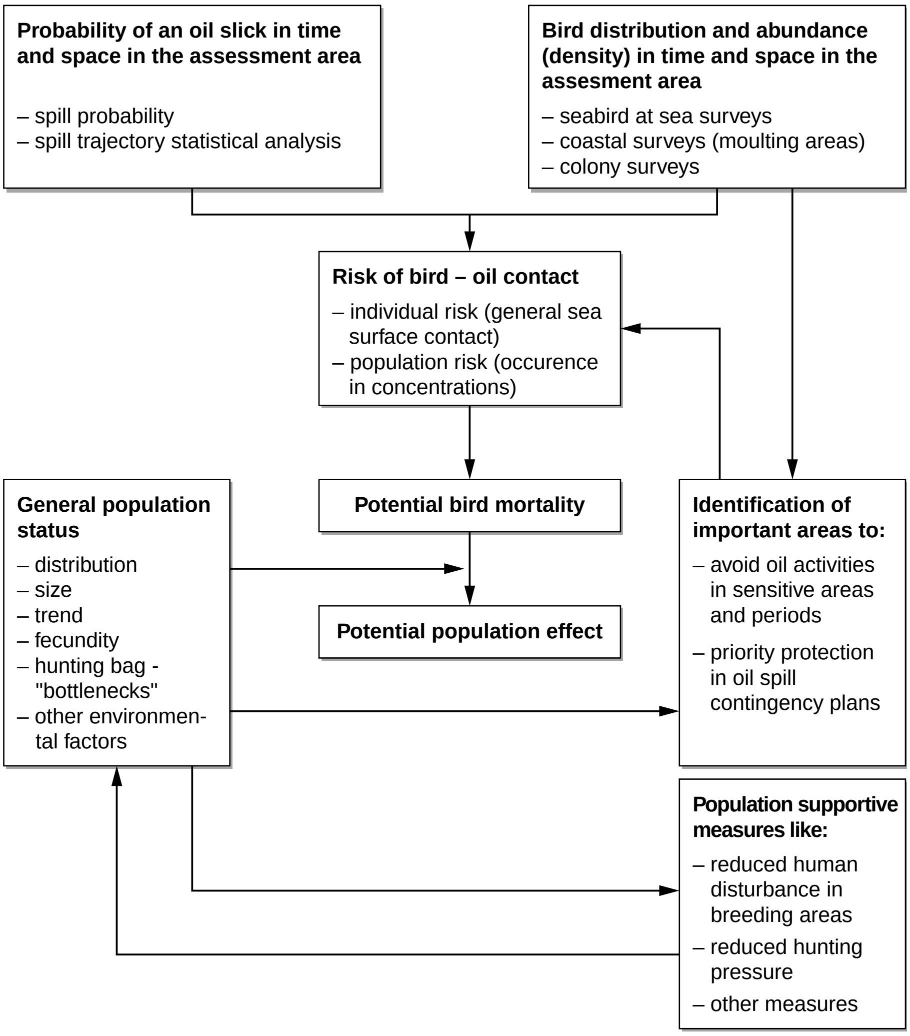

Figure 7.3. Basic principles of analysis to assess seabird vulnerability to oil activities (Mosbech 1997). Solid lines indicate the main analysis of potential effects on bird populations and broken lines the main effect of possible mitigative measures (indirect effects omitted for simplicity).

Conclusion

Scientific knowledge is generally not adequate to predict the impact of a large oil spill on bird populations. The immediate mortality can only be crudely estimated and the restitution of the population can only be assessed in very broad terms with considerable uncertainty. There is a lack of understanding of the capacity for resilience in most species populations dynamic, of natural fluctuations and of the effect of other human impacts.

Experiences with impacts from actual spills, and other mass mortalities are important in the assessments because of lack of scientific understanding of the population dynamics. Also populations resiliency to hunting can be valuable information.

The resiliency must however be assessed in relation to the specific status of each population.

There is a need for focused long-term studies of species susceptible to serious impacts, to improve the understanding of resilience and thus the predictive ability and the potential for population supportive measures.

To improve impact assessments there is a need to view the effects of oil activities of marine birds in a more holistic analysis of important bird populations that can be significantly affected. There is a need for analysis of flyway populations, identifying population dynamic parameters, bottlenecks (main regulating factors) and integrating the extra risk in management plans addressing the total impact and general situation of the population.

The most important possibility for minimising the potential effect of a large oil spill is to plan (unavoidable) risky activities so the most important areas and periods are avoided. And if possible to improve the status for populations (and subpopulations and colonies) which faces the risk of serious impacts, if a large oil spill occurs.

7.4 Assessment of knowledge gaps in relation to Greenland

Improved general knowledge on the impact of oil on bird populations e.g. bird behaviour in relation to oil slicks and bird mortality and subletal effects of oiled birds could be useful and improve impact assessments in Greenland. However, population specific information on important areas and periods (hot spots) as well as status and ecology of Greenlandic populations (see fig. 7.3) is much more needed, both for impact assessment and for minimising the potential effects of a large oil spill. Improved population specific knowledge has for some species the potential to reduce the population risk through careful planning of oil activities, incorporation of *oil spill sensitivity maps* in contingency plans and measures to improve the status of the population (see fig. 7.3). This section is therefore an assessment of whether there is adequate bird information to:

1) pinpoint important areas (concentrations, hot spots),

2) identify populations at risk, which potentially could need remediation after an oil spill and identify the potential population supportive measures,

3) conduct of risk evaluation / impact assessment of oil activities (exploration, production, transport) for decision making

As the level of knowledge differs considerable between different regions in Greenland the assessment is done separately in three regions. The assessment is done in general terms although species specific assessments of oil spill vulnerability and data gaps have been done for the Southwest Greenland area where the information level is highest (Mosbech et al. 1998; Boertmann et al. 1998).

We have grouped the needed information in the categories:

- **adequate**
- **questions remain**: information is lacking , but it is possible to indicate what information is needed and how to obtain it**,**

- **basic questions remain:** so little is known about the system that it is difficult to identify in detail what needs to be known (Table 7.1).

For species which do not occur in concentrations the distribution and abundance information is usually poor, but these populations are not as vulnerable to oil spills so the information is not as important in this context.

Bird colony database

All major bird colonies at the coast of Greenland have been identified and mapped and rough estimates of their sizes are available from a database maintained at NERI. However, in a number of areas especially in Southeast Greenland the survey effort has been limited and probably only the major colonies are known included in the database (Boertmann et al. 1996). In most cases the data are insufficient to provide baselines against which to measure change (or assess damage from an oil spill). However, the data are considered sufficient to determine the approximate sizes of the populations at risk.

Data on the distribution and abundance of seaducks, mergansers, loons and shorebirds are generally less precise. Although the coastal postbreeding moulting and staging areas for seaducks and mergansers in Southwest and West Greenland are rather well known from aerial surveys (Mosbech and Boertmann 1999; Boertmann and Mosbech 2001; Mosbech et al. 2000). These data from the West coast of Greenland are probably sufficient in most areas for rough estimates of the numbers of birds that could be exposed to an oil spill where these birds assemble after breeding. However, such data is generally non-existing from the East coast of Greenland and will be needed before oil activities commence.

Undersampling in potential staging areas

Visits to coastal staging areas during migration by large numbers of birds can be very brief- but still of critical importance. Given the generally sparse sampling effort, the large range of variation and the general lack of data on temporal patterns of use, it is possible that there are unrecorded important staging areas even in West Greenland.

Offshore information scattered

NERI-AE and Ornis Consult has since 1988 collected data concerning seabird distribution in the waters off West Greenland to improve knowledge on offshore distribution, abundance, and distributing factors. Survey platforms have been both aircraft and ships. The ship-based surveys have mainly been surveys of opportunity carried out from ships with other tasks such as fish and marine biological studies and seismic surveys. Results of offshore ship-based surveys between 62 and 68 N have been reported in Durinck and Falk (1996), Mosbech et al. (1996) and Mosbech et al. (1998). Results of offshore aircraft-based surveys have been reported in Mosbech and Johnson (1999). In general the information on the pelagic distribution of marine birds is scattered, more effort is needed and also further analysis of bird distribution factors. Very few offshore data exist from east Greenland.

Table 7.1 Assessment* of quality and availability of biological information relating to birds for decision making (impact assessment /risk evaluation); and status of knowledge of where populations are concentrated.

South and Southwest Greenland / The Davis Strait 60-68 N

Habitat	Concentrations (Hot spots)	Risk evaluation	
		Exploration.	Production, transport
Offshore, Open water			
summer	questions remain	adequate	questions remain
Winter	questions remain	questions remain	questions remain
Near shore / fjords,			
summer	adequate	adequate	questions remain
winter	questions remain	questions remain	questions remain
Pack Ice, summer and winter	questions remain	questions remain	questions remain
Leads, polynyas winter	questions remain	(questions remain)	questions remain
Fast ice, winter	adequate	(questions remain)	questions remain

West and North Greenland / The Baffin Bay and Avanersuaq 68- 80 N

Habitat	Concentrations (Hot spots)	Risk evaluation	
		Exploration.	Production, transport
Open water, summer	questions remain	adequate	questions remain
Near shore / fjords, summer	adequate	adequate	questions remain
Pack Ice, winter	adequate	questions remain	basic questions remain
Leads, polynyas, winter	questions remain	questions remain	basic questions remain
Fast ice, winter	adequate	questions remain	questions remain

East Greenland

Habitat	Concentrations (Hot spots)	Risk evaluation	
		Exploration.	Production, transport
Open water	questions remain	basic questions remain	basic questions remain
Near shore / fjords	questions remain	questions remain	basic questions remain
Pack Ice	questions remain	basic questions remain	basic questions remain
Leads, polynyas	questions remain	basic questions remain	basic questions remain
Fast ice	questions remain	basic questions remain	basic questions remain

*Assessments are based on current information and may change with new information and technology and should not be regarded as final judgements, because it is impossible to know exactly what information is needed until the size nature and location of the oil and gas resources are known.

The Open Water Area

During winter there is usually open water along the coast and on the banks off west Greenland between 63 and 67 ^{0}N. It is a unique wintering area of international importance with large concentrations of eiders, king eiders, harlequin ducks, Brünnichs guillemot and little auks. Some studies have been done on distribution and abundance in this area (Durinck and Falk 1996; Mosbech and Johnson 1999) and som studies are ongoing in a collaboration on "the seabird winter ecology" between The Greenland Institute of Natural Resources and NERI-AE (DMU). Given the international importance of this area as wintering area, further studies will be needed before the impact of oil production in the area can be assessed.

Fresh water oil spills

Oil spills in fresh water habitats - lakes, ponds and wetlands - has much less potential to impact bird populations in Greenland. First of all oil spills will have a limited geographical extension, a single lake, wetland or watershed, and secondly are the number of birds present at such habitats generally small compared to the total populations. The most concentrated birds at freshwater habitats are geese. Greenland white-fronted geese assemble at feeding habitats in early spring in West Greenland, and pink-footed geese and barnacle geese assemble in moulting flocks at lakes and marshes in East Greenland. The highest numbers of geese recorded at such sites, which could be affected by a single oil spill, is so small that even if all birds were exterminated, impacts on the population level are not likely. There is however an exception. The extremely low-numbered population of light-bellied brent goose (total 6000 birds) occurs in northernmost East Greenland with up to 25% of the total population. The moulting segment of these birds stay at rivers, and significant parts of the population could be exposed to a single oil spill.

Data insufficient to specific recovery predictions

Some basic ecological knowledge on food habits and reproduction are available. However, the data is insufficient to construct life tables, to predict how birds would respond to major shifts in the environment, and to predict how their population ecology would change after a major loss of individuals. Thus the data is insufficient to precisely predict impact of oil spills on bird populations. However, it would also generally be impractical to obtain necessary information for more than generalised predictions, which underlines the importance of focusing on adaptive management, where the oil spill risk is seen as one among several factors in the management of the species. This is especially important for species where an extra mortality from oil spills could make a significant difference. Thus, research should be focused to support this adaptive management.

If populations are under severe stress, their natural capacity for resiliency can not be counted on. An example could be Brünnich's guillemot colonies in West Greenland, which has been declining for decades due to hunting, disturbance and by-catch in gillnets (Kamp et al. 1994, Boertmann et al. 1996). Many large colonies have been abandoned, and the colonies have not been re-colonised, although by-catch in gillnets has ceased and the detrimental spring and summer hunting has been reduced. The total population in West Greenland is still rather large, but we do not know how the colonies (metapopulations) interact, and recolonization or restocking of extirpated colonies seems to be a difficult process (Parker et al. 1997).

Key species with populations which could be significantly impacted by marine oil spills and have or maybe have populations under stress are primarily Brünnich's guillemot, eider, king eider and harlequin duck, and secondary little auk, puffin, redbreasted merganser, long-tailed duck and light-bellied brent goose.

7.5 Knowledge centres and research groups

Research based analysis of the impact of oil development in Greenland is taking place at NERI AE, where preliminary oil spill impact analysis and identification of data gaps for West Greenland was initiated about 10 years ago. A number of impact analysis have been carried out and we have done research in the methodology of seabird oil analysis. Two researchers have been involved at NERI-AE.

Field and laboratory studies on the effect of oil on birds has in recent years mainly been carried out in Norway (Tromsø) and USA. In USA an immense research effort was started after the Exxon Valdez oil spill in Prince Williams Sound in 1989. Especially the detailed and elaborate studies in Prince Williams Sound are very important as they try to test whether there are long-term effects of the oil spill. At NERI-AE we have been following the research on the effects of oil on birds. Contacts to the international community are maintained through participation in various workshops and the Circumpolar Seabird Working Group, a CAFF working group under the Arctic Council.

As concluded in the previous section research is in demand concerning distribution, abundance, population dynamic and ecology of Greenland seabirds. The research in these topics is mainly based at four institutions: The Greenland Institute of Natural Resources, NERI AE, Ornis Consult and The Zoological Museum in Copenhagen. The four institutions have each from one to three researchers involved in projects producing information on marine birds relevant in oil spill context. The researchers form an informal network and most projects are carried out in collaboration between two or more institutions. A core of about 6 researchers has been involved for more than 5 years.

7.6 Conclusion and recommendation

Mapping of seabird hot spots

There is still work to be done before the seabird hotspots in the seas around Greenland are mapped with reasonable certainty. Particular information gaps: offshore areas in general, and particularly the Open Water Area during winter, Avanersuaq and East Greenland.

Information gap: Long-term studies of key species at risk

There is a need for focused long-term studies of species susceptible to serious impacts, to improve the understanding of resilience, and thus the predictive ability and the potential for population supportive measures. Key species with populations which could be significantly impacted by marine oil spills and have or maybe have populations under stress are primarily Brünnich's guillemot, eider, king eider and harlequin duck, and secondary little auk, puffin, redbreasted merganser, longtailed duck and light-bellied brent goose.

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8 Impacts on mammals

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8.1 Introduction

Impacts on marine mammals in general

Whales and adult seals are not particularly vulnerable to oiling, mainly because they do not rely on their fur for insulation, but on a well developed blubber layer (St. Aubin 1990a, Geraci 1990). Moreover, marine mammals may be able to avoid oil on the surface at least in ice-free waters (St. Aubin 1990a, Geraci 1990). Seal pups are more vulnerable to oiling because they are dependent on their natal fur for insulation (St. Aubin 1990a). The oil is usually conveyed to the pups by the oiled mother seals while nursing. Seals whelping in aggregations like hooded seal and harp seal are more exposed to mass oiling of their pups than dispersed whelpers, like ringed seals. The presence of ice may restrict the open water areas on which the marine mammals rely. If an oil spill is caught in leads and cracks in the ice, seals and whales may be forced to breathe air with toxic petroleum vapours. To what extent the vapours can be sufficiently concentrated to harm marine mammals is not known for sure (St. Aubin 1990a). However, the mechanism of inhalation of toxic fumes was involved when at least 302 harbour seals died during the Exxon Valdez oil spill (Peterson 2001). White whales, narwhals, bowhead whales, ringed seals, walrus and bearded seals in particular are at risk as their primary habitat is ice-covered waters (Boertmann et al. 1998).

According to Born et al. (1995) walrus are more vulnerable to oil spills than other seals. They are gregarious and have a pronounced thigmotactic behaviour (physical contact), they usually stay in pack ice and they have benthic feeding habits; benthic invertebrates are known to accumulate petroleum hydrocarbons from the sediments and the water. Bearded seals, like walrus, often feed on benthic fauna and may also be vulnerable for similar reasons (Boertmann et al. 1998).

In contrast to the other marine mammals, individual polar bears are very sensitive to oil spills (St. Aubin 1990b). Oiling may disrupt the insulation created by the fur, on which polar bears rely in contrast to the seals and whales. They may also ingest oil from the fur when grooming (Stirling 1990). Oil is toxic to polar bears and ingestion has resulted in lethal poisonings in an experimental study (Øritsland et al. 1981, Hurst & Øritsland 1982, Hurst et al. 1982).

8.2 Impacts on marine mammals in Greenland

Seals and whales

As mentioned above particularly the white whale, the narwhal and the bowhead could be exposed to petroleum vapours from an oil spill caught in the ice. All these species occur in Greenland. The white whale suffer moreover from a decreasing population (Heide-

Jørgensen & Reeves 1996), and the bowhead whale from a very small population size due to the whaling terminated decades ago (Reeves & Heide-Jørgensen 1996). Both of these populations may be vulnerable to extensive oil spills affecting many individuals. The narwhal population is not considered as decreasing and is much larger than the bowhead whale population, why it seems much less vulnerable.

Seals are not particularly sensitive to oil spills, and for only a few seal populations in Greenland oil spills may have an impact on the population. One is the stationary harbour seal population, which to day is very small and decreasing in numbers (Teilmann & Dietz 1994). Such a population is vulnerable even to a small increase in mortality, f. ex. caused by an oil spill. Hooded seals have a whelping area in central Davis Strait (Bowen et al. 1987, Boertmann et al. 1998). Even though the pups become rapidly independent, they stay in the whelping area for some time. These young hooded seals in the Davis Strait seem to be in a rather bad condition for a prolonged period due to insufficient feeding abilities (Kapel 1998). Although many pups can be affected by an oil spill in this area, it is unlikely that an oil spill significantly will affect the population as a whole, due to its large size. Walrus occur in winter in the drift ice off W Greenland, and year round in Avanersuaq and NE Greenland (Born et al. 1994, 1995). As mentioned above there is some concern for walrus and their sensitivity to oil spills. The winter population in W Greenland is small, and likes the Avanersuaq population heavily hunted.

Except for the few haul out sites for harbour seal (which probably could be boomed during a spill), there seems to be no appropriate mitigation measures applicable in relation to marine mammals in Greenland. However, in case of increased mortality from oil spills, the hunting pressure could be lowered through hunting regulations in order to secure a higher survival of non-affected individuals and a more rapid population recovery.

Polar bear

As polar bears are vulnerable to oil spills as individuals (see above), populations may be impacted in areas where a large number of bears may be affected. The most dense polar bear populations occur in Avanersuaq and NE Greenland, but whether a large oil spill here may impact so many individuals that the population will suffer is an open question.

8.3 Knowledge gaps

Several haul outs sites for harbour seal are known in Greenland. Many of these are at sites where booming is applicable if threatened by an oil spill. However, there is no knowledge on whether these sites are still in use or have been abandoned for long. A review of these sites and the degree of their utilisation will be relevant in an oil spill sensitivity mapping and response context.

Inhalation from petroleum vapours may be a problem for marine mammals living in ice covered waters. Whether this is an actual threat has not been investigated, and eventual short and long-term effects is unknown.

Oil spill induced population level effects on polar bears in Greenland remain to be studied.

8.4 Research groups and knowledge centres

No research is carried out on oil spills and its (short- and long term) impact on marine mammals, either on individuals or populations in Greenland. But on the other hand, the Greenland Institute of Natural Resources carries out research and have an extensive knowledge on the abundance and ecology on marine mammals in Greenland, particularly the harvested species (= almost all except for some whales). NERI-AE also has extensive knowledge on marine mammals in Greenland based on literature studies and on original research (harbour seal, narwhal, white whale, and humpback whale).

In USA, effects of oil spills on marine mammals have been studied after the Exxon Valdez spill in 1989, when the involved species were sea otter and harbour seal (e.g. Frost et al. 1999).

Canadian and US researchers have compiled the knowledge on oil spill effects on marine mammals a comprehensive work (Geraci & St Aubin 1990).

8.5 Conclusions and recommendations

The knowledge on temporal and spatial occurrence of marine mammals in Greenland is generally sufficient and adequate for oil spill sensitivity mapping and response. Particular gabs are related to harbour seal haul outs, whether they still are occupied or not, and to the exposure to and inhalation effects of petroleum vapours on marine mammal living in ice covered waters.

8.6 Impact on terrestrial mammals

The current knowledge on potential impacts and the ecological significance of impacts of terrestrial oil spills on mammals is limited. Terrestrial mammals easily detect oil from smell and sight, and it is not likely that significant numbers will be affected. The literature on the issue is sparse. This is considered to reflect that the problems are relatively small and simple.

Oil spills in the terrestrial environment may originate from pipeline breaks or blowouts from wells, and will most often be confined to relatively small areas.

In Greenland on-shore oil exploration was carried out in Jameson Land in east Greenland in 1985-1990 without drillings. In 1995 a full scale exploration drilling was performed in Nuussuaq, West Greenland. Relatively few terrestrial mammal species occur in Greenland: caribou, muskox, arctic hare, arctic fox and lemming. Caribou and muskox are the most important species in terms of subsistence hunting. In the southernmost parts of West Greenland sheep farming is widespread. Caribou occur only in West Greenland, and the areas where caribou occurrence and oil explorations may coincide are limited, and in these areas caribou are few in numbers and occur rather dispersed. The distribution of muskox include Northeast Greenland, where also are extensive areas with oil exploration potential are known. Muskox is moreover introduced to West Greenland, but hitherto in areas without oil exploration potential.

In case of a terrestrial oil spill, it is assessed, that it will be detected quickly, and in many cases it will be possible to restrict large terrestrial mammals from getting into contact with the oil.

The effects of oil spills on terrestrial mammals can be either toxic, or related to the highly viscous properties of oil, which can affect the isolating properties of the fur. It is assumed that such effects will be small on the population level although individuals infested with oil may die of hypothermia. Indirect effects can occur if foraging areas are covered with oil. These effects will, however, most likely only be of minor importance at the population level.

Large oil spills have occurred in Usinsk in Komi republic, Russia, during several years. No reports are available about effects on terrestrial mammals.

Despite the lack of relevant literature no important knowledge gaps have been identified relating to terrestrial oil spills in Greenland.

It is concluded that:

1. Terrestrial oil spills in Greenland most likely only will have minor effects on the population levels of caribou and muskox.
2. Terrestrial oil spills will only affect small areas, where it will be relatively easy to prevent terrestrial mammals to get in contact with the oil.

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415 Potential environmental impacts of oil spills in Greenland

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