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The EU Horizon 2020 project GRACE: integrated oil spill response actions and environmental effects

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Abstract

This article introduces the EU Horizon 2020 research project GRACE (Integrated oil spill response actions and environmental effects), which focuses on a holistic approach towards investigating and understanding the hazardous impact of oil spills and the environmental impacts and benefits of a suite of marine oil spill response technologies in the cold climate and ice-infested areas of the North Atlantic and the Baltic Sea. The response methods considered include mechanical collection in water and below ice, in situ burning, use of chemical dispersants, natural biodegradation, and combinations of these. The impacts of naturally and chemically dispersed oil, residues resulting from in situ burning, and non-collected oil on fish, invertebrates (e.g. mussels, crustaceans) and macro-algae are assessed by using highly sensitive biomarker methods, and specific methods for the rapid detection of the effects of oil pollution on biota are developed. By observing, monitoring and predicting oil movements in the sea through the use of novel online sensors on vessels, fixed platforms including gliders and the so-called SmartBuoys together with real-time data transfer into operational systems that help to improve the information on the location of the oil spill, situational awareness of oil spill response can be improved. Methods and findings of the project are integrated into a strategic net environmental benefit analysis tool (environment and oil spill response, EOS) for oil spill response strategy decision making in cold climates and ice-infested areas.

Background

Accidental oil spills have occurred—and will occur—in different sea areas of the world as long as oil drilling, production and transport activities continue on our planet. The degree of damage of the spills on local ecosystems, and the effectiveness of different response technologies are highly dependent on prevailing environmental conditions and immediately available oil spill response resources. In polar and sub-polar regions, the marine ecosystems are especially vulnerable to oil spills, mainly due to the coldness and slow degradation of the spilled oil compounds. Furthermore, the cold and often ice-infested sea poses serious challenges for oil combating measures. Along with other differences in critical environmental characteristics, it is obvious that each marine region needs risk assessment, monitoring and response methods more or less tailored to fit its specific characteristics.

The Baltic Sea is the second largest brackish water basin in the world and is characterised by strong stratification, high nutrient concentrations, continuous oxygen deficiency in most deep water basins and low salinity [1]. With a coastline shared by nine highly industrialised countries, it supports approximately 15% of the world's total maritime traffic, including the transport of different types of oil [2, 3]. Since large amounts of oil are used,

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transported and stored in this region, oil and oil spills are considered a major threat to the Baltic Sea ecosystem [3]. In the Baltic Sea, the rate of oil transportation continuously increases on an annual basis, and therefore possible environmental risks should be taken into consideration [4]. Marine pollution arising from illegal oil discharges from ship tank or bilge pumping is much greater than that from spectacular ship accidents, and is mainly detected along essential navigation routes [4, 5]. With regard to oil spill response activities, the description of the type, location, extent and state of oil at sea is of prime importance for predicting the trajectory of oil slicks and areas of shoreline likely to become polluted [4, 6]. The detection of oil spills and the description of their location and extent is performed using remote sensing imagery (SAR data) [4, 5].

In the Arctic parts of the North Atlantic, the risk of oil spills due to both oil and gas exploration as well as climate change is increasing, the latter opening new shipping routes. Navigation and operations in ice-infested waters are presenting extra challenges to oil spill response [7], and increase the risk rate of ship accidents and related oil spills [8]. Arctic seas, such as the Barents Sea and the East Greenland coast, constitute important areas for fisheries [9, 10], seabirds [11] and marine mammals [12]. Oil pollution in cold subarctic and arctic seas may therefore have serious ecological effects [13] as well as large socioeconomical impacts related to fisheries [14].

The chemical composition of crude oils is a complex mixture of thousands of organic compounds containing alkanes, cycloalkanes, aromatic compounds and asphalthenes. However, it differs significantly among the oils, depending on their origin [15]. Organic compounds containing oxygen, nitrogen, sulphur, as well as organometallic compounds are also found in smaller amounts [3, 16]. Crude oils containing large and heavy hydrocarbon molecules ranging from 5 to 40 carbons in length do not dissolve readily in water [3, 6]. The most toxic components of crude oils are the polycyclic aromatic hydrocarbons (PAHs), many of which possessing mutagenic and/or carcinogenic properties [2, 17]. Moreover, the chemical and physical properties of oil begin to change when it enters the sea and undergoes the so-called weathering. Initially, the oil spreads on the water surface forming a thin film. Some of the oil compounds evaporate, some dissolve in the water, and some form emulsions. Waves contribute to oil becoming mixed into the water column as oil droplets that may aggregate, and oil slicks may also sink and be deposited on the seafloor (sedimentation). The viscosity and behaviour of the oil is greatly affected by the ambient temperature as higher temperatures accelerate the vaporisation, dissolution, and biodegradation of the oil compounds [6]. The longest persistence

of an oil spill has been found in soft sediments and on shorelines protected against strong wind and waves. In general, rocky headlands are quickly cleansed by wave and tidal actions. Oil contamination of sediments can be very long lasting, and long-term effects on benthic organisms have been seen in several cases [18].

During an average winter, ca. 40% of the Baltic Sea area is covered by ice. In Arctic marine environments, the spilled oil can be frozen into the ice sheet in various ways, and this preservation is expected to reduce evaporation, dissolution, and degradation. The preservation also implies that the oil will retain much of its potential toxicity upon release from the ice [19]. The estimation of the pathways, release rates, and chemical characteristics of the remaining oil provide the basis for eventual environmental risk and impact assessments [20].

Today, different response methods for removing oil are applied in order to minimise the environmental consequences of oil spills. Oleophilic skimmers are the most used type of mechanical oil spill response equipment. When employed on a large scale, the mechanical recovery method may be very time consuming and expensive due to its low recovery rates [21]. In situ burning, where an oil slick is ignited and burnt in a controlled manner, is considered to be a response method with high potential of oil removal in Arctic conditions [22]. The use of dispersing chemicals is aimed at increasing the natural potential for oil removal from the sea surface by dispersing the oil in the water column [23]. This oil spill response method was the main method used during the *Deepwater Horizon* blow-out accident aboard an oil-drilling platform in the Gulf of Mexico [24]. However, there is not much experience on the effectivity and hazardous effects of use of dispersants in Arctic areas. Currently dispersants are not used in the Baltic Sea because they are not recommended by the Helsinki Commission (HELCOM).

It is well known that in case of an oil spill, seabirds are among the groups of animals that are most vulnerable (e.g. [25]). Even small amounts of fresh oil can have lethal effects on seabirds by destroying the waterproofing of their plumage, leading to loss of insulation and buoyancy and causing rapid death by hypothermia, starvation or drowning [26]. In the Arctic, these impacts are intensified, as the cold water leads more rapidly to hypothermia. Marine animals can take up PAHs and other crude oil components both passively, i.e. through diffusion over gills (invertebrates and fish) and lungs (birds and mammals), and actively, e.g. through feeding. Biomarkers, indicating changes at the lowest levels of biological complexity (molecular, cellular, tissue-level), provide an "early warning" of ecosystem health deterioration and have been recently suggested by the effect-based tools report of the European Commission to be used for monitoring

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under the EU Water Framework Directive [27]. In addition, marine monitoring programmes are increasingly including biomarkers in the assessment of biological effects of pollutants. Assessments of the consequences of oil spills is necessary for providing information on the maintenance of biodiversity and the integrity of marine communities and food webs, as well as for protecting critical habitats and safeguarding human health [28, 29].

Aims

The core aim of the GRACE project is to develop, compare and evaluate the effectiveness and environmental effects of different oil spill response methods in cold climate conditions. To date, several approaches have been proposed in the polar region, each catering to specific governmental or environmental requirements that inhibit broad application. GRACE aims to develop such a broadly applicable decision-support tool. Furthermore, a system for the real-time observation of underwater oil spills and a strategic tool for choosing oil spill response methods are developed. Currently, there are no automated systems available that can perform oil spill identification and monitoring in a single united integrated system consisting of remote sensing and in situ sensing. Furthermore, the satellite-detected (e.g. by EMSA's CleanSeaNet) oil spills are validated by eye [30].

The overall objective of the project is to explore the environmental impacts and benefits of a suite of marine oil spill response technologies in the cold climate and ice-infested areas of the North Atlantic and the Baltic Sea. The response methods considered include mechanical collection in water and below ice, in situ burning, use of chemical dispersants, natural biodegradation, and combinations of these. The impacts of naturally and chemically dispersed oil, residues resulting from in situ burning, and non-collected oil on fish, invertebrates (e.g. mussels, crustaceans) and macro-algae are assessed by means of highly sensitive biomarker methods, and specific methods for the rapid detection of the effects of oil pollution on biota will be developed. By observing, monitoring and predicting oil movements in the sea by using novel online sensors on vessels, fixed platforms including gliders and the so-called SmartBuoys together with real-time data transfer into operational systems that help to improve the information on the location of the oil spill, situational awareness of oil spill response can be improved. Methods and findings of the project are integrated into a strategic net environmental benefit analysis tool for oil spill response strategy decision making in cold climates and ice-infested areas.

Project concept and approach

GRACE aims to achieve the research goals over a period of three and a half years, starting in 2016 and ending in 2019. The project includes a genuine transdisciplinary consortium comprising experts in the fields of oil monitoring and on-line observations, as well as oil spill response authorities. It makes use of bioanalytics, field and laboratory studies, environmental impact assessment, monitoring and assessing the fate of oil pollutants as well as oil-degradation-related biotechnology, and also contributes to the development of oil spill response technology.

Beyond producing relevant knowledge on technologies that can be used for oil spill response and on their impacts, GRACE develops a tool for strategic net environmental benefit analysis, the environment and oil spill response (EOS) tool for deciding suitable oil spill response strategies in cold climates and ice-infested areas. The EOS results can be used in cross-border and transboundary co-operation and agreements. All gathered knowledge will be fed into the development of a beyond state-of-the-art response system based on high-end detection methods and environmentally friendly yet highly efficient mitigation and remediation techniques.

Project consortium

The genuine trans-disciplinary consortium with workgroups and scientists from Europe and Canada conducting the GRACE project consists of 13 partners. Leading research scientist Kirsten Jørgensen from the Finnish Environment Institute SYKE coordinates the project. The project partners are grouped into six work packages (WP), presented below with their contributing members and specific project tasks (Table 1).

Work packages

WP1—Oil spill detection, monitoring, fate and distribution (Lead: Tarmo Kõuts, TUT)

The main objective of this WP is to make in situ operational oil spill detection more accurate and cost-effective. The oil-in-water sensors, the core of in situ oil detection, are commercially available nowadays. However, their performance varies to a large extent, which is why the potential of in situ measurement technologies in respect to their accuracy and representativeness to detect oil spills in surface water of the sea needs to be analysed and tested. The existing oil spill detection and monitoring sensors could also be integrated with new platforms, such as ships of opportunity (SOOP), Smart Buoys, gliders or drifters for in situ oil spill detection. Furthermore,

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Table 1 Composition of the GRACE project consortium

Participant organisation name	Acronym	Country	Person in charge	Contribution to WP number
Coordinator				
Finnish Environment Institute	SYKE	Finland	Kirsten S. Jørgensen	1,2,3,4,5,6
Aarhus University	AU	Denmark	Susse Wegeberg	2,3,4,5,6
University of Tartu	UTARTU	Estonia	Jaak Truu	2,3,4,6
Tallinn Technical University	TUT	Estonia	Tarmo Kõuts	1,3,4,5,6
RWTH Aachen University	RWTH	Germany	Thomas-Benjamin Seiler	1,2,3,4,6
University of the Basque Country	UPV/EHU	Spain	Ionan Marigomez	2,3
Norwegian Univ. of Science and Technology	NTNU	Norway	Bjørn M. Jenssen	3
Greenland oil spill response A/S	GOSR	Greenland	Lonnie Bogø Wilms	4,5
LAMOR corporate Ab	LAMOR	Finland	Rune Högström	2,4,5
Meritaito Oy	MTOY	Finland	Seppo Virtanen	1
SSPA Sweden AB	SSPA	Sweden	Björn Forsman	1,4,5
Norut Narvik AS	Norut	Norway	Christian Petrich	2,4
University of Manitoba	MICB	Canada	Feiyue Wang	4

Table 2 The main methods and expected outcome the work of WP1: oil spill detection, monitoring, fate and distribution

General experimental procedure	Aims and expected outcome	Refs.
Development and characterisation of novel systems for the online exposure of zebrafish embryos under flow-through conditions	A novel biosensor based on the behavioural responses of zebrafish embryos for the detection of oil in water	Steffens et al. [31] Nüßer et al. [32]
Integration of UV—fluorometers into FerryBox and SmartBuoy platforms	Operational, real-time oil spill detection on fairways	Petersen [33] Lambert [34]
UAVs and gliders are used to monitor localised oil pollution. UAVs are used for mapping of oil spread on the surface. Gliders determine the spatial distribution of an oil spill and its temporal evolution underwater	Monitoring and mapping the oil pollution from a shipwreck using UAVs and gliders	OGP/IPIECA [35] URready4OS [36] Vasilijevic et al. [37] American Petroleum Institute [41] IPIECA-OGP/IMO/CEDRE [38] Fingas and Brown [39]
Combined use of drifters and UAVs to improve oil spills situational awareness in tactical scale	UAV systems together with drifter buoys is a cost-effective way to monitor different marine parameters in case of oil spills, improving considerably situational awareness of operations	Lumpkin et al. [40] IPIECA-OGP/IMO/CEDRE [38] American Petroleum Institute [41]
Lagrangian model is applied to assess oil short-time fate in the realistic marine environment combined by meteorological and oceanographic models	Oil fate modelling: hind- and forecast module ready to be integrated with measurement systems	Wolk [42] Gräwe and Wolff [43]

a new local scale model system for oil dispersion, evaporation and fate should be developed (Table 2).

WP2—Oil biodegradation and bioremediation (Lead: Jaak Truu, UTARTU)

The main objective of this WP is the assessment of natural degradation rates of different oil fractions in seawater, seawater–ice interface, sediments, and shoreline taking into account environmental parameters, dispersants application, cleaning and washing agents, and electrokinetic treatment. Based on the determination of key bacterial species and metabolic pathways responsible for

the degradation of different oil fractions in different sea compartments of the Baltic Sea and the Northern Atlantic, a metagenomic prediction platform for inferring oil biodegradation activity parameters (including biodegradation kinetics) in cold marine environment is being constructed (Table 3).

WP3—Oil impacts on biota using biomarkers and ecological risks assessment (Lead: Thomas-Benjamin Seiler, RWTH)

The main objective of WP3 is the achievement of knowledge on (i) biological impacts and adverse outcome

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Table 3 The main methods used and expected outcomes of WP2: oil biodegradation and bioremediation

General experimental procedure	Aims and expected outcome	Refs.
Seawater microcosms with Crude oil water accommodated fraction (WAF) and addition of chemical dispersant at cold temperature. Chemical oil analysis and molecular biology analysis	Oil and dispersed oil biodegradation rate and kinetic parameters at low temperature. Knowledge on main microbial taxa participating in oil biodegradation	Reunamo et al. [2] Venosa and Holder [44]
Sea ice experiments with encapsulated oil in laboratory scale. Chemical oil analysis and molecular biology analysis	Natural degradation rate of crude oil in seasonal sea ice covered water. Knowledge on key microbial species and metabolic pathways responsible for biodegradation of oil	Brakstad et al. [45] Garneau et al. [46]
Omics data integration and meta-analysis of project-obtained and public domain data by recovery of individual genomes from obtained metagenomics datasets	Information about microbial community taxonomic composition and metabolic markers. Better understanding of the role of uncultivated microbial species in oil biodegradation	Huang et al. [47] Klemetsen et al. [48]
Field pilot test with electrokinetic treatment of petroleum hydrocarbon contaminated marine sediment. Chemical oil analysis and molecular biology analysis of field samples	Documented information on the performance of electrokinetic treatment as a method for marine sediments clean-up	Masavat et al. [49]
Effect-based assessment of remediation success by cellular level bioassays	Success of the remediation method evaluated for the mixed contamination using bioassays	Brack et al. [50]

Table 4 The main methods and expected outcomes of WP3: oil impacts on biota using biomarkers and ecological risks assessment

General experimental procedure	Aims and expected outcome	Refs.
Effect biomarkers in blue mussels from a North Atlantic transect and seasonal samples from Baltic Sea	Latitudinal and seasonal biomarker baselines and variability for exposure assessment	Leiniö and Lehtonen [51]
Passive sampling of oil components in the study area and extract testing in vitro	Environmental relevance of oil contamination	Posada-Ureta et al. [52]
Investigation and storage of specimen samples	Build-up of an environmental specimen bank for oil spill impact diagnosis and prognosis	Villares et al. [53] Garmendia et al. [54]
Effects of WAF of pure and dispersed oil on mussels, copepods, zebrafish and endemic sticklebacks using biomarkers and gene expression	Understand how molecular modes of action cause apical effects	Counihan [55] Hansen et al. [56] Knag and Taugbøl [57] Van der Ost et al. [58] Turja et al. [59]
Zebrafish embryo and larvae toxicity test at different salinities and with WAFs prepared at different temperatures	Adapt the assay to Baltic Sea conditions, also as a pre-requisite for the biosensing in WP1	Perrichon et al. [60] de Soysa et al. [61]
Measurement of the effect of WAFs of different oil types by means of a large bioassay battery	Derive toxicity profiles as fingerprints and relate to differences in oil composition, complement chemical analysis	Singer et al. [62]
Biomarker measurement in field-exposed mussels and snails (WP4)	Effects of in situ burning on aquatic invertebrates and environmental assessment of this method for oil spill response	Turja et al. [63] Marigómez et al. [28, 29]
Risk analysis oil spills and dispersants use by means of the PETROTOX model	Refine the risk assessment of oil spills and responses using the data produced in WP3 and feed the result into WP4	Redman et al. [16]

links elicited after oil spills, and (ii) the effects oil spill responses in different environmental and biological conditions at a regional scale. Furthermore, it aims at the development, adaptation and optimisation of effect-based methods for oil pollution monitoring, and at the assessment of the efficiency of each response method. In addition, scenario-targeted environmental risk assessments (ERA) are conducted (Table 4).
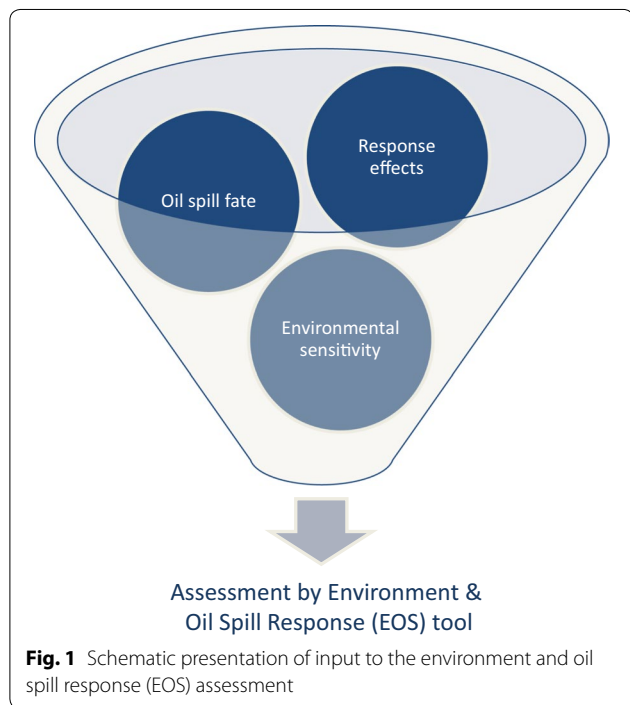
WP4—Combating oil spill in coastal Arctic waters—effectiveness and environmental effects (Lead: Kim Gustavson, AU)

The main objective of this WP is to improve the knowledge base for combating oil spills in ice-infested and cold waters. In addition, a mechanical unit for removal of oil under sea ice is being designed and tested. Environmental fate and effects of stranded oil, shoreline cleaning by in situ burning and shoreline clean-up by chemical agents in Arctic regimes are also assessed. The results of the experiments will provide valuable information for decision makers regarding oil spill response options to be included in the EOS assessment for oil spill response strategy and capacity building in the Arctic and the Baltic Sea (Table 5).

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Table 5 Main methods and expected outcome of WP4: combating oil spill in coastal Arctic waters—effectiveness and environmental effects

General experimental procedure	Aims and expected outcome	Refs.
Controlled outdoor experiments with burning of oil in sea ice	New knowledge on temperature development, burning efficiency and melt pool behaviour	Buist [64]
Field tests with in situ burning of oil on the shore line and in the open water in Greenland after obtaining permission from the authorities. Monitoring of impact on seaweed and invertebrates of burning and burning residues in seawater and on the shore	New knowledge on how to ignite and control the burn and function of pyro booms. New experience in how to collect burning residue. New information on long-term monitoring of impact on biota by in situ burning	Fritt-Rasmussen et al. [65]; Fritt-Rasmussen et al. [66]
Small-scale field studies on coasts in the Arctic, represented by a north–south gradient in Greenland by deploying oiled tiles in the tidal zone	Evaluation of the self-cleaning potential and biodegradation of stranded oil on of rocky coasts in the Arctic by deploying oiled tiles and *Fucus distichus* tips in the tidal zone	Fukuyama et al. [67]
Establishment of an "Oil in ice code" to describe ice formation and interaction with oil	Tool for facilitation and streamlining of efficient communication between all professionals and stakeholders involved in oil spill issues related to sea ice	Lewis et al. [68]
Design and testing of a new mechanical under ice unit for collection of oil under ice	Commercial product for mechanical collection of oil under ice to be used with existing remotely operated vehicles (ROVs)	Singsaas et al. [69]

Fig. 1 Schematic presentation of input to the environment and oil spill response (EOS) assessment

WP5—Strategic net environmental benefit analysis (SNEBA) (Lead: Susse Wegeberg, AU)

The main objective of the WP is to develop and launch a strategic net environmental benefit analysis (SNEBA) tool for decision-making. During the project the title of the tool to be launched was changed to environment and oil spill response (EOS) and it will be used for designing an appropriate and rapid oil spill response strategy combining the right mix of interventions (e.g. mechanical recovery, in situ burning, chemical dispersants, and/or bioremediation) for closed basins with extreme cold temperatures, based on relevant scenarios (Fig. 1).

An EOS assessment should not be confused with a net environmental benefit analysis (NEBA)/spill impact mitigating assessment (SIMA) for acute oil spill situations (Table 6).

Prospects for the GRACE project

The work obtained in the different work packages is strongly interlinked, and the results will be communicated not only to the scientific community, but also very actively to the relevant stakeholder groups such

Table 6 Main methods and expected outcomes of WP5: strategic net environmental benefit analysis (SNEBA)

| General experimental procedure	Aims and expected outcome	Refs.
Development of matrices for data collection to serve as input for a strategic analysis. Gathering of data on biodiversity and oil ecotoxicology and national frames for oil spill sensitivity. Modelling of relevant oil spill scenarios (Disko Bay, northern part of Baltic Sea)	Matrices and decision tree tool approaches to be used in the further development of the EOS tool	Wegeberg et al. [70] Liungman and Mattsson [71]
Application of logistic tools and operational selection guidance. Defining operational requirements. Designing Risk assessment model based on existing knowledge	General operational requirements for the operational window and resource logistics. Description of the background data on spill risk modelling and the design of the designated spill risk assessment model for application in GRACE	Lewis et al. [68]
Construction of a strategic the environment and oil spill response (EOS) tool. Design, input flow and potential value calculations. Evaluation using a fuzzy logic model. Interactions with stakeholders in workshop	EOS tool based on matrices, explanatory boxes and decision trees Compiling of data from Grace. The fuzzy logic model allows merging experts' opinion per compartment into one single score	Bock et al. [72] Laanemets et al. [73] Wenning et al. [74]
Development of an e-learning course for EOS	Framework for an E-based distance learning, video lectures, exercises and a final report on the EOS tool	Jensen and Fritt-Rasmussen [75]
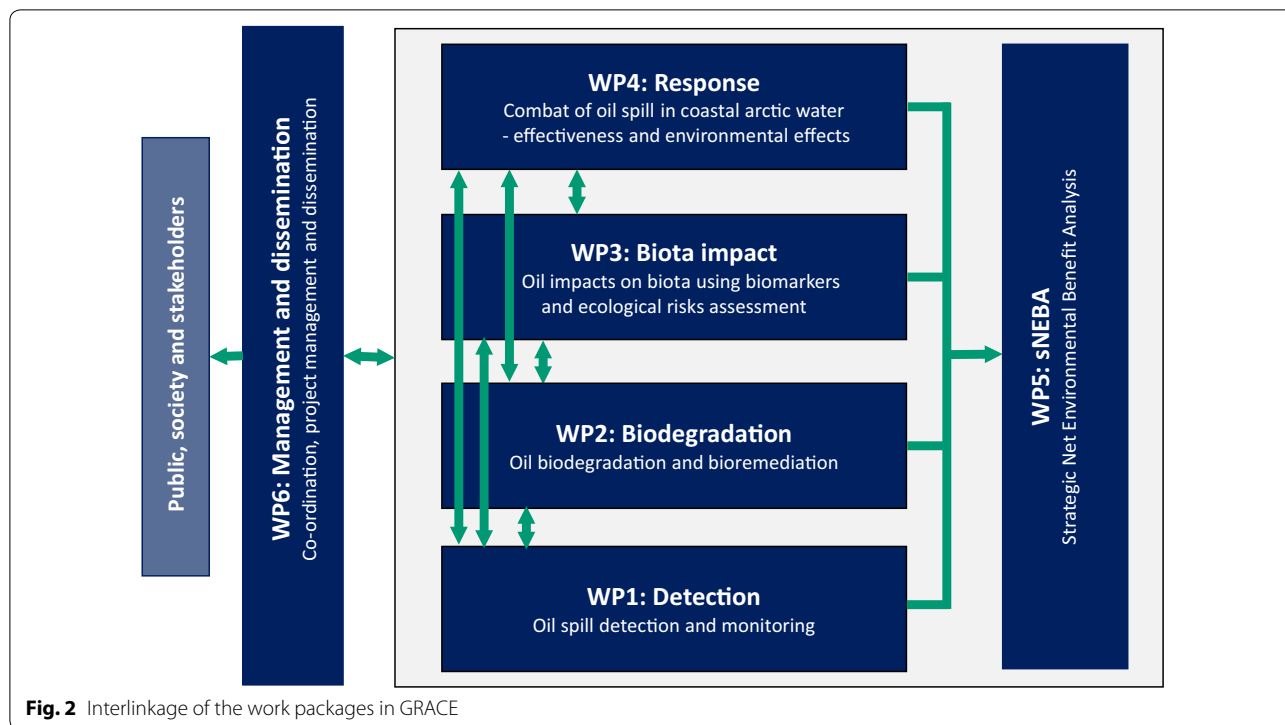
Fig. 2 Interlinkage of the work packages in GRACE

as cross-border working groups dealing with oil spill response in the Arctic including, e.g. the EPPR (Emergency Prevention, Preparedness and Response) working group of the Arctic Council and the HELCOM RESPONSE working group (Fig. 2).

The project has already produced a large number of reports that are available at the GRACE project web site http://www.grace-oil-project.eu. The expected impacts of GRACE are several:

- Mitigate negative impacts of oil pollution and response activities on the marine environment, coastal economies and communities.
- Better decision support tools for oil spill response strategy in different conditions.
- Improve the integration between the scientific community and relevant government agencies charged with dealing with pollution, including cross-border and trans-boundary co-operation.
- Better business potential for companies producing oil response equipment and monitoring services.

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Abbreviations

EU: European Union; GRACE: Integrated oil spill response actions and environmental effects; SAR: search and rescue; PAHs: polycyclic aromatic hydrocarbons; EMSA: European Maritime Safety Agency; SNEBA: strategic net environmental benefit analysis; EOS: environment and oil spill response (EOS); SYKE: Suomen ympäristökeskus; WP: work package; TUT: Tallinn University of Technology; SOOP: ships of opportunity; UV: ultra violet; AUV: autonomous underwater vehicle; UAV: unmanned aerial vehicle; UTARTU: University of Tartu; RWTH: Rheinisch-Westfälische Technische Hochschule; WAF: water-accommodated fraction; ERA: Environmental Risk Assessment; AU: Aarhus University; ROV: remotely operated vehicle; NEBA: net environmental benefit analysis; SIMA: Spill Impact Mitigation Assessment; EPPR: Emergency Preparedness and Pollution Response; HELCOM: Helsinki Commission on the protection of the marine environment of the Baltic Sea; IMO: International Maritime Organization.

Availability of data and materials

Not applicable.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests. Henner Hollert is Editor-in-Chief of Environmental Sciences Europe.

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