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Integrated Environmental Mapping and Monitoring:

A methodological approach for end-users

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Through my whole career, during my studies, while working with the pollution control authorities and in the oil and gas industry, I have been working with environmental monitoring and environmental monitoring related issues. During this time I have seen large technological advances, potentially enabling a much better understanding of the environment and environmental processes. When moving between academia, the regulating authorities and industry my impression is that we, in most cases, all see the need for collaboration to obtain satisfactory results. That said, there are unfortunately still cultures that are primarily concerned with "feathering one's own nest". I am convinced that to solve the environmental challenges we need a holistic approach that utilises the technological opportunities, that makes data available and that develops analytical methodologies for further exploration of the inherent knowledge available in the data. To manage this we have to work with an interdisciplinary mindset. I truly believe that the proposed approach and the different papers included in this thesis can contribute to show the potential for enhancing the environmental knowledge through proper planning, data sharing and interdisciplinary collaboration and communication. Such an approach is a precondition for a successful integrated environmental mapping and monitoring (IEMM) and thereby reasonable environmental management.

I would like to thank Statoil for given me the opportunity to perform this industrial PhD. Furthermore I would like to thank my open minded and interdisciplinary supporting supervisors; Geir Johnsen, Tim W. Nattkemper, Asgeir J. Sørensen, Ståle Johnsen and Vidar Hepsø. Thanks to Mona Låte and Ingvar Eide for all your help and support, to all co-authors, colleagues at Statoil Research Centre in Trondheim and staff and fellow students at Trondheim Biological Station (none mentioned, none forgotten). This has been a great interdisciplinary journey and I have learned so much from each of you. The last four years have been hard work and a lot fun; it has been a true honour working with each of you!

I would also like to thank my family for all their support. A special thanks to Helge who have encouraged and supported me 24/7. You are patient, kind, a brilliant amateur cook and rather strict when required. I believe you have balanced the performance of these characteristics pretty well through this 4-years journey.

Ingunn Nilssen
Preface

“The world has only seen a few geniuses.
The rest of us need to collaborate.”

Asgeir J. Sørensen
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III. Johnsen, S., Nilssen, I., Pinto, A. P. B., Torkelsen, T., 2014. Monitoring of impact of drilling discharges to a calcareous algae habitat in the Peregrino oil field in Brazil. SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, Long Beach, California, USA. Doi: http://dx.doi.org/10.2118/168356-MS


Contribution

The principles presented in Paper I were the preconditions for the initiation of my thesis. The paper presents a methodological approach for optimised data sampling and knowledge gathering. The paper was initiated after a UNIS course on underwater robotics (AB834) at Svalbard in 2014. IN and ØØ were the main contributors to the paper and IN had the lead of the writing process.

Paper II was initiated by three of the professors from the UNIS course in underwater robotics (AB334/834). These professors were also co-authors of Paper I. The paper focuses on how enabling technologies can contribute to increase knowledge about the Arctic ecosystem. The paper is published in a journal without a peer-review process. IN was involved in the final stage of the paper contributing with the methodological principles for the approach presented in paper I.

Paper III is a conference paper summarising the experiences from the Peregrino environmental monitoring of calcareous algae (PEMCA) project in Brazil with particular focus on hardware. The conference does not provide peer-review of the presented papers. The paper was initiated by SJ. IN took an active part in the planning and execution of the PEMCA project, as well as in writing the paper.

Paper IV is part of the PEMCA project and presents the results from the long-term exposure study, establishing threshold levels for particulates on two species of red calcareous algae. The paper was initiated by SJ. Planning, sampling of organisms, building of the flow through system and laboratory experiments were carried out by the team of MAOF, IR, ABV-B, FTST, GCF and RC. IE performed the experimental design, the multivariate data analyses and led the writing process. In addition to her contribution in the planning and execution process of the PEMCA project, IN took an active part in writing the paper, with specific focus on the biological parts.

Paper V is also a PEMCA paper, using automatic image analysis to detect changes in size and colour from photos of red calcareous algae from long-term exposure to particulates. JO initiated the work and was the main contributor. IN contributed with biological skills in discussions and in the writing process, particularly Introduction and Discussion. An important part of the writing process was to facilitate the text for an interdisciplinary audience.
Paper VI is another PEMCA publication, using multivariate data analysis on various field measurements and discharge data to investigate possible influence of water-based drill cuttings on a calcareous algae habitat. IE and FW did all the data processing and the multivariate data analysis. IE led the writing process, while IN took an active part in writing the paper, with specific focus on the biological parts.

Paper VII uses the results from PEMCA, including threshold levels from laboratory study (Paper IV), measured field data and data on drilling discharges (Paper VI), as input data to the dispersion and risk modelling to improve the risk assessment. IN initiated the paper and led the writing process. The modelling was performed by FdS, NG and MMC.

Paper VIII uses photos from the online LoVe Ocean Observatory, Norway, for development of algorithms to monitor shrimp abundance in a cold-water coral reef automatically. The work was initiated by JO. JO was the main contributor and led the writing process. IN contributed with biological skills in the planning and writing process, particularly the Introduction and Discussion chapters. An important part of the writing process was to facilitate the text for an interdisciplinary audience.

Paper IX is a conference paper where photos from the online LoVe Ocean Observatory, Norway, are used to develop algorithms for simultaneous and automatic detection and grouping of organisms. The paper was initiated and the main contribution has been performed by TM. IN contributed with biological skills in the writing process and in the process of facilitating the text for an interdisciplinary audience.

Paper X describes the potential of images to improve environmental knowledge in general. Why images have the potential of being good communicative and collaborative tools and how interdisciplinary communication and collaboration can contribute to enhance the inherent knowledge available in the images is being elucidated. The work was initiated by VH and IN. IN was the main contributor and led the writing process.
Abbreviations and definitions

Adaptive sampling – sensors or sensor carrying platforms are operating automatically and/or autonomously. Sensors can be programmed to automatically switch on/off when certain conditions are present or the sampling mission is programmed to autonomously follow a given phenomenon, parameter or object of interest.

Automatic – The system follows a defined program. In the context of this thesis, the term “automatic” is used to describe data sampling and/or data interpretation

Autonomous – action initiated independent of control from outside, e.g. the system makes choices without human interaction. In the context of this thesis “autonomous” is exclusively used with respect to sensor carrying platforms

CPI – Carbon Preference Index

Drill cuttings – particulates of crushed rock originating from the formation rock a well is drilled through

Flexible environmental mapping and monitoring – the measured parameters and the spatial and temporal coverage and resolution are selected based on (and will vary dependent on) the purpose of the mission, the area of interest and possible anthropogenic influence in the area

Infauna – Aquatic animals that live beneath the surface of a sea or lake floor, such as clams or burrowing worms

IEMM – Integrated environmental mapping and monitoring, is performed as a part of an already ongoing activity, such as the daily operations of an oil field or routine cruises for fish stock estimations. Such an approach can provide cost-efficient monitoring through targeted measurements, multiuse of data, e.g. leak detection and current measurements, or access to additional sampling for limited costs due to available infrastructure.

Interdisciplinary – collaboration between/activity involving two or more scientific disciplines

IOP – Inherent Optical Properties

Lander – stationary sensor carrying platform

LoVe – Lofoten-Vesterålen

Ocean Observatory – stationary sensor carrying platform

PAH – Polycyclic Aromatic Hydrocarbons
Parameter – a coefficient that might be either constant or time varying, in contrast to a variable that is a time varying state of a dynamic system. So, all variables are parameters but a parameter might not necessarily be a variable. For instance is a manually set white balance in a camera or a threshold value derived from literature a constant (parameter) and not a variable. The term parameter is in the context of this thesis used for both terms.

PCA – Principal Component Analysis

PEC – Predicted Exposure Concentration

PEMCA – Peregrino Environmental Monitoring of Calcareous Algae

Photosynthetic efficiency – *in vivo* maximum quantum yield of charge separation in photosystem II in dark acclimated cells ($\Phi_{\text{PSII, max}}$)

PLS – Partial Least Squares

PNEC – Predicted No Effect Concentration

RGB – Red, Green, Blue (the three colour channels utilised in ordinary cameras)

ROV – Remotely Operated Vehicle

SSD – Species Sensitivity Distribution

TAR – Terrestrial-Aquatic Ratio

Transect – a path or track investigated by a sensor carrying platform counting and/or recording occurrences of parameters or species

Variable – In the context of this thesis used related to the multivariate data analysis, describing the characteristic of a unit

Water-based drill cuttings – particulates from the formation rock mixed with residuals of water-based drilling fluids. Drilling fluids are used to lubricate and withstand the pressure from the formation when drilling a well
1 Introduction

The motivation for this thesis is to describe a methodological approach for integrated environmental mapping and monitoring (IEMM). Furthermore, to demonstrate how IEMM can benefit from a flexible and interdisciplinary approach by adjusting sampling strategy and data interpretation to mission and processes, object and/or area of interest. To optimise data processing and visualisation of the results presented to end-users and decision makers, joint effort from a suite of scientific disciplines is required. Data with adequate temporal and spatial coverage and resolution can either be utilised as recorded or as input to applications such as dispersion models, ecosystem modelling, risk assessment and/or being visualised in portals for shared situation awareness. Access to such data can improve environmental management and enhance environmental performance, if provided to the end-users in due course.

In the following sections the importance of 1) measurements adjusted to purpose, 2) use of enabling technologies 3) awareness of the human capabilities of interpreting objects and movements and 4) interdisciplinary communication and collaboration will be elaborated. The latter covering both, utilising the inherent knowledge available in the images themselves and their communicative capabilities for use in decisions and for management purposes. The pullet points listed above are all essential aspect of awareness for a flexible environmental monitoring. The thesis presents the entire concept. The different aspects (steps) will briefly be described in the main text and the different papers (Paper I – X) will be used to exemplify and elucidate the individual aspects. The thesis is, to a large extent, organised in accordance with the layout of Paper I and Paper X, describing the planning, execution and knowledge accumulation steps, human factors related to data interpretation and visualisation and interdisciplinary communication and collaboration, respectively.

1.1 Background

Recent advances in enabling technologies are expected to enhance the current understanding of the environment and its dynamic processes. Some examples from the Arctic where use of enabling technologies has led to new knowledge about the ecosystem during the polar night are Berge et al. (2015a), Berge et al. (2015b) and Cohen et al. (2015). Although the human visual system has an impressive ability in recognising human movements in time and space, research shows that it performs worse when confronted with objects and
unfamiliar organisms (Shiffrar and Thomas, 2013; Smith and Kosslyn, 2014), such as marine organisms. According to the technology philosopher Don Ihde, it is the applied sensor technology used that determines the nature of the captured data and how they are presented (Ihde, 1979; 1991). From this perspective the rapid technology developments are challenging the human ability to interpret and understand the variety of novel data provided. Ultimately, this might even contribute to challenge the implementation of integrated environmental management systems.

Globally, a variety of approaches for environmental management systems exist and challenges related to implementation have been described, among others, by Borja and Dauer (2008), Elliott (2014) and Leslie and McLeod (2007). The European Commission launched in 2010 the Europe 2020 strategy on a “smart, sustainable and inclusive growth” (European Commission, 2010). The Blue Growth strategy represents the maritime area of the strategy. It states that “The individual sectors of the blue economy are interdependent. They rely on common skills and shared infrastructure …” and “They depend on others using the sea sustainably” (Directorate-General for Maritime Affairs and Fisheries, 2012). Examples of increased focus from industry on the benefits of an integrated use and monitoring of the environment are Hepsø et al. (2012) and Kongsberg Maritime (n.d.). Several guidelines, of instance from CCME (2015) and USEPA (2006) describes planning procedures to ensure a cost-efficient selection of the data needed (qualitatively and quantitatively) to address possible impact on resources present when evaluating different alternatives, such as infrastructure developments, use of chemicals and/or discharge regimes. A similar approach has been established for risk assessment related to oil and gas related activities in cold-water coral areas in Norway (DNV, 2013). The principles of environmental risk assessment implemented among others by the European Commission (ECHA, n.d.) and in the United States (USEPA, 2016) are based on the PEC/PNEC ratio (Predicted Exposure Concentration and Predicted No Effect Concentration). The PEC/PNEC approach is commonly used by offshore operators in Europe (Smit et al., 2011). These principles are accepted by the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) as a basis for environmental management of produced water discharges (OSPAR, 2012a, b). Under such a regime dispersion and risk modelling is used to identify the major risks related to added chemicals and/or natural occurring substances of planned discharges from a specific activity or a set of simultaneously ongoing industrial activities. Typical inputs to the models predicting the concentrations of the discharges in the environment (PEC) are
discharge characteristics (type, amounts, rates or volumes, density, depth, etc.) and geographical information such as bathymetry, water depth and current speed and direction (modelled or preferably measured). The risk is then assessed based on the comparison of PEC and PNEC, where PNEC is commonly derived from species sensitivity distribution (SSD) curves (de Zwart and Posthuma, 2005; Harbers et al., 2006; Smit et al., 2008) or by application of an assessment factor to the most sensitive species (ECHA, 2008). The lack of ecosystem relevance by the use of standard toxicity data is a major criticism against the PEC/PNEC approach. However, if available, species specific effect data can replace the standard toxicity data in the risk modelling (Beyer et al., 2012; Larsson et al., 2013; Purser and Thomsen, 2012).

Systems accepting a risk-based approach require an environmental monitoring that is flexible in all aspects from selection of parameters and sensor carrying platforms to data access (online or offline) and methodology for data processing and analyses. The measured parameters and the spatial and temporal coverage and resolution should in each case be selected based on the mission, the identified risks, the object of interest and anthropogenic influence in the area (Godø et al., 2014b; Hepso et al., 2012). The aim of mission can span from measuring natural fluctuations to monitoring of point discharges from anthropogenic activities. The object of interest can either be a phenomenon, (an) organism(s), an area (habitat) or a piece of infrastructure. In addition to sampling of data with adequate temporal and spatial coverage and resolution, getting access to already existing data from the area of interest is of importance for the interpretation. Furthermore, of particular importance for decision makers, also the timeframe for data deliveries are crucial. For mapping purposes an offline solution should normally be sufficient, while monitoring in cases where immediate mitigation measures are crucial, online solutions for data access will be required. Also use of models should constitute a vital part of IEMM, as modelling as part of the planning process can be used to optimise both the design of the environmental monitoring programme by predicting the area of influence (Nilssen and Johnsen, 2008) and/or to extrapolate results obtained from a limited part of an habitat to the habitat in general or experiences from one area to similar habitats in other geographical areas (Godø et al., 2014b; Godø et al., 2014c; Hepso et al., 2012).

In addition to a flexible IEMM concept, including use of models, an interdisciplinary effort is also required to enhance the environmental knowledge (Brown et al., 2015; Rylance,
2015; Wuchty et al., 2007) by utilising the inherent knowledge available in the data. According to Carlile (2004) development, change and extension of knowledge occurs when actors with different scientific background use their already existing knowledge and experiences on new tasks. A constructive dialogue between open minded actors, experts within their own disciplines and interested in others, are essential to succeed in interdisciplinary collaborations (Brown et al., 2015). Elliott (2014) emphasises the importance of educating graduates “… willing and able to link the natural and social sciences …” to successfully achieve an “… integrated marine management framework …”\(^1\). In addition, Brown et al. (2015) pinpoint institutional support and bridging research, policy and industry as absolute preconditions to facilitate interdisciplinary collaboration in daily work. The importance of building interdisciplinary scientific capacities has also been stressed, among others, by Leslie and McLeod (2007).

Due to the vast amounts of novel and complex data, focus on human factors such as mindset, interdisciplinary communication and the human capability to interpret and understand various types of data are all essential when presenting data to end-users and decision makers. A comprehensive interdisciplinary collaboration therefore requires development or access to appropriate communicative tools (boundary objects) that are understood by all actors involved (Carlile, 2004). Based on the human cognitive capacities to detect and classify objects and movements (Biederman, 1987; Shiffrar and Thomas, 2013; Smith and Kosslyn, 2014), images could be expected to be well suited for the purpose. Although use of imaging has a long tradition within disciplines such as geology (Almklov and Hepsø, 2011) and archaeology (Adams, 2013), and that use of photos and video recordings in marine environmental mapping and monitoring increases rapidly, the numbers of well established analytical tools are currently relatively limited, with few exceptions (Beijbom et al., 2016; Faillettaz et al., 2016; Orenstein et al., 2016; Osterloff et al., In Press; Prasad et al., 2016; Purser et al., 2009; Schoening et al., 2012).

\(^1\) Integrated refers here to cross sectorial management
1.2 Scientific contribution

The flexibility introduced with the IEMM concept enhances the need of a methodological approach where, in each case, all aspects from planning to interpretation and visualisation of results should assist users and decision makers to identify elements of consideration (Figure 1). Selection of technology with appropriate sensitivity, resolution and coverage (sensor carrying platforms, software etc.) as well as efficient data gathering and access, interpretation and visualisation are all essential if end-users such as operators or decision makers shall be provided with optimised data in due course for mitigation measures to be made. Furthermore, a methodological approach will identify gaps in knowledge, methodology and technology, and thereby any needs for further development and improvements in the different steps of the concept from planning and execution to interpretation of results.

As illustrated in Figure 2, the individual papers of the thesis are all linked to one or more of the steps in Figure 1 (where the papers are positioned in Figure 2 indicates their area of contribution). In paper I and II the methodology is proposed and the different aspects of the methodological approach are addressed and discussed. The planning step (Step 3 in Figure 1) is exemplified and discussed more in depth in Paper III and IV, hardware development and bridging gaps of knowledge with laboratory experiments, respectively. In Paper III the technological experiences and proposed changes with respect to robustness, handleability and sensors are given. Establishment of threshold levels for sedimentation of inorganic particulates to the calcareous red algae *Mesophyllum engelhartii* (Foslie) Adey and
Figure 1: Methodological approach for IEMM, covering the steps from planning of a mission, data gathering and access to interpretation of data as a basis for decision making (Figure 2 in Paper I). For details, please confer the module sections in Chapter 2 and 3 or Paper I.
**Lithothamnion** sp. is described in Paper IV. In Paper V, VIII and IX development of algorithms for automated and semi-automated data analysis of photos related to biological questions, such as detection of organisms and measurement of biological behaviour, is described (Step 5, 6 and 10, Figure 1). Paper VI and Paper VII are examples on data analysis and different data processing and interpretation strategies. In Paper VI multivariate data analyses were used to increase environmental knowledge identifying correlations in the complex datasets. Paper VII uses data from exposure studies (lab) on relevant organisms (Paper IV), field measurements and discharge data (Paper VI) as input data to the dispersion and risk modelling to reduce the uncertainties in the risk assessment at the Peregrino oil field (Step 6 and 10 in Figure 1). Paper X demonstrates why and how images are suitable communicative tools in communication and collaboration between different research fields. Furthermore, the contribution of interdisciplinary communication and collaboration to improve environmental understanding in general through enhanced use of the inherent knowledge available in images, is illustrated. The advantages of using images, such as photos, video recordings and visualisations from modelling in future applications for end-users are also addressed. Since Paper X addresses both current use and future opportunities provided by images, it is located between Step 10 and 11 in Figure 1.
Figure 2: Illustration of the individual papers’ area of contribution in the proposed methodological model. The shaded green boxes are placed in accordance with their area of contribution in the methodology figure (Figure 1) and the corresponding steps are indicated in each of the boxes.

1.3 Data sources

The data used for this thesis are mainly generated from the Peregrino environmental monitoring of calcareous algae (PEMCA) project (Salgado et al., 2010) and from the Lofoten-Vesterålen (LoVe) Ocean Observatory (Godø et al., 2014a; Statoil, n.d.). The experiences from PEMCA, together with other environmental monitoring programmes using lander technology, such as Morvin (Godø et al., 2014b), formed the basis for the technology improvements prior to the LoVe deployment. Technology development was related to robustness, reliability and logistical issues. Also the experiences with photo collection and processing for documentation of possible impact from drilling discharges at Peregrino (unpublished data) and Morvin (Buhl-Mortensen et al., 2015; Godø et al., 2014b) initiated
several changes. For more details, see section 2.1.2 Sensors and sensor carrying platforms and Paper III.

Figure 3: Illustration of the lander hardware development from the PEMCA-lander (a) to the frame deployed at LoVe (b). The weight and the height have been reduced and, for instance the fragile echo sounder system has been much more protected from the surroundings. Illustrations: Terje Torkelsen, Metas AS.

The three-year PEMCA project was initiated at the Peregrino offshore oil field in Brazil (23.31° S, 41.31° W)\(^2\) in 2010. The purpose of the PEMCA project was to monitor the possible impacts from discharges of water-based drill cutting to the calcareous algae habitat present at the Peregrino oil field and to develop and perform an alternative environmental monitoring programme, aligned to the actual discharges and the resources present in the area of interest (Paper III - VII). Since the dominant calcareous algae habitat at Peregrino is present at >100 meters water depth, it was anticipated that discharge of additional particulates from the drilling operations could harm the calcareous algae due to increased sedimentation, appearing as bleaching. The drill cuttings could potentially also increase the turbidity in the water column above the calcareous algae habitat, reducing the irradiance (E) and change the spectral composition of the light (E(\(\lambda\))) reaching the calcareous algae. However, the latter was for practical reasons not included in the experimental design of the PEMCA project. Threshold levels for exposure of particulates to red calcareous algae (\textit{M. engelhartii} and \textit{Lithothamnion} sp.) under realistic light conditions were obtained from laboratory studies.

\(^{2}\) WGS84 given in decimal degrees
Furthermore, the results from the laboratory experiments were, together with field measurements and discharge data from the drilling log (Paper VI), used as input data to the dispersion and risk modelling to improve the environmental risk assessment at the Peregrino field (Paper VII).

The LoVe Ocean Observatory was deployed in September 2013 at a cold-water coral area, 20 km off the north western coast of Norway (N 68°54.474', E 15°23.145') at approximately 260 meters water depth (Godø et al., 2014a). Time-lapse photos (RGB) of the coral habitat, dominated by Lophelia pertusa, were taken with a temporal resolution of one hour. In addition, key environmental parameters such as temperature, salinity, echograms presenting zooplankton and fish biomass at different depths, current speed and direction at several depths, sound, concentration of Chlorophyll a presenting phytoplankton biomass, coloured dissolved organic material (indicating fresh water run-off and different water types) and total suspended matter (water clarity) were measured (Godø et al., 2014a; Statoil, n.d.). The LoVe Ocean Observatory serve several purposes: To 1) further develop and test technology, 2) gather data for improved ecosystem understanding and knowledge of the area in general and 3) improve understanding and knowledge of the cold-water coral reef habitat in particular, and 4) develop methodology for automated data analysis and visualisation. The online-cabled ocean observatory enables observations with high temporal coverage and resolution of a variety of organisms in their natural environment. So far, two different approaches for automatic or semi-automatic image analysis of organisms have been demonstrated at LoVe. For more details see section 4.2 Images in environmental monitoring, Paper VIII, Paper IX and Osterloff et al. (In Press).

3 WGS84 given in degrees and decimal minutes
2 Methodological approach

The proposed approach is meant to be generic and should therefore be relevant for authorities, industry, academia and public in general. The individual steps for IEMM are described in Figure 1 and Step 3-10 will be further elaborated and exemplified under the sections in Chapter 2 and 3.

Step 1 (number 1 in Figure 1) represents the \textit{a priori} knowledge and understanding of the processes, ecosystems, object or area of interest. The mission objectives, formulated based on existing knowledge (Step 1), are given in Step 2. The operational constraints cover availability of appropriate technologies and methods, environmental limitations and cost, detailed planning and replanning/adaption that may take place both autonomously and/or with human-in-the-loop during execution of the mission (Step 3-6). Criteria for sufficient data gathering and basis for decision-making (Step 7) will either define a positive result where mission is completed in accordance with objectives (Step 10), or a negative result where the research questions and mission objectives may need to be reformulated or divided into new sub-goals (Step 8). Considering the given operational constraints the mission will then either be repeated with the new input conditions (Step 3-6) or terminated (Step 11). Step 11 could either give input to further research and development needs or the conclusion is noted without further actions.

2.1 Selection of sensors, sensor carrying platforms and exposure studies

Step 3 in the methodological approach (Figure 4) represents the planning phase where the appropriate parameters (sensors), sensor carrying platforms and exposure (lab) studies (if needed) are selected according to the mission objectives and data requests defined in Step 2, 5, 6 and/or 9, respectively. Depending on the environment, there will be a minimum number of parameters that always should be measured, either as essential parameters or as supporting parameters for interpretation of data gathered. In addition to measuring essential parameters, the quality of the interpretation is dependent on the temporal and spatial resolution and coverage of the data. Hence, considering the dynamics both in time and space is crucial in the mission planning process to enable proper interpretation of the measurements.
Figure 4: Step 3 Selection of sensors and sensor carrying platforms, including exposure (lab) studies. Exposure studies include both laboratory studies, as in this thesis, and field experiments.

### 2.1.1 Temporal and spatial coverage and resolution

Data with sufficient temporal and spatial coverage and resolution is a precondition for a reasonable interpretation of the data and thereby to gain environmental knowledge. Such data is crucial for appropriate decisions and hence, for sustainable management of our ecosystems. For instance, the increasing numbers of fixed ocean observatories will provide data with high temporal coverage and resolution, data that can provide new insight in the natural dynamics of hydrographical data, chemistry and species specific distribution. Paper V, VIII and Paper IX describe different approaches using photos to detect and document natural species specific behaviour and/or distribution (Paper VIII and IX) and potential impact from anthropogenic activities, such as increased sedimentation from drilling discharges (Paper V) with time. Use of photos will be further described under section 4.2 Images in environmental monitoring. When combining various sensor measurements, for instance by using multivariate data analysis, it is important to note that the sampling frequency may vary between different sensors and preprocessing of the data is needed to align them to the same temporal resolution (Paper VI). Taking this into consideration, the
maximum sampling frequency of the individual sensors should be carefully considered as this might be a limiting factor for the entire analysis. On the other hand, if high temporal resolution is of less importance, the sampling frequency should be reduced to avoid unnecessary “noise” and to reduce storage volume.

Figure 5: Spatial and temporal coverage and resolution of different sensor carrying platforms (Figure 3 in Paper 1). ROV (remotely operated vehicle), AUV (autonomous underwater vehicle), UAV (unmanned aerial vehicle) and glider (buoyancy driven autonomous underwater vehicle).

The suitability of the different sensor carrying platforms will vary based on the spatial and temporal coverage and resolution on the data needed, and their capabilities are illustrated in Figure 5 (Figure 3 in Paper I). Often, a combination of sensor carrying platforms will be needed to fulfil the mission requirements. Figure 5 is also illustrating the need for an integrated approach in general. In addition to the different sensor carrying platforms, the figure
is also applicable for dynamic processes on different biological taxa in time and space or to sensor technologies and how the different technologies determines the nature of the captured data and how they are presented, as described in Paper X, Figure 1.

2.1.2 Sensors and sensor carrying platforms: Technology development and improvement

Although sensor carrying platforms with appropriate temporal and spatial coverage and resolution are used, the platform and/or sensors might be inappropriate for the specific mission either due to the environmental conditions in the area or, if applicable, the vessel dedicated for deployment, maintenance and/or recovery (Godø et al., 2014b). One example of the latter is the stationary sensor carrying platform, or lander technology, used as part of the PEMCA project (Figure 3 a) (Paper III). The chosen lander was relatively large and heavy (approximately 2.5 meter high and weighing 3 tonnes). In general, the lander did not represent a good design with respect to robustness and handleability. This suboptimal design, combined with the vessel available, led to complicated deployments and recoveries related to downloading of data and maintenance operations. In addition, unexpected environmental conditions with respect to the continuous strong currents and the corrosive properties of the seawater at Peregrino affected the sensor carrying platform (Paper III) and made the field missions challenging. The experiences from PEMCA lead to a considerable change of the lander design before the LoVe deployment, both with respect to weight (handleability), robustness in general and particularly with respect to protection of fragile instruments such as the echo sounder system. Also the camera settings were improved based on the experiences from PEMCA. First and foremost the camera was moved from a fixed position on the lander with fixed settings and flash to a standalone satellite where the camera and corresponding flash could be adjusted both vertically and horizontally. The angle of the camera, the light scattering on the photos induced by the unexpected high levels of marine snow, and some technical problems related to the settings of the flash, resulted in uneven illumination and overexposure in a majority of the photos from the PEMCA project. Furthermore, at LoVe the collaboration between biologists, engineers and computer scientists was initiated on an early stage of the planning process enabling, as far as possible, to meet the needs from the different disciplines. In contrast to the solution on Peregrino using batteries, the cabled online two-way
communication at LoVe also allowed high temporal resolution of the photos and opportunities with respect to adjustments of camera settings after deployment.

2.1.3 Laboratory experiments to close gaps of knowledge

Another important aspect, normally not a part of the traditional environmental monitoring, is to identify lack of key knowledge with respect to the mission objectives. For instance, being able to evaluate if a specific activity could impact the abundance or dynamics of species negatively, certain background knowledge about the species itself is required. To bridge such knowledge gaps, laboratory studies and/or field experiments might be required to establish threshold levels for the possible impacts. Two examples where such laboratory studies have been performed to establish threshold levels for exposure of water-based drill cuttings are the coral risk assessment, monitoring and modelling (CORAMM) project (Purser and Thomsen, 2012) and the PEMCA project (Paper IV; Salgado et al., 2010). These studies were initiated to establish general knowledge and thresholds for exposure of water-based drill cuttings to the cold-water coral *L. pertusa* and the calcareous red algae species *M. engelhartii* and *Lithothamnion* sp., respectively. Furthermore, controlled experiments can also be performed to investigate how some parameters, such as the composition of the water inherent optical properties (IOPs), might affect other data, such as image quality due to the absorption and/or scattering of light (Johnsen et al., 2013).

In Paper IV the physiological status of the calcareous algae, measured as photosynthetic efficiency ($\Phi_{PSII\_max}$) as function of sediment coverage, was studied in a flow-through system as function of the three design variables light intensity, flow rate and added amount of sediment, in addition to exposure time. Multivariate data analysis, using Partial Least Squares (PLS) regression, showed that added amount of sediment was the major factor reducing photosynthetic efficiency, while water flow rate, light intensity and exposure time had only minor impact within the experimental domain. Exposure–response curves for photosynthetic efficiency as function of sediment coverage were created based on results from the PLS-model predicting photosynthetic efficiency and corresponding effect of sediment coverage by varying the added amount of sediment within the experimental domain (within the maximum and minimum levels). Using the exposure-response curve, the photosynthetic efficiency was reduced by 50% after 1-2 weeks with 70% sediment coverage. These results were further used to establish impact categories with the purpose of reducing
the uncertainties in the field specific environmental risk assessment and to enable common acceptance of stress criteria adjusted to the present ambient conditions, as described in Paper VII.
3 Data sampling and processing

In Step 4–6 data sampling and processing is performed (Figure 6), based on the sampling regime specified in Step 3. If data collected in Step 4 is not in accordance with the data request, a new adjusted request can be made either autonomously/automatically (Step 5) or manually (Step 6) before going back to Step 3. Types of requests could typically be: Restrict the sampling area to where the object of interest is present (mobile sensor carrying platform or movable echo sounder), adjust sampling frequencies (increase sampling when object of interest and/or parameters important for objective of mission is present), adjust range (if mobile sensor carrying platform), etc. until request information has been obtained.

Figure 6: Step 4-6 covering data sampling, autonomous/automatic and manual analyses, interpretation of data and knowledge accumulation.

In addition to optimisation of sampling with sensor carrying platforms, Step 4-6 also cover issues such as automatic or semi-automatic image analysis. Image analyses are further described under section 4.2 Images in environmental monitoring.

3.1 Adaptive sampling

Adaptive sampling can increase the value of the measurements. In addition to an approach being adjusted to purpose as part of the planning process (Step 3), adaptive sampling enables a selective sampling also during a mission. Sensors could be programmed
to switch on and off based on predefined settings, such as concentrations or presence of a certain parameter could trigger other sensors to be switched on. Furthermore, the sensor carrying platform itself could be preprogrammed to follow a desired target (a phenomenon or given organism) of interest instead of a pre-defined transect, which is the common situation. Due to a more targeted data sampling, providing more relevant data and less “noise”, adaptive sampling can also reduce the mission time for data gathering and thereby reduce the operational risk. The approach requires access to real-time data deliveries, or at least fast data processing if the data requests are being made manually.

Adaptive sampling will not be further elaborated as part of this thesis. Power consumption, software development, signal processing guidance and control of sensor platforms are currently at a level that allows implementation of autonomous adaptive sampling (Brito et al., 2012; Cruz and Matos, 2010). However, AUVs for instance still face operational limitations with respect to shortages of power supply and lack of the autonomy needed.

3.2 Data processing and knowledge accumulation

While access to data with sufficient temporal and spatial resolution still is a main limitation when trying to understand the marine environment, the ability to handle, analyse and interpret the increasing amounts of data has become another bottleneck for knowledge accumulation (Step 6). When including images and video recordings, new multi-modal data collections are approaching big data dimensions. Examples of different methodological approaches of data interpretation are given in Papers V - IX. Paper V, VIII and IX describe different approaches for analysis of marine organisms from photos, and these are further described in section 4.2 Images in environmental monitoring. In Paper VI multivariate data analyses are used on a variety of field measurements to evaluate the possible impact of discharges from water-based drill cuttings on a calcareous red algae habitat. In Paper VII species specific toxicity data obtained from laboratory studies are combined with measured discharge and oceanographic data as input in the risk modelling to reduce the uncertainty in the environmental risk assessment.
3.2.1 Interpretation of complex data sets from field measurements

Paper VI demonstrates the benefit of multivariate data analysis for optimized data interpretation in IEMM by enabling integration of a high number of variables. A total number of 178 variables (initially 81 plus 97 derived), 300 sediment trap samples from three sediment traps, and more than 20000 observations from the lander were combined and interpreted by the multivariate data analyses. The lander and sediment traps were deployed at different distances downstream of the discharge point. Current speed and direction at several depths, turbidity, temperature and salinity were measured at the lander, while the sediment traps were used to determine suspended particulate matter which was characterised with respect to a number of chemical parameters (26 alkanes, 16 polycyclic aromatic hydrocarbons (PAHs), nitrogen, carbon, calcium carbonate and barium). Data on discharges of drill cuttings and water based drilling fluid was provided from the drilling log on a daily basis.

Principal component analysis (PCA) was used to evaluate similarities and differences among samples and correlations between variables. PLS regression was used to identify correlations between predictor variables (x) and response variables (y). The multivariate data analysis showed no systematic difference in levels of sedimentation or measured organic and inorganic components between campaigns or traps. In addition, the analysis showed a strong co-variation between suspended particulate matter and total nitrogen and organic carbon, suggesting that the majority of the particles sampled had a natural and biogenic origin. Furthermore, the PLS showed no correlation between discharges of drill cuttings and sediment traps data or turbidity data from the lander in periods with prevailing current directed against these sensors. The different multivariate models supported each other and they were also supported by chemical indicators, such as the Terrestrial-Aquatic Ratio (TAR), the carbon preference index (CPI) and the isometric ratios for PAHs, and numerical modelling of dispersion and deposition.

3.2.2 Combining laboratory experiments, field measurements and modelling in environmental risk assessment

Paper VII describes how the uncertainty in environmental risk assessment can be reduced by utilising data obtained from exposure studies on organisms relevant for the particular area of interest in combination with measured discharge data and measured oceanographic data as input to risk modelling (Figure 7). Dispersion modelling of drill
cuttings was performed for a two-year period using measured oceanographic data and discharge data with a temporal resolution of 24 h (Paper VII). The same model (Beyer et al., 2012; Durgut et al., 2015; Johnsen et al., 2000; Rye et al., 2008) was used to assess the risk of impact on the two algae species *M. engelhartii* and *Lithothamnion* sp. from the Peregrino oil field after establishing four species specific impact categories: No, minor, medium and severe impact. The corresponding intervals for photosynthetic efficiency ($\Phi_{\text{PSII}_{\text{max}}}$) and sediment coverage were obtained from exposure-response relationship for photosynthetic efficiency as function of sediment coverage for the two calcareous red algae species (section 2.1.3 Laboratory experiments to close gaps of knowledge and Paper VI). The temporal resolution enabled more accurate model predictions as short-term changes in discharges and environmental conditions could be detected. The assessment shows that there is a patchy risk for severe impact on the calcareous algae stretching across the transitional zone and into the calcareous algae habitat at Peregrino.

The impact category approach presented in Paper VII (no impact – severe impact) provides improved management flexibility as the accepted impact level can be adjusted based on varying geographical environmental conditions. One can, for instance, expect that areas with low current velocity will tolerate less discharge of particulates than areas with stronger currents since stronger currents should be expected to give both less sedimentation due to a broader dispersion and lead to increased resuspension. For industrial developments this knowledge may allow a site specific evaluation of the discharge strategies, adjusting the acceptance of stress criteria expressed by the impact categories to the health of the present habitat and ambient conditions.
Figure 7: Schematic overview of the data sources used to assess the risk of impact on the two red calcareous algae species *M. engelhartii* and *Lithothamnion* sp. The different data sources include dispersion modelling, using input data from field (oceanographic data), discharge data from discharge log and the effect data, derived from the exposure studies. The latter was used to establish impact categories (Paper VII). The sedimentation experiment enabled sediment coverage from the exposure studies to be converted to sediment deposition, data required for the modelling (Figure 2 in Paper VII).
4 Basis for decisions: Tools enabling improved collaboration and communication

Step 10 represents the enhanced knowledge acquired from Step 4-6 and is considered sufficient as basis for end-users and decision makers (Figure 8). Results considered not adequate for decisions or to give the sufficient understanding needed should be further specified or divided into “sub questions” (Step 8) before directed via Step 9 either back to Step 3 (replanning of mission) or Step 11 which covers input to further research or “leave as is” (“no further actions”).

In Paper X Don Ihde’s (1979, 1991) theory on instrumental realism is used to explain why images in general are easy to understand and discussed by humans independent of background and experiences and therefore have the potential of acting as a boundary object in interdisciplinary communication and collaboration. Furthermore, Carlile’s (2004) model on innovation and collaboration across disciplines is used to argue for how interdisciplinary collaboration, utilising such boundary objects, can create new knowledge and understanding of the environment.

Figure 8: Step 10 representing knowledge which in each case is acquired during the mission and considered as sufficient for end-users and decision makers.
4.1 Interdisciplinary communication and collaboration

In addition to optimised data sampling and aggregation (Step 3-6), a sufficient unified understanding among the actors involved in the task(s) in question is crucial to generate new knowledge. As described by, among others, Elliott (2014), Leslie and McLeod (2007) and Rylance (2015) interdisciplinary collaboration is a precondition to solve complex environmental problems and to perform sound environmental management. To succeed when working across interests and disciplines, both domain specific and common knowledge must be acknowledged by the actors (Carlile, 2004). The inverted triangle presented in Figure 9 a) illustrates the different levels of complexity that categorises a task, from syntactic to semantic and pragmatic level, with the latter as the most complex. The complexity of a task corresponds to the scientific deviation and experiences between the actors involved; the more complex, the more deviated. Furthermore, Carlile (2004) claim that innovation has occurred and new knowledge is established and visible only after new tasks (Semantic and Pragmatic level in Figure 9) have been institutionalised in new methods, tools and representations (Syntactic level in Figure 9).

Figure 9b) exemplifies the different levels of complexity with use of photos, from a standard digital red-green-blue (RGB) photo of a coral reef (syntactic level), via the semantic level where the photos are converted to numerical values, here presented as a heat map where different colours visualise the varying densities of shrimp. Due to the transformation of the RGB photo (syntactic level) to numerical values (semantic level), quantifying object of interest and segmenting regions of interest, photos can be incorporated in multivariate data analyses, here represented by a PCA plot (pragmatic level).
Figure 9: A general model describing collaboration across boundaries on tasks of varying novelty, or complexity. a) The syntactic, semantic and pragmatic levels represent data of increasing novelty and uncertainty with a corresponding decrease in confirmation of the data. Discipline A and discipline B represents different research fields or scientific disciplines. b) The three levels (syntactic, semantic and pragmatic) are exemplified with different methods for detection of biological behaviour and multisensory data from an ordinary photo, the shrimp abundance represented as numerical values (heat map) and incorporation of photos in multivariate data analysis, represented by a principal component analysis (PCA) plot, respectively. The more transformed the data is from how humans visually perceive the world, the more specialised knowledge is required to understand the data (Figure 3 in Paper X).

4.2 Images in environmental monitoring

Due to human ability to understand images the rapid increase in use of photos and video recordings in environmental mapping and monitoring should contribute to enhanced environmental understanding and knowledge. The increasing numbers of long-term deployed cameras should therefore enable a much better understanding of the natural dynamics of different species. The technology is non-destructive, it measures the visual fauna in its natural environment and it enables increased temporal coverage and resolution compared to e.g. ship campaigns. Understanding the natural dynamic is a precondition to distinguish between anthropogenic impacts and natural variations. However, use of underwater photos is not
always applicable. For instance, in cases where the mission is focused on the infauna, other imaging techniques penetrating into the sediments would be more suitable.

The vast amounts of underwater photos and video recordings with increasing temporal and/or spatial coverage and resolution are challenging our capability to interpret these data. The obstacle can be solved with an interdisciplinary effort, developing and applying algorithms for (semi)automatic image analyses. In addition to enhance environmental understanding and knowledge as such, our general perception of photos can also be utilised in communication to explain more abstract and complex data, such as the results of multisensory data and multivariate data analysis.

Different biological questions require different algorithmic approaches to image analysis. As part of this thesis one approach has focused on identifying behaviour of specific species of interest, information that can be used to measure health status and habitat function in environmental monitoring (Paper V and Paper VIII). In these cases the species are known and manual annotations form the basis for the algorithm development. The other approach has focused on use of unsupervised computer learning to detect and group interesting events, such as presence and behaviour of different mobile species, independent of the level of a priori knowledge of the area or habitat (Paper IX). Due to the lack of knowledge about the present species the algorithms are designed to detect any kind of change patterns from regular events.

In Paper V changes in size and colour is monitored in single individuals of red calcareous algae with time. A machine learning based approach was used on photos collected from laboratory experiments to assess the potential impact of water-based drill cuttings on deep-water rhodolith-forming calcareous algae. In this pilot study (Paper V), imaging technology was used to quantify and monitor the stress levels of calcareous algae caused by various degrees of light exposure, flow intensity and amount of sediment, further described in Paper IV. Due to the selected colour normalisation strategy combined with a new flexible classifier design, the algorithm enable to measure change in size and colour of the calcareous algae over time. With this approach the photos were converted to numerical values, enabling to perform multivariate data analysis of the results from the image analysis and the experimental variables. The study showed correlation between calcareous algae size as a function of time, as well as correlation between colour and fluorescence. These results are consistent with the findings in Paper IV.
In Paper VIII the change in abundance of organisms of one species is quantified (by colour) in time and space. An automatic detection of shrimp in photos from the fixed camera at the LoVe Ocean Observatory with high temporal resolution (one hour) over a time period of six weeks is presented. Also in this approach the photos are converted to numerical values, providing unique opportunities to study shrimp behaviour (number and abundance at different locations within the camera frame) in their natural environment over time. This is the first time a feature representation based on local temporal colour contrast has been applied to detect the semi-transparent shrimp from the challenging background of the coral reef.

In an IEMM context the species composition of a habitat might not be known beforehand. In such situations algorithms are required to search incoming image streams for any kind of events or patterns that could be of interest, mark these events in the images and build up links between similar events/patterns, such as passing species or changes in colour, size or shape of fixed objects. In contrast to Paper V and Paper VIII, Paper IX proposes an approach applying algorithms that automatically categorise and group mobile organisms simultaneously. As described above, this approach based on categorising events based on features and change detection pattern does not require a priori knowledge of the specific habitat. The approach detects a large number of local changes, such as different species that passes the photo frame in a given temporal sequence. In addition to the automatic grouping, an applied relevance index presents the most relevant representatives for the group first. The observer can then quickly check the preferred groups and only focus on the relevant findings of each group. With this method the observer can bypass the time consuming inspection of the whole data set.
5 Conclusions and future perspectives

5.1 Concluding remarks

The proposed concept for IEMM is a flexible system adjusted to purpose and object of interest. As a planning tool, the methodological approach proposed assists to, in each case, optimise selection of parameters and the most suitable sensor carrying platforms providing data with adequate temporal and spatial coverage and resolution. In addition to improving the quality and relevance of the data, the concept also helps to secure a mutual understanding between the actors involved with respect to what should be done and why before, under and after the mission. It can also help to reveal gaps of knowledge related to the objects of interest or enabling initiation of experiments in due course before a field study. The approach is cost-efficient as more targeted data and less “noise” is gathered in a time efficient way.

Access to data of sufficient spatial and temporal coverage and resolution is a precondition for environmental knowledge in general. The rapid advances in enabling technology permit access to technology for adequate data sampling.

Technology development challenges the human ability to interpret new data due to the limitations in detecting and interpreting unfamiliar features. How the different measurements are perceived is determined by the sensor technology. The more transformed the data is from how humans visually perceive the world, the more specialised knowledge is required to understand the data.

Images are in general understood by humans independent of background and experience. They should therefore be suitable boundary objects for interdisciplinary communication and collaboration. To exploit the inherent knowledge available in the vast amounts of photos and video recordings of high temporal and/or spatial coverage and resolution, interdisciplinary collaboration is a precondition. The collaboration between biologists and computer scientists on use and interpretation of photos has resulted in new insights in the dynamic responses of several marine species over time. By converting photos to numerical values, as demonstrated in this thesis, they can be incorporated with other data, such as current speed, current direction and temperature, for instance in multivariate data analysis and modelling.
5.2 Future perspectives

Established methods for image analysis of marine species are a present relatively limited. However, the rapid increase in use of underwater images for environmental mapping and monitoring purposes has lately resulted in high focus on further development of suitable analytical methodology. In addition to the work presented in this thesis, several workshops in connection with this year’s 23rd International Conference on Pattern Recognition (ICPR) are dedicated to underwater imaging. Also a workshop on marine imaging is planned in Kiel early 2017. Commercially available analytical tools for image analysis are a precondition for future cost-efficient use of environmental data.

The potential of images to act as a boundary object in interdisciplinary communication and collaboration should in a future perspective be utilised to ensure better decisions in operational settings and for management purposes.

From an industrial perspective, the most important drivers for introducing an approach such as the IEMM concept are improved environmental performance and cost reduction. Both these aspects are within reach with the present methodology and technology, as described in the present thesis. Thus, a successful implementation will require a significant practical and political effort to create a common interest in sharing and assessing data. Institutional acceptance and focus on interdisciplinary collaboration will be critical success factors in this process.

By pinpointing important aspects and opportunities that can improve how IEMM is being performed, this thesis can hopefully contribute to the early stage discussion within the offshore oil and gas industry on how to improve environmental management with introducing more flexibility in future environmental monitoring and by strengthening the link between risk assessment and monitoring. Flexible environmental monitoring also challenges the regularity needed for the authorities monitoring of trends, both with respect to impact between different sites and/or areas and the development within the area with time. In Norway, the discussion between authorities and the offshore oil and gas industry has been initiated. More experiences with the IEMM concept, open discussions and communication will enhance environmental knowledge through implementation of new technologies and

4 http://www.icpr2016.org/site/
5 http://marine-imaging-workshop.com/
furthermore, that the IEMM concept will be an advantage for all end-users of the data provided.
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Integrated environmental mapping and monitoring, a methodological approach to optimise knowledge gathering and sampling strategy

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\section{1. Introduction}

Better understanding of ecosystems and how natural processes (abiotic and biotic) and anthropogenic factors might influence them has during the last decade attained increased attention from authorities, scientific community and industry. The complexity of integrated environmental management is described by Elliott (2014), Borja and Dauber (2008) describe adaptive management, as one of several management approaches, and that the results of such an approach may lead to corresponding changes in data needs, analytical procedures and interpretation. In this paper we argue that integrated environmental mapping and monitoring (IEMM), using different instrument (sensor) carrying platforms combined with proper analytical methods, are essential in creating such an understanding (Fig. 1).

Exploration and mapping of unknown areas requires that a varied and wide scope for data gathering must be applied. Mapping, or exploration, in a research context is often aiming to discover or reveal hitherto unknown objects, organisms, processes and phenomena. Although there are usually one or several features or qualities that one are particularly looking for, a general understanding of an area requires mapping of basic environmental characteristics such as topography, temperature and oxygen concentration to get an overview of an unknown environment. In an environmental management perspective, understanding of the area as part of the larger eco-system is considered important. Hence, parameters to measure, choice of sensors and sensor platforms subject to operational constraints are decisions to be made and remade in an environmental mapping process. This will supply relevant data for better accommodation of diverse and complex mission purposes with potentially multiple stakeholders, representing different needs and requirements.

Environmental monitoring is focusing on current status and any change detection of behaviour and characteristics of key parameters and objects of interest (OOI). The selection of parameters to monitor is based on the best available understanding of the

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resources, processes and other relevant qualities present in the area of interest. Efficient monitoring depends on the ability to acquire relevant data at relevant temporal and spatial resolution to optimise information for knowledge-based decisions. For authorities and industry mapping is often conducted to establish a baseline and monitoring related to follow-up and repeat measurements of key parameters relative to the baseline data provided. This means that also parameters essential in a monitoring perspective must, as far as possible, be taken into consideration during the baseline study.

By integrating mapping and monitoring into the same operational framework in terms of tools for data acquisition and knowledge production, the relevance of data for different purposes should increase. As gathering of data is time-consuming and often also expensive, it is essential to spend the time and money available in a cost-effective manner according to relevant data gathering and expectations. Easy access to already existing data from the area of interest is also an important aspect in this context.

The spatial and temporal coverage and resolution needs will vary dependent on mission purpose (e.g. processes, organisms of different sizes) and the different decision-makers may have individual needs and requirements. In general, the requirements from authorities are often related to status and trends; e.g. has the area of influence from a particular activity increased or decreased since last sampling? For industry this knowledge may have less value as long as the information may be reported months or even years after an occurrence. To make monitoring data useful in industry’s daily operations, data sampling must be adjusted to the activity of interest (Hepsø et al., 2012).

While surveys have traditionally been performed as ship campaigns with temporal and spatial resolution limited to the capabilities of the ship with its installed sensors, a variety of fixed and mobile sensor platforms now enables gathering of vast amounts of, more or less, continuous or online real-time multisensory data. This is reflected through several initiatives where authorities e.g. MAREANO (MAREANO, n.d.), industry e.g. the PEMCA project (Johnsen et al., 2014; Salgado et al., 2010) and academia e.g. AMOS (AMOS, n.d.) and NORUS (NORUS, 2011) have supported multi sensor and multiplatform approaches by the use of a variety of sensors mounted on different types of instrument platforms to measure parameters of interest (Hepsø et al., 2012; Schofield et al., 2010). Sensor platforms can typically be fixed e.g. buoys, moorings (Berge et al., 2009; Johnsen et al., 1997) and landers (Ocean Network Canada, 2014; Statoil, n.d.) or mobile e.g. Remotely Operated Vehicles (ROVs) (SERPENT, n.d.), Autonomous Underwater Vehicle (AUVs) (Kukulya et al., 2010; Maxson et al., 2011; Moline et al., 2005) and gliders (MBARI, 2014).

The problem of undersampling (Munk, 2000), have to some degree been alleviated by advances in technology (Goda et al., 2014), but still huge scientific efforts are in general necessary to fill the knowledge gaps and understanding of marine ecosystems. Many recent developments in platforms and sensors have been guided by needs in the marine sciences, seeing end-users with specific applications often involved in the engineering process (Bellingham, 2014; Glenn et al., 2005; Moline et al., 2005). As new technologies helps to fill knowledge gaps in the understanding of the environment, the level of complexity regarding data management and processing also increases. When the amount of data increases, the work necessary to transform these data to useful information increases accordingly. The scientific community, authorities and industry are at present struggling with optimising the use of these data and to utilise the opportunities of enhanced knowledge that can be obtained from combining multi sensor data (Eugéräs, 2011; Hepsø et al., 2012; Johnsen et al., 2011). The time aspect is also of great importance as data must be transformed into information in due time for decisions or as input for dependent operations and processes. The increased volume and diversity in gathered data, including on-line data, requires better analytical tools to meet requirements for rapid data analysis and immediate action.

This paper presents an IEMM concept for data acquisition, processing and knowledge production. The challenges related to availability of analytical tools and data processing that must be solved to provide users or decision makers with relevant data in due time will be discussed. The use and functionality of the concept will be illustrated by a generic model showing steps and sequences, and two case studies using new technologies relevant for marine environmental mapping and monitoring purposes. In Case study 1 the IEMM concept is exemplified by scientific knowledge production from an arctic research project. Case study 2 shows the IEMM concept for a monitoring project initiated by the oil and gas industry.

2. Methodological approach

The methodological approach in IEMM is proposed to be generic and therefore relevant for authorities, industry and academia. Furthermore, it may be applicable independent of the operational environment, e.g. terrestrial and marine environments in situ, including laboratory experiments.

Using the systematic approach described in this section will aid users and decision makers to identify essential elements for consideration when planning a mission, help in selecting enabling technology (sensor, sensor platforms, software, etc.) for sufficient
mapping and monitoring and to optimise data gathering and interpretation to provide end-users such as operators or decision makers with appropriate data in due time. A methodological approach will also in a systematic way identify gaps in knowledge, methodology and technology, and thereby any needs for further development and improvements in the different steps of the concept from planning to execution of e.g. a survey.

The proposed steps in the IEMM concept are illustrated in Fig. 2 and described below. Step 1 is the a-priori knowledge and understanding of e.g. ecosystems, any object or area of interest. Subject to the defined mission objectives (Step 2) and operational constraints such as availability of appropriate technology and methods, environmental limitations and cost, detailed planning and re-planning may take place both autonomously and with human-in-the-loop during the execution of the mission (Steps 3–6). Criteria for sufficient data gathering in addition to metrics for decision-making (Step 7) will define either a positive result where mission is completed in accordance with objectives (Step 10), or a negative result where the research questions and mission objectives may need to be reformulated or divided into new sub-goals (Step 8). Considering the given operational constraints the mission either will be repeated with the new input conditions (Steps 3–6) or terminated (Step 11). Step 11 could either give input to further research and development needs or the conclusion is noted without further actions. We will describe Steps 3–6 in more detail. In the following the term “data request” is used to describe a set of data attributes or qualities such as resolution, sampling rate and quality required for current purpose (i.e. information needed to answer mission objective).

2.1. Selection of parameters, sensors and sensor platforms (Step 3)

Step 3 represents the planning phase, comprising of a toolbox and sequences of activities where the appropriate sensors and platforms (including laboratory studies, if needed) are selected, adjusted and applied according to the mission objectives and revised data requests defined in Steps 2, 5, 6 or 9, respectively. The wide range of available sensors and platforms allows the requests to be formulated in both broad and specific manners. Based on the data request, selections of sensors, platforms and parameters are made within appropriate temporal and spatial ranges, coverage and resolutions. A decision could also be made to enable other sensors and sensor platforms additional to the ones necessary to meet data request. The rationale behind such an approach could be multiple; access to the area of interest, capacity of data sampling and an awareness of knowledge gaps or information needs beyond the scope of the present mission or, most likely, a combination of these.

2.1.1. Experimental studies

A certain basic knowledge of the object and/or area of interest related to the mission objective in question (Step 2) is essential. If this basic knowledge is missing, initial experimental studies both in laboratory or in situ may be performed in order to establish e.g. the biological basis to guide the mission planning (Step 3) and to enable interpretation of data gathered (Steps 4–6).

2.1.2. Measurements adjusted to purpose

Selection of parameters to measure should fit the environment in question and the aim of mission. Dependent on the environment, there will be a minimum set of parameters that always should be measured, either as an essential or supporting parameter for interpretation of other data gathered. When working with organisms the measurements of oxygen concentration may e.g. be an essential parameter since it reflects bacterial, photosynthetic and respiration activity. Since oxygen solubility is dependent on temperature in water, this is an essential supporting parameter interpreting the oxygen data. Presence of anthropogenic activities or possible anthropogenic influence in the area of question should also be considered when planning the sampling design. In the Arctic, the latter could typically be long-range transported pollutants.

2.1.3. Sensor platforms covering different spatial and temporal scales

In addition to measurements of essential parameters, the quality of the data interpretation is dependent on the spatial and temporal resolution and coverage of the data. Hence, the dynamics in both space and time have to be considered in the mission planning process. As illustrated in Fig. 3, the temporal and spatial resolution and coverage capabilities varies between the different platforms and corresponding sensors.
Remote sensing platforms have high spatial coverage with varying resolution. For satellites in particular, improvements in optics, navigation and communications have made it possible to produce geo-localised images with 1–1000 m spatial resolution per image pixel (Johnsen et al., 2011) at high speed providing very large areal coverage. However, for marine applications, satellites have their limitations as they, dependent on illumination from the sun light, cloud cover, sun glint and waves can characterise the sea surface and upper water column only. Aircrafts provide similar capabilities as satellites and are useful to map and monitor shallow water areas and coastlines in an effective manner. However, being closer to the sea surface the spatial resolution increases, while the areal coverage decreases. As for the satellites, sensors mounted on aircrafts will be able to analyse the uppermost part of the water column only due to water transparency. Lately, research on unmanned aerial vehicles (UAV) and autonomy has increased the interest to apply low-cost UAV as sensors platforms and communication hubs between sensor platforms in the surface or the air and e.g. a mother vessel supporting AUV operations with some distance to the launching vessel (AMOS, n.d.).

The payload capacity and spatial coverage of a ship can be high. The ship serves as both a sensor platform as well as a mother platform launching and supporting other sensor platforms such as ROVs and AUVs. The ship can provide data from the sea surface, the water column and the seabed. The ship may be an excellent platform as the laboratory with its scientist is brought out on the sea.

For fixed platforms, such as landers, moorings and ocean observatories, the temporal resolution can be high by providing sufficient energy supply and data storage capacity. However, the spatial resolution will be limited to the coverage and range of the mounted sensors. Most sensors are point samplers, while others, such as active acoustics can cover a wide area. The range of active acoustics is dependent on the frequencies used, varying from metres to several kilometres (Godø et al., 2014).

Mobile sensor platforms operating in the water column are normally deployed from a ship/floater. The ROV can be equipped with different sensors and manipulators for sampling and, dependent of type and size of the ROV, the depth range varies from 100 to 6000 m. Recent ROV motion control systems (Dukan and Sørensen, 2014; Sørensen et al., 2012) provides manoeuvring capabilities with station keeping/hovering (dynamic positioning) and target and bottom tracking. High-resolution data for targeted area can be provided with detailed seabed mapping and sampling with down to mm spatial resolution. The umbilical gives unlimited electrical power and high bandwidth communication. AUVs may be divided into small AUVs (0–100 m depth) and large AUVs (0–6000 m). Small AUVs may be operated from small boats and from shoreline. Torpedo shaped survey AUVs are mostly used in mapping providing good hydrodynamic and manoeuvring capabilities for tracking and path following (Moline et al., 2005). So far, there is limited access to AUVs with station keeping/hovering capabilities. This is at present also the situation for AUVs with manipulator capabilities doing light intervention and sampling. The AUVs main strength is the longitude, latitude and depth mapping capabilities. AUVs can provide seabed and water column mapping with high spatial resolution data over large areas. The survey area coverage per time is significantly higher compared to ROV as the ROV has limited spatial range due to the exposed current loads/drag forces on the umbilical (Johnsen et al., 2011). Gliders’ operational range and spatial coverage are high compared to AUVs and ROVs. The speed is rather low, following ocean current systems at a minimum of energy, using principles of buoyancy driven propulsion. Since the operation may go on for weeks, the spatial range is high. For measurements in the water column, the glider is good. However, the accuracy in navigation and control is limited. The ability for benthic surveys is also limited (Testor et al., 2010). More details on underwater sensor platforms, including ships are found in Appendix A.

From signal reconstruction theory it is well established that a time-periodic signal at least should be sampled twice each period (Nyquist frequency), or ideally 20–40 times each period in order to reconstruct the evolution including mean, maximum and minimum values (Åstrøm and Wittenmark, 1997). The same approach may also be considered for reconstruction of spatial variations of the area of interest. For a homogenous system the geographical location of the measurements is not essential. However, if horizontal and vertical spatial variations are of interest or concern, proper area planning and selection of technology platform(s) are critical. For instance, a lander (Appendix A) may provide both high
temporal and even high spatial resolution, however, on a limited spatial coverage. This motivates use of mobile platforms such as AUV and ships. On the contrary, data from mobile platforms may be limited by the temporal resolution on a given location dependent on how often that point is re-visited. Hence, providing simultaneously high spatial and temporal resolution and coverage might, in addition to proper planning of mission, require a combination of several platforms. Other constraints such as payload capacity, energy endurance and level of autonomy related to energy and control system intelligence including communication capabilities will impact the sensor platforms’ spatial and temporal resolution. The accessibility of the data depends on the solution for power and data transfer from the sensor platform and, if not cabled, the duration of the deployment and any communication network and methodology set up using e.g. acoustics, optics, satellites or radio waves.

2.2. Data sampling (Steps 4–6)

In Steps 4–6 the sampling/data acquisition is in progress. Adaptive sampling may occur if specified in Step 3, depending on data request, or if sensor data triggers predefined interdependent sequences. If data collected in Step 4 is not in accordance with the data request, new adjusted data request can be made either automatically (Step 5) or manually (Step 6) and fed back to Step 3 e.g. adjust sampling area (if mobile platform or active acoustics with movable echo sounder), adjust sampling frequencies, adjust range (if mobile platform), etc. until request is satisfied.

In Steps 5 and 6 data are processed, analysed and transformed into information contributing to e.g. answering research questions and mission objectives. After assessment of information and comparison with prior knowledge, it will be accumulated knowledge. An assessment of the acquired information with regard to the original research question (Step 2) is made (Step 7). If acquired data is insufficient in terms of scope, resolution, etc., then either reprocessing in Step 6 or the data request is re-specified (Step 8). If information from acquired data is irrelevant to the original question (Step 2), or the question turns out to be erroneously formulated or imprecise, a new request must be formulated based on accumulated knowledge (Step 10), or else Step 11.

2.3. Data processing (Steps 5 and 6)

While the understanding of the oceans in the past has been limited due to sampling constraints such as lack of technology and distributed observations, it could now be stated that the ability to handle, analyse and interpret the vast amount of data, including data noise, received from an increasing variety of sensors has become the main bottleneck for transforming data to knowledge. For monitoring purposes, multisensory data can be processed to produce early warning information on a few key parameters critical to whatever is to be monitored (Blüthgen et al., 2010). The key parameters are chosen based on the understanding of the process or environment to be observed. Hence, unless there is an exhaustive understanding of what to be mapped or monitored, the selection of key parameters is liable to change in time with change in level of knowledge.

Allowing development of new data analyses and interpretation of knowledge over time requires appropriate long time storage, accessibility and sharing of data. First and foremost is storage of raw data essential to secure that the data can be used independent of software development and available analytical tools. Secondly, easy access to the stored data is essential. Data availability is dependent on several issues from selected software solution, to the semantic structure of the data and organisational attitude or strategy for data sharing. Further, the present bottleneck of data processing of the vast amount of incoming data requires development of automated and/or semi-automated systems helping humans to pinpoint the object and/or event of interest.

3. Case studies

Two case studies are selected to demonstrate the applicability of the IEMM concept for mapping (Case study 1) and monitoring (Case study 2) purposes. Detailed results from case studies will not be presented as such, as these are reported in separate publications.

Case study 1 is from a survey carried out in Ny-Ålesund, Svalbard, Norway in January 2014. The study was performed as part of a Master/PhD course at the University of Svalbard (UNIS) in underwater robotics, comprising laboratory studies and use of mobile platforms for in situ data gathering. The case study shows how a widely formulated research question was approached by use of different sensors deployed on different platforms, depending on the changing need for specific data to produce relevant information in a challenging environment. The study was performed in a remote area (78°55'30"N, 11°55'20"E) during the polar night, which entails low temperatures down to −30 °C and darkness (nautical polar night). The main aim of the Svalbard survey was to gather knowledge about how organisms are adapted and react to the present ambient light climate such as moon, star and northern light during the polar night when the sun is under the horizon for months in general, and to identify the environmental trigger for zooplankton diurnal vertical migrations (DVM) in particular.

The second case (Case study 2) is from the Peregrino Environmental Monitoring of Calcareous Algae (PEMCA) project carried out related to the Peregrino offshore oil field in Brazil (at about 23°31’S, 41°31’W). This case study shows how new and non-destructive technology can be applied to obtain more relevant knowledge about the environment in question. The main challenges related to this case study were the limited background knowledge about the organisms of interest (calcareous algae), the corrosive environment, the strong currents and the robustness of the monitoring platform. The purpose of the PEMCA project was to monitor whether discharges of drill cuttings had an impact on a calcareous algae bed located on around 100 m water depth and approximately 1.5 km away from the discharge point.

3.1. Case study 1: importance of light on marine life in the polar night

Several recent studies have indicated that the polar night is an important period for key process such as reproduction, e.g. for polar cod (Boreogadus saida) (Graham and Hop, 1995) and amphibious Onisimus caricus (Nygård et al., 2009). Low photon fluxes of diffuse light from the sun which is below the horizon, moonlight and the northern light (Aurora borealis) are important environmental parameters utilised by arctic organisms (Berge et al., in press). Berge et al. (2005) and Båtnes et al. (2013) documented that zooplankton continue to perform DVM also during the polar night. Furthermore, overlapping presence of phytoplankton and zoo- plankton during night was documented by Berge et al. (2014).

To understand these mechanisms and to gain knowledge about how to measure these mechanisms in situ (Step 2 in model), dedicated experimental work with key marine organisms were performed in the laboratory (Step 3) on the two krill species Thysanoessa longicaudata and Thysanoessa inermis to identify their threshold levels for light (spectral sensitivity and intensity) (Step 4). Furthermore, for further understanding of the importance of light in predator–prey interactions in the arctic ecosystem, the presence of bioluminescent zooplankton and reflectance in several macroalgae (Laminaria digitata, Saccharina latissima, Alaria
esculenta, Palmata palmata and Ulva sp.) were also measured, both in the laboratory and in situ (Step 4) (Unpublished results). Several sensors and sensor and fauna were selected (Step 3) to detect and measure presence/activity of pelagic organisms in the water column, including DVM (Step 4). An AUV equipped with a suite of sensors to map aggregations of zooplankton and phytoplankton in the water column (Step 6). Increased concentration of chlorophyll a [Chl a] indicating biomass of phytoplankton, while decreased oxygen concentration [O2] and increased concentrations of coloured dissolved organic matter [cDOM] indicated presence of organisms, grazing and decay (release and decomposition of organic material), respectively. The addition of conductivity (to obtain salinity), temperature and pressure (to obtain depth) by CTD measurements complemented the biological datasets with physical characteristics of the water masses. In shallow waters (4–30 m) two ROVs were used for visual mapping of benthic species distribution according to depth. To document the temporal resolution of the biological activity (macrofauna) over a period of some days, a stationary time-lapse camera took images every 30 min. In addition, divers collected and documented macroalgae and fauna in the shallower parts of the study area twice a day (day and night).

In the Svalbard case study, adaptive sampling was considered on daily basis during the campaign by the course supervisors evaluating the data recorded (Steps 5 and 6). Operational constraints such as low temperatures, strong wind, snow showers and waves did influence the operations on hourly and daily basis. This clearly indicated the need to plan for sufficient days of operation. The scope of the mission was well defined prior to the course, sensors needed were deployed, no discharges from point sources were present and, if other sensor needs should have been identified, the needed were deployed, no discharges from point sources were present and, if other sensor needs should have been identified, the sensors could not reach the remote area in due time (Step 9). Challenges related to data processing were experienced. While discrete values of [O2], [cDOM], [TSM], salinity and temperature easily could be presented in a joined figure for a visual comparison of the spatial presence of the parameters, the data processing from e.g. the side scan sonar was much more time consuming and difficult to integrate with the former data. The Svalbard Study 2014 gave new insight into the importance of polar night light regime and how it affects marine organisms and parts of the physiological mechanisms behind this (Step 7) which will be brought along till future studies (Steps 10 and 11). However, during the study also technical restrictions on the sensor platforms were made clear when planning for overlapping sampling areas (Step 9). Umbilical on the ROV was too short to reach the location of the fixed time-lapse camera and the region of interest was also too shallow for the AUV (Step 9).

3.2. Case study 2: Peregrino Environmental Monitoring of Calcareous Algae

Another project where the IEMM approach is used is the PEMCA project (Johnsen et al., 2014; Salgado et al., 2010). The objective (Step 2) of the PEMCA project was to monitor whether discharges of drill cuttings, which is a mixed rock generated when drilling a borehole, had an impact on calcareous algae bed located on around 100 m water depth and approximately 1.5 km away from the discharge point. The drill cuttings discharged were not toxic, but due to the limited light available there was a fear that the particulates could lead to calcareous algae death due to reduced light levels and/or gas exchange by increased sedimentation. A monitoring programme using non-intrusive methods was planned (Step 3). Due to lack of knowledge about the impact of increased sedimentation on calcareous algae in a light limited environment in general, there was also a need to perform laboratory studies to measure the calcareous algae’s threshold levels for effect of sediment coverage (Step 3). A set of laboratory experiments, some lasting up till 9 weeks were exposing calcareous algae for particulates (drill cuttings and sediments mimicking the grain size of drill cutting) (Step 4). In the field, the monitoring equipment were deployed and retrieved several times during a sampling period of approximately 2.5 years (Step 4). The fixed platform (lander) was equipped with a surface buoy for online data transfer. The data transfer lasted only for a short time before the weak link mounted on the cable between the fixed platform and the surface buoy broke. The weak link was designed to break at a certain force and the exact cause is unknown (Johnsen et al., 2014). Due to this, the lander, in addition to the sediment traps used in the field measurements, had continuous offline sampling. Hence no on-line analysis or options for adaptive sampling (Step 5) were available. Knowledge accumulation after each retrieval campaign (Step 6) did not identify needs to broaden the parameter measurements.

However, when working with the time-lapse images from the field, we see that there is a high degree of movements on the seabed. The rhodoliths (calcareous porous structures on which the calcareous algae is growing) changed location and occasionally also the seabed topography changed. The temporal resolution of the images (two hours intervals) gives the opportunity to identify the movement of rhodoliths in different areas of the images (Unpublished results), but the temporal resolution is too low to track individual rhodolith movements. The knowledge gained from the PEMCA study (Step 10) has been used as basis for a new proposed monitoring programme at the Peregrino field (Johnsen et al., 2014). Further, as described in Johnsen et al. (2014), the experiences with the lander lead to a redesign. It was made more robust as the sensors now are more protected by the platform frame and the weight has been reduced to improve deployment and retrieval. As the discharges of water-based drill cuttings at the Peregrino field are determined to have a low risk for impacting the calcareous algae seabed (Unpublished results), the proposed monitoring programme does not include further on-line measurements. Furthermore, the outcome from the laboratory studies (Step 10) has used to optimise the environmental risk assessment on the Peregrino field (Unpublished results). Results also show that there might be a temporal aspect related to the impact on the calcareous algae. The 9 weeks experiment showed that, within the experimental domain, the impact was related to sediment cover and that irradiance was of minor importance (Figueiredo et al., 2015). However, the photosynthetic efficiency (maximum quantum yield of charge separation in photosystem II: \( \varphi_{PSII} \)) of the experimental controls that were kept in darkness without added sediments, decreased slightly at the end of the experiment. This might indicate an incipient light limited impact on the calcareous algae (Figueiredo et al., 2015). This finding is input to further research (Step 11). The experiences with the temporal resolution with the images have initiated further research activities (Step 11).

4. Discussion

The IEMM concept has through the case studies, demonstrated that the model (Fig. 2) enables holistic and flexible approaches adjusted to the environment(s) in question and aim of mission regardless if it is initiated by authorities, academia or industry. Using existing data and/or identifying areas where knowledge
Figueiredo et al. (2015) describes the use of laboratory experiments to establish exposure threshold levels for drilling discharge on calcareous algae. These results were used as input to the risk modelling to improve the risk assessment for drilling discharges at the Peregrino oil field (Unpublished results). Another example where laboratory studies have been successfully performed in order to gain knowledge on key species with limited knowledge is the coral risk assessment, monitoring and modelling (CORAMM) project (Purser and Thomsen, 2012) where threshold values for water-based drill cuttings were established in the laboratory for the cold water coral Lophelia pertusa.

In contrast to the past, recent sensor developments and increased use of mobile sensor platforms enables mapping and monitoring technology that are non-destructive to the environment as many of the measurements are based on optical measurements which is not depending on physical sampling of the environment. As described in Section 2.1.3 and Appendix A, different sensor platforms have their pros and cons and, if used in an optimised way, alone or in combination, they can enable sampling with the right temporal and spatial resolution and coverage adjusted to purpose of mission. However, besides of some “lessons learned experiences”, such as with the time-lapse camera described in the various movements in Case study 2, operational experiences with combined use of sensor platforms in an IEMM concept are still limited.

The need to optimise data sampling has increased the focus on the need of real-time observations of what is being sampled. Being able to alter a real-time mission plan could increase the value of the gathered data. Reduced mission time, and thereby reduced risk related to the operation, is an additional important advantage of such an adaptive sampling approach. The potential gain of changing the mission plan in real-time is well known (Brito et al., 2012). For Case study 1 it is obvious that an improved autonomous adaptive sampling capability using AUV to document both DVM and zooplankton grazing on phytoplankton would have optimised the time and energy consumption of the AUV operation. Since the zooplankton migration will be at different depths throughout the day, the AUV could utilise the ADCP data to alter its desired depth, while the other sensors measuring [Chi a], [cDOM], [TSM] and oxygen consumption only were activated when the desired target was found. Such an approach would provide more valuable scientific data, in addition to higher temporal resolution and lower power consumption. As there were several parallel operations ongoing, the AUV could also have been used for other missions at an earlier stage. Another example describing the use of autonomous adaptive sampling is the use of an AUV to track and sample the thermocline of the Portuguese coast, as reported in Cruz and Matos (2010). The AUV was programmed to descend to a certain temperature gradient and then stay within the depth interval containing the desired temperature. Other relevant examples can be found in Berge et al. (2012), Ferri et al. (2010), Giguere et al. (2009), Moline et al. (2005) and Zhang et al. (2012).

Adaptive control based on sensor readings does, however, require the data to be processed in real, or near real-time, which places strict requirements on the computer processing capacity and power on the sensor platform. Only recently the computational power versus electrical power consumption, as well as the development of software architecture, rapid signal processing and multivariate data analysis, guidance and control of sensor platforms has reached a point that allows practical implementation for autonomously adaptive sampling (Brito et al., 2012; Cruz and Matos, 2010). One challenge in data analysis will be to adapt model reduction schemes in order to improve real-time performance. The main operational limitations for e.g. an AUV are the shortage in endurance due to limited power supply and lack of needed autonomy. Research attention and efforts on battery and autonomy capabilities, including real time data analysis, guidance, navigation and control systems, will increase the abilities providing smarter, safer and more efficient operations in an unstructured environment with on-board planning and re-planning capabilities such as collision avoidance for handling of unexpected events and optimised data gathering near real-time. However, it is essential to bear in mind that even though sensor platform developments enable adaptive sampling, the quality of the data gathered is dependent on the sensors mounted on these platforms. In this perspective it is important to be aware of the individual sensor’s constraints when it comes to signal quality and degradation due to response time and any sensor faults, including platform generated noise.

Despite improved coverage of mapped and monitored areas due to extended use of mobile platforms, there are still huge demands related to data gathering. Modelling might be used to predict similar occurrences in similar habitats in a broader geographical scale. Furthermore, modelling should also be used to optimise the environmental monitoring programme. Data from monitoring programmes should also be of such quality (type of parameter(s) with sufficient temporal and spatial resolution) that it can be used to improve future model predictions. Modelling can help optimising the environmental monitoring programme by optimising the mission plan and sampling strategy (Nilssen and Johnson, 2008). The importance of linking monitoring and environmental monitoring is described, among others by Gode et al. (2014), Nilssen and Johnson (2008) and OGF (2012). In a real-time monitoring concept also systems enabling online risk modelling should be developed.

Optimising knowledge gathering requires more than just methods for autonomous adaptive sampling. Optimised use and understanding are also to a large extent linked to development of analytical tools combining a variety of data types from various data sources. Results both from the laboratory and from the field part of Case study 2 have been processed using multivariate data analysis. However, none of the case studies involved “on the fly” analysis. If data is to be used for decision support as an integrated part of the industry’s daily operations, the time aspect is specifically critical for real-time monitoring and control. Ideally, information enabling actions before impact should be available. Use of multivariate analyses is starting to become more commonly used for real-time monitoring. However, suitable software and analytical tools processing particularly big data, such as sound, optical images, hyperspectral data, acoustic images and others, are with few exceptions (Purser et al., 2009; Schoening et al., 2012a,b), lacking. Hence, important data is at present not included in existing multivariate data analysis. Effort to overcome this bottleneck is essential if these data is to be used with other sensor data.

Despite all the advantages with the IEMM’s holisitic approach for mapping and monitoring and all the recent development in sensor and sensor platform technology, there are several external factors that have to be fulfilled if the IEMM concept shall be a success. National regulations are diverse (Borja and Dauer, 2008; Borja et al., 2010), and an implementation of the IEMM concept requires e.g. that the regulatory bodies are willing to re-think the basis for...
their regulatory framework and accept the flexibility needed. In general the need for an integrated management system is accepted but there are still challenges with regards to implementation (Elliott, 2014; Leslie and McLeod, 2007). To ensure a positive implementation of IEMM in industries’ daily operations, recognising the value of multidisciplinary use of already existing data as well as mutual needs for new data is vital, e.g. is leak detection both a maintenance and an environmental related issue. We believe that data sharing and availability of data e.g. from industry to academia can drive research and innovation, and thereby lead to further improvement of all aspects from sensors and sensor technology to analytical tools and use of knowledge.

In addition to available technology and opportunities provided by a multidisciplinary team, it is also crucial to be aware of the need for mutual understanding and the need for behavioural change between the actors involved to drive innovation (Carlile, 2004). Carlile (2004) describes the need to acknowledge both domain-specific and common knowledge when working across interests and disciplines. In addition he presents a model describing how the need for communication increases with the degree of complexity. According to Carlile, successful implementation of a complex model such as IEMM will require a significant practical and political effort to create a common interest in sharing and assessing data. This is also in line with Elliott (2014), claiming that the only way to obtain an integrated marine management framework is to have sectorial managers willing to think across both vertical and horizontal levels of integration. Establishing common knowledge and understanding the complexity of each other’s needs is necessary for mutual trust, to understand the individual data needs and for a successful data sharing and interpretation. Seeing these contexts, using a system facilitating data flow and access and having systems processing the data on an appropriate temporal scale, authorities can utilise them for regulatory purposes, while industry can take the knowledge into their day-to-day operations.

5. Conclusion

The proposed IEMM concept is a flexible system which enables a case-by-case approach adjusted to purpose and object of interest. The purpose can span from measuring natural variations to monitoring of point discharges from anthropogenic activities, and the object of interest can either be (an) organism(s), an area or a thing/an infrastructure. With this flexibility the concept can facilitate easier cross disciplinary cooperation, utilisation of common infrastructure and sharing of data among different stakeholders. As a planning tool the IEMM concept aids to optimise selection of parameters to measure and sensor platforms to use to get the best temporal and spatial resolution fitted for purpose in each case.

The concept will also help to reveal gap of knowledge of the object of interest, which could enable initiation of laboratory experiments in due time before a field study, if deemed needed. In an operational phase an adaptive sampling, either fully automated or with human interactions, can optimise the data gathering either through switching sensors on/off or through an adjusted sampling mission following the object of interest instead of following a pre-programmed sampling route in dynamic and changing environments. As for data processing and analytical tools, there is still a lack of knowledge/available systems to perform a cost-efficient adaptive sampling. However, we believe that the IEMM concept will contribute to optimise knowledge gathering and sampling strategies through data and information feedback loops. In addition it addresses areas with potential for further development and optimisation for mapping and monitoring purposes.

6. Abbreviations and definitions

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ADCP</td>
<td>acoustic doppler current profiler</td>
</tr>
<tr>
<td>AUV</td>
<td>autonomous underwater vehicle</td>
</tr>
<tr>
<td>Big data</td>
<td>huge amount of complex data collected with high velocity, cauterised by non-linearity and high intrinsic dimensions</td>
</tr>
<tr>
<td>cDOM</td>
<td>coloured dissolved organic matter</td>
</tr>
<tr>
<td>CTD</td>
<td>conductivity, temperature, depth</td>
</tr>
<tr>
<td>DVM</td>
<td>dial vertical migration</td>
</tr>
<tr>
<td>IEMM</td>
<td>integrated environmental mapping and monitoring</td>
</tr>
<tr>
<td>Parameter</td>
<td>a coefficient that may be either constant or time varying, in contrast to a variable that is a time-varying state of a dynamic system. As both parameters and variables may be time varying the term parameter is used for both.</td>
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<tr>
<td>ROV</td>
<td>remotely operated vehicle</td>
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<tr>
<td>Sensor platform</td>
<td>fixed or mobile instrument carrier</td>
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Acknowledgements

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Appendix A. Underwater sensor platforms

<table>
<thead>
<tr>
<th>Platform</th>
<th>Characteristics</th>
<th>Pros</th>
<th>Cons</th>
<th>Arctic challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Senders and moorings</td>
<td>• Instrument platform either standing on the seabed (ladera) or suspended in the water column moored to the seabed or tethered to floating device at the surface</td>
<td>• Limited risk for collisions when installed</td>
<td>• Samplings limited to location, i.e. low spatial coverage</td>
<td>• Increased risk and cost during deployment</td>
</tr>
<tr>
<td></td>
<td>• Offline or accessible via cable or satellite/radio communication</td>
<td>• High payload capacity</td>
<td>• Bio fouling and corrosion complicates calibration and degrade the sensors and data quality over time</td>
<td>• Access to instruments/data limited by harsh environment and ice</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High temporal resolution of data sampling (time series)</td>
<td>• For online systems high cost for installation of power and communication systems</td>
<td>On shallow water ice bergs may damage equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Low cost operation when installed</td>
<td>• Lander and cables exposed for damage due to e.g. trawling and dredging</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• When online, access to real-time data</td>
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</table>
Appendix A (continued)

<table>
<thead>
<tr>
<th>Platform</th>
<th>Characteristics</th>
<th>Pros</th>
<th>Cons</th>
<th>Arctic challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ships</strong></td>
<td>Important components: hull, deck space, crane, power, thruster and propulsion system, DP system, sensors. Mother ship and control center for payloads such as ROV, AUV, UAV.</td>
<td>Very large payload capacity. Very large temporal and spatial coverage and resolution. Conduct and handle samples from any gear and sensor platforms.</td>
<td>Ship-based sensors will have limited resolutions for increasing water depth. Costly operation.</td>
<td>Ice and icebergs limit the operability. Icing on sensitive equipment and sensors.</td>
</tr>
<tr>
<td><strong>Remotely Operated Vehicle (ROV)</strong></td>
<td>Main components: vehicle, umbilical and control stations. Delivered in different sizes, depth and thrust ratings. Functionality, manipulator and sensors. Power supply and communication by umbilical. Navigation by means of acoustics, INS, DVL. ROV is normally launched from crane on ship with station keeping capability by anchors or dynamic positioning (DP) system.</td>
<td>High payload capacity. High temporal and spatial resolution data for targeted area providing detailed seabed mapping and sampling. Unbilled gives almost unlimited electrical power and high bandwidth communication. Manipulator arms for sampling and intervention. Collection units (water masses and seabed).</td>
<td>Limited spatial range and coverage: usually &lt;1 km transect lines. &lt;190 m2. Unbilled is exposed to current loads/drag forces limiting spatial coverage even more on deeper waters. Expensive operation due to day high rates on ships. Data quality could be degraded by poor ROV guidance, navigation and control.</td>
<td>Increased risk and cost during operations. Ice and icebergs reduce spatial coverage and increase risk for collisions. Ship may be unable to maintain position due to ice drift.</td>
</tr>
<tr>
<td><strong>Autonomous Underwater Vehicle (AUV)</strong></td>
<td>Main components: vehicle, control station, acoustic navigation and for larger AUVs launch and recovery system. Delivered in different sizes, depth and thrust ratings, functionality, and sensors. Carries its own power supply. Operates supervised or autonomously with limited communication ability.</td>
<td>High payload capacity (however less capacity compared to ROV). 3D (long, lat and depth) mapping capabilities are unique. High spatial resolution data for large area providing detailed seabed and water column mapping and monitoring. High spatial coverage per time. Operates unattended and autonomously. New research on autonomy improves AUV intelligence and ability to operate in an unstructured environment. Allows operations in areas that have limited or no accessibility with other platforms.</td>
<td>Risk of operation – loss of data and vehicle. Limited power supply on-board. Today: need for competence on AUV crew for launch and recovery, planning of operation and troubleshooting during different operational scenarios. Possible limitations in operation due to ship traffic and risk for collision.</td>
<td>Increased risk and cost during operations. Ice and icebergs reduce spatial coverage and increase risk for collisions. Low temperature reduce battery efficiency. Ice coverage prevents direct ascent to surface for GPS fix for navigation and increase risk for loss of AUV.</td>
</tr>
<tr>
<td><strong>Giders</strong></td>
<td>Components: vehicle and control station. Delivered in different sizes, depth and power ratings, and sensors. Carries its own power supply. Operates normally autonomously. Operation typical 15–30 days covering 600–1500 km range. Deployed from boats and quayside. Buoyancy driven propulsion by variable ballasting of water.</td>
<td>Very large water column coverage over long distances. Few personnel involved during operation. Follow large ocean current systems.</td>
<td>Low payload capacity. Slow speed operation – 0.4 m/s average. Due to control concept useless for benthic (seabed) investigations. Limited power, payload, control and navigation accuracy. Risk of operation – loss of data and vehicle. Limited on-line control. Possible limitations in operation due to ship traffic and risk for collision.</td>
<td>Ice and icebergs reduce spatial coverage and increase risk for collisions. Low temperatures reduce battery efficiency. Ice coverage prevents direct ascent to surface for GPS fix for navigation.</td>
</tr>
</tbody>
</table>

References

Paper II

that marine zooplankton have a (circadian) biological clock entrained by the day/night cycle and that this clock is adaptive in initiating a migratory response even when external light cues are limited at depth. However, during the polar night, when the strongest source of illumination is no longer coming from the Sun, moonlight probably plays an important role in entraining migratory behaviour. Which species are implicated, and what the ultimate drivers are at this time, remains to be discovered.

As shipping routes open up through the Northwest and Northeast passages and the expanding oil, gas, fishery and mineral industries become increasingly active, the risk of environmental damage in the Arctic increases. There is a growing demand for sound management, decision making and governance guidelines that rely on a thorough research-based understanding of the ecosystem, not just snapshots from the bright part of the year.

For example, we now know that many species across most phyla and trophic levels utilise the polar night for reproduction, hence increasing their potential vulnerability, particularly during this part of the year. Knowledge of the patterns and processes that characterise the entire marine habitat during the polar night is, therefore, one of the most important gaps in knowledge, preventing the informed management and sound decisions of the Arctic.

The unknown
The exploration, mapping and monitoring of unknown areas are not trivial tasks. In a research context, and particularly so when related to the Arctic Ocean during the polar night, these are often aimed at discovering or revealing hitherto unknown objects, organisms, processes and phenomena. Although there are usually one or several features or qualities that one is specifically looking for, a general understanding of an area requires the identification and
Cutting-edge interdisciplinary research involving technology and marine science fields such as marine biology and archaeology will provide the needed bridge to make high levels of autonomy a reality towards autonomous underwater operations.

Enabling technology
Platforms included in the AMOS landscape (Fig. 1) are remotely operated vehicles (ROV), autonomous underwater vehicles (AUV), gliders, landers/moorings, floating buoys, benthic landers, autonomous sensor arrays operating in sea ice, and unmanned aerial vehicles (UAV).

The ability to sample in complex environments creates a need for onboard, in situ and autonomous data collection, quality control and signal processing. Through the Mare Incognitum projects (www.mare-incognitum.no), we are working closely with the Centre for Autonomous Marine Operations and Systems (AMOS) at NTNU (Norway).

Complex environments
Operations in cold and distant areas with limited communication possibilities motivate research on autonomous, multifunctional, drifting observational platforms with reliable energy supplies, adaptive functionality and optimisation of technology and modes of operation.

The ability to sample in complex environments creates a need for onboard, in situ and autonomous data collection, quality control and signal processing. Through the Mare Incognitum projects (www.mare-incognitum.no), we are working closely with the Centre for Autonomous Marine Operations and Systems (AMOS) at NTNU (Norway).

AMOS
AMOS is, as a ten-year research programme and a centre of excellence (2013-2022), addressing research challenges related to autonomous marine operations and systems applied in, for example, maritime transportation, oil and gas exploration and exploitation, fisheries and aquaculture, oceans science, offshore renewable energy, and marine mining.

Fundamental knowledge is created through multidisciplinary theoretical, numerical and experimental research within the knowledge fields of hydrodynamics, structural mechanics, guidance, navigation and control. AMOS is engaged in the research challenges, achievements and experiences of selected field trials related to integrated autonomous underwater operations for mapping and monitoring purposes in coastal waters in Norway and Arctic operations outside Svalbard.

An example on how such technological development provides new insight into ecological processes under the ice comes from a recent work, in which enabling technology allowed for sampling on broader spatial scales than previously possible. It had been suggested in the scientific literature that massive pelagic under-ice blooms occurred in the Arctic and that these were of vital importance to understanding and reliably predicting the fate of production in ice-covered waters. Recently, however, Professor Johnsen and his colleagues have demonstrated, based upon an unprecedented campaign using an AUV under the Arctic pack ice (Fig. 2), that such pelagic under-ice blooms are most likely a result of advection of phytoplankton from open water areas, at least in the Eurasian sector of the Arctic.

Analogous studies could be designed to sample across temporal scales or extended periods in great detail to investigate, for example, the phenology of ice-algal bloom development. Autonomous measurements and observations could then guide experimental studies to test for mechanisms responsible and could provide important data for numerical models assessing ecosystem sensitivity.
Winds of change

Changes in the Arctic ocean-sea ice-atmosphere interface are leading to rapid shifts in the structure, resilience and function of Arctic ecosystems. Rapid decline in sea ice extent and thickness, increased air and ocean temperatures, increased water-column stratification, and multiple dynamic physical and chemical changes significantly alter the patterns of productivity at the base of marine food webs. Such changes are also anticipated to affect ecosystem structure and productivity higher in the food web.

Ultimately, Arctic marine ecosystem structure and productivity within the next decades may be very different from what we observe today. Predictions as to how Arctic marine ecosystems may change are hindered by our inability to understand the year-round response of the Arctic system.

The implementation of new enabling technologies in marine research is therefore likely to drastically increase our ability to understand the Arctic marine ecosystem as one interlinked and connected system and, moreover, will provide the essential tools needed to explore one of the least known realms of our planet – the Arctic Ocean during the polar night.

References


Berge J, et al.: In the dark: paradigms of Arctic ecosystems during the polar night challenged by new understanding. Progress in Oceanography. In press


Johnsen, S., Nilssen, I., Pinto, A. P. B., Torkelsen, T., 2014. Monitoring of impact of drilling discharges to a calcareous algae habitat in the Peregrino oil field in Brazil. SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production. Long Beach, California, USA.
Doi: http://dx.doi.org/10.2118/168356-MS
Please note that the following manuscripts were under preparation at the time the paper was written and consequently the references are incorrect. The correct citations are as follows:

Eide et al. (2013):

Elbers et al. (2013) has not been published

Figueiredo et al. (2013):

Godø et al. (2013):

Nilssen et al. (2013):
Monitoring of Impact of Drilling Discharges to a Calcareous Algae Habitat in the Peregrino Oil Field in Brazil

Ståle Johnsen, Ingunn Nilssen, and Ana Paula Brandão Pinto, Statoil ASA, and Terje Torkelsen, METAS

Abstract

The Peregrino field, operated by Statoil ASA, is located 80 km south of Cabo Frio, in the Campos Basin area, Brazil. The field is operated with two well head platforms drilling production and injection wells and a FPSO located between these. The seabed hosts a calcareous algae (CA) habitat, an area with relatively rich biodiversity. Conventional sediment monitoring has been found not to give sufficient information about potential impact of drill cuttings.

A tailor suited, in-situ sensor based monitoring approach was developed for the field including testing and qualification of a number of sensor systems for visual observation, oceanographic parameters, light and turbidity, all placed on a seabed observatory frame. 4, 6-months sampling campaigns were carried out with this system. In addition, three sediment traps were placed at different locations, over totally 7, 4-months campaigns. Data were combined with discharge information and laboratory studies of drill cuttings effects to CA and associated species, to identify potential exposure and impact in the field. Discharge and environmental risk modeling were performed to identify which data gave significant and vital information for the purpose of environmental monitoring of the CA habitat.

Combining discharge information with in-situ observations and modeling gives a strongly improved basis for identifying impact of drill cuttings discharges in a field like Peregrino. Technology for this has been developed to a readiness level available for multiple use. A new, cost beneficial monitoring program is proposed as an alternative to traditional sediment monitoring.

Introduction

The Peregrino oil field is geographically located 80 km off the coast of Brazil, south of Cabo Frio, in the Campos Basin area. The field consists of two fixed well head platforms for drilling of production and water injection wells, and one floating production storage and offloading unit (FPSO). The two well head platforms (WHPA and WHPB) are located 10 km apart with the FPSO in between (Figure 1a). Drilling at Peregrino commenced in November 2010, and until May 2013, 19 production and 3 injection wells had been completed. The field came in production in May 2011. The well streams are transported to the FPSO through subsea pipelines, while produced water (water that is produced together with the hydrocarbons from the reservoir) is routed back to the well head platforms and re-injected to the reservoir. Drill cuttings with residuals of water based drilling fluid are discharged to the sea, while cuttings from the hydrocarbon containing reservoir section are sent to shore for disposal.

Water depth in the area varies from 90 – 120 m and seabed sediments consist in general of sand and silt with a hard surface. The more shallow part of the Peregrino seabed (<110m) hosts a calcareous algae (CA) community. At the Peregrino field the CA forms calcified structures up to a few cm diameters (rhodoliths) built of dead CA and other calcifying organisms such as Bryozoan and different species of Polychaeta. The rhodoliths act as substrate for a large number of marine fauna species. The living CA grows on the surface of the rhodoliths at a very low growth rate. The density of rhodoliths on the seabed varies, but may for some areas be very high, including several layers where CA lives on top of dead rhodoliths. Figure 1 outlines the
infrastructure of the Peregrino field and shows an example of a typical CA rhodolite.

The CA habitat of Peregrino is regarded as a deep water rhodolith bank, the species probably living on the very limit of physical conditions sufficient for their survival, an assumption is supported by the fact that CA communities are not observed at water depths larger than 110 – 115m in the area. While shallow water communities have been subject to several scientific studies over the past decades (Steller et al., 2007; Steller et al. 2009), less knowledge exists on the function, the sensitivity and the importance of the deep water communities of these rhodolith beds.

When Statoil acquired the operation of the Peregrino field in 2008, it was therefore decided to launch a R&D project to increase the knowledge of deep water CA communities, with the purpose of enabling sustainable environmental management of the Peregrino CA habitat, under the regime of discharges of water based drilling fluids and cuttings. The Peregrino Environmental Monitoring and Calcareous Algae (PEMCA) project was initiated in 2010 and completed in 2013, under the Brazilian National Petroleum and Gas Agency (ANP) Federal Participation Program (FPE). The project included four main activities; i) taxonomy studies of the habitat, ii) exposure and effect studies of drill cuttings, iii) environmental risk assessment and iv) development of environmental monitoring technology.

A comprehensive taxonomy and classification study of the Peregrino seabed was carried out by sampling CA and associated species through four field campaigns, followed by analyses and characterisation of the samples by the Federal University of Rio de Janeiro. In general, the Peregrino seabed is characterized as a rich biodiverse habitat. More than 200 species were identified through this activity a comprehensive overview over these have been given by Tâmega et al. (2013).

Figueiredo et al (2013) performed controlled laboratory studies on exposure impact of light variation, sediment (representing drill cuttings) coverage and water flow rates on CA and associated species (Bryozoa and Polychaeta). The exposed CA species proved to be relatively robust towards fluctuations in these parameters compared to other species reported in the literature, with highest sensitivity towards sediment coverage. Dose-response relationships were established for all variables and utilised as input to the environmental risk assessment studies performed in the project.

Nilssen et al (2013) performed environmental risk assessment of discharges of drill cuttings to the CA habitat by applying the Dose-related Risk and Effect Assessment Model (DREAM). DREAM has been developed of E&P operators in the North Sea (Johnsen et al. 2000, Singsås et al 2008, Nilssen and Johnsen 2008, Smith 2009) and is frequently used for discharges to the marine environment from the E&P industry. By utilising the results from the exposure and effect studies of the PEMCA project, in-situ oceanographic data and the discharge logs from the field, Nilssen et al. (2013) found that after two years of drilling, a significant risk of impacting the seabed environment close to the two well head platforms was present. This result would be expected for such an operation. However, since the well head platforms are located in deeper waters, outside the CA bank, the environmental risk for the CA habitat was less evident. Nevertheless, areas in the CA bank closest to the discharge points were found to be exposed to a significant environmental risk. Nilssen et al. (2013) underlines that even realistic and representative input data were used for the modelling, the output still represents a conservative approach to the real situation.

Only by designing an environmental monitoring program able to validate the environmental risk estimated from the above studies, can the true impact of drilling discharges be documented. In general, Statoil’s ambition is to utilise environmental risk assessment to identify the vital environmental variables to include in the environmental monitoring program for a specific field. The traditional approach to environmental monitoring of drilling discharges implies sampling and analysis of the upper layer of the sediment in the vicinity of the discharge point. Physical, chemical and biological parameters are normally included in this approach. Components like barium, alkanes and PAH are frequently used as markers for drill cuttings discharges, and are normally analysed along with grain size distribution, biodiversity and species (International Association of Oil & Gas
Producers (2012), Climate and Pollution Agency (2011)). A similar approach to sediment monitoring in the vicinity of discharges of drill cuttings is also applied by the regulatory authorities in Brazil (IBAMA). In the operational licence for Peregrino sampling of sediment by grab/box corer is required for a transect system around each of the two well head platforms, covering an area out to 1600 m in the direction of the prevailing current (IBAMA 2010). By 2013, two surveys have been performed, showing, as expected, increased levels of barium in the area close to the platforms. However, no information concerning potential impact on the CA community can be extracted from these surveys. For the Peregrino seabed, it was evident from the baseline environmental survey that conventional sediment sampling by grab system and box corer would not give satisfying results. Due to the hard sediment surface and the presence of rhodoliths these systems were not able to bring an undisturbed sample to the surface, which indeed is the core of the traditional monitoring approach.

The PEMCA project was partly designed to compensate for this and to develop, install and qualify an alternative monitoring approach, using in-situ observations of environmental variables to validate and document potential impact of the discharges to the CA habitat. The ambition and the approach of this development were described by Salgado et al. (2010). In short, the approach included the building and deployment of a seabed platform with different sensor systems to observe presence, exposure and effects of drill cuttings with drilling fluid residues in a location at the CA bank in the Peregrino field. The use of such systems, known as ‘landers’ or ‘ocean observatories’ has over the past decade found a number of applications within oceanographic and marine environmental research. The NEPTUNE (NEPTUNE, 2013) and ESONET/EMSO (ESONET, 2013) programs are probably the most recognized within the international scientific community, representing US/Canadian and EU initiatives, respectively. For the E&P industry, use of this type of technology represents a relatively new approach. Statoil has used sensor based systems, mounted on landers or floating devices for the monitoring of drilling discharges in areas with cold water coral reefs in the Norwegian Sea, at the Morvin and Hyme fields (Godø et al. 2013, Frost et al, 2013). These operations have, however, lasted for relatively limited time windows, over a few weeks. For the Peregrino field the horizon of the drilling activity represents minimum 5 – 7 years, implying more stringent requirements for system reliability and robustness.

The present paper outlines the results of this development along with a cost-benefit analysis of the technology and a potential implementation approach in the Peregrino field.

System design and functionality

Original system design and functionality

The design and functionality of the Peregrino ocean observatory described by Salgado et al. (2010), was based on the use of real-time observations through different sensor systems. The idea was to install the system in the vicinity of well head platform B, approximately 1.5 km southwest of the platform, in the direction of the prevailing current. This area represents the outer boundary of the CA bank, since the water depth increases closer to the platform. Figure 2 shows a schematic drawing of the overall system featuring the surface buoy, the anchor, the lander or sensor platform and a satellite holding the time lap camera. The figure also includes pictures of the buoy and the lander with the mounted sensor systems.

Figure 2: Schematic drawing of the Peregrino ocean observatory system and pictures of yhe surface buoy and the main instrument frame (the lander)
The surface buoy was designed to serve as a communication unit, enabling communication through satellite, a wireless router for short range communication (vessel based) and wireless internet through a base station installed on Peregrino well head platform B.

In the original design, the buoy was moored to an anchor with further connection to the lander which in turn was connected to a stainless steel frame holding a time lap video camera. The anchor mooring from the buoy was a steel armored cable with 2 pcs of single modus fiber and 4 x 1.5 mm² power leads, working load 3 tons. A ‘weak link’ with a breaking strength of 1.5 tons was mounted on the mooring cable. Amore detailed description of materials, cables, connections and power supply setup is given by Salgado et al. (2010).

In addition to the ocean observatory system, three sediment traps were included in the monitoring development project. These were deployed at different positions in and outside the expected influence area to verify the settling of natural particles and cuttings. The sediment traps were deployed with moorings placing the collection funnel 10 m above the seabed. A detailed outline of the applied sensor systems is given in Table 1.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Producer</th>
<th>Type</th>
<th>Spec:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Echo sounder 1</strong></td>
<td>Simrad</td>
<td>Echo sounder EK60</td>
<td>Power: 2,000 kW</td>
</tr>
<tr>
<td></td>
<td>Simrad/Metas</td>
<td>X-GPT transceiver, 38 kHz</td>
<td>Frequency: 38 kHz</td>
</tr>
<tr>
<td></td>
<td>Simrad</td>
<td>Transducer: ES-38DD</td>
<td>Sensitivity: -202,5 dB re 1V per µPa</td>
</tr>
<tr>
<td></td>
<td>Simrad</td>
<td>ER60 Software</td>
<td>Transducer beam: 7º</td>
</tr>
<tr>
<td><strong>Echo sounder 2</strong></td>
<td>Simrad/Metas</td>
<td>Echo sounder EK60</td>
<td>Power 500 W</td>
</tr>
<tr>
<td></td>
<td>Simrad</td>
<td>X-GPT transceiver, 120 kHz</td>
<td>Frequency: 120 kHz</td>
</tr>
<tr>
<td></td>
<td>Simrad</td>
<td>Transducer: ES-120 CD</td>
<td>Sensitivity: -187 dB re 1V per µPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ER-60 Software</td>
<td>Transducer beam: 7º</td>
</tr>
<tr>
<td><strong>ADCP</strong></td>
<td>AADI -Aanderaa</td>
<td>RDCP600</td>
<td>Frequency: 600 kHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Beams: 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Depth Capacity: 300m</td>
</tr>
<tr>
<td><strong>Light sensor</strong></td>
<td>Biospherical Instruments Inc</td>
<td>QCP-2000 Cosine PAR sensor</td>
<td>1,4x10⁻³ µE/cm² sec to 0,5 µE/cm² sec</td>
</tr>
<tr>
<td><strong>Depth/Temp sensor</strong></td>
<td>AADI -Aanderaa</td>
<td></td>
<td>Accuracy: ± 0.005 S/m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Resolution: 0.0002 S/m</td>
</tr>
<tr>
<td><strong>Oxygen sensor</strong></td>
<td>AADI -Aanderaa</td>
<td></td>
<td>Accuracy: &lt; 8 µM</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Resolution: &lt; 1 µM</td>
</tr>
<tr>
<td><strong>Turbidity sensor</strong></td>
<td>AADI -Aanderaa</td>
<td></td>
<td>Accuracy: 2% of full scale Resolution: 0,1% of f.s</td>
</tr>
<tr>
<td><strong>Salinity sensor</strong></td>
<td>AADI -Aanderaa</td>
<td></td>
<td>Accuracy: ± 0.005 S/m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Resolution: 0.0002 S/m</td>
</tr>
<tr>
<td><strong>Compass, tilt and roll sensor</strong></td>
<td>METAS</td>
<td>MC 1500</td>
<td>Compass accuracy: &lt; 0,5°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tilt: ± 90°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Roll: ± 180°</td>
</tr>
<tr>
<td><strong>Tilt sensor</strong></td>
<td>METAS</td>
<td>MT 1500</td>
<td>Range: ± 180°</td>
</tr>
<tr>
<td><strong>Sediment traps</strong></td>
<td>McLane LTD, USA</td>
<td>Parflux Mark 78H-21</td>
<td>Equipped with 21 collection inits for sequential sampling</td>
</tr>
</tbody>
</table>
Pre-deployment adjustments

The technical approach applied for the PEMCA ocean observatory implied the use of relatively large and heavy equipment, leading to relatively comprehensive requirements to the vessel used for deployment and retrieval of the system. A vessel with sufficient lifting capacity and heave compensated cranes was necessary to deploy and retrieve the whole system. A work-class ROV was also needed. In practice, these requirements were not met by Statoil supply vessels, and some adjustments to the plan were made to simplify the operations.

The plan of a separate camera satellite platform was abandoned and the camera was mounted directly on the Lander frame. This led to an adjustment of the angle of the camera that was mounted in a 45 degree angle, pointing downwards. It was assumed that this would not affect the quality of the images.

To reduce the weight of the lander, the battery containers were redesigned. The weight was reduced with approximately 10%.

The lander was originally equipped with an Aanderaa RDCP (ADCP) unit for ocean current and conductivity, temperature and pressure measurements. The RDCP unit was only able to measure the current in the lower 60 m of the water column, but this was regarded as sufficient since the cuttings discharge point is at 50 m water depth. However, Statoil internal Met Ocean group agreed with Peregrino asset that full water column current measurements were needed and an additional ADCP unit, a Nortek Continental was installed on the lander frame. This unit was not connected to computer and power system in the lander, but operated on separate batteries and stored data on an internal hard disc.

Field campaigns

Totally, 4 field campaigns were planned during the three year PEMCA project, each lasting approximately six months. Table 2 presents an overview over these, including the main outcome of the campaigns with respect to data collection.

Table 2: Overview over field campaigns

<table>
<thead>
<tr>
<th>Period</th>
<th>Location</th>
<th>Overall results</th>
</tr>
</thead>
<tbody>
<tr>
<td>May – Oct 2010</td>
<td>250 m S of WHPB</td>
<td>Data collection failed after 3 weeks due to leak in GPT container (-included main computer)</td>
</tr>
<tr>
<td>Jan – Jun 2011</td>
<td>1.4 km SW of WHPB</td>
<td>Data collection for only 4 months due to high power consumption. Poor images, light sensor failed. Leaks and corrosion. Major service and upgrading performed</td>
</tr>
<tr>
<td>Nov 2011 – Apr 2012</td>
<td>1.4 km SW of WHPB</td>
<td>Communication buoy deployed but weak link broke. Concept abandoned. Data collection successful, except light sensor failure and overexposure of parts of the images</td>
</tr>
<tr>
<td>Jul 2012 – Jan 2013</td>
<td>1.4 km SW of WHPB</td>
<td>Data collection successful except light sensor</td>
</tr>
</tbody>
</table>

Field campaign 1

The first campaign was designed to start before drilling discharges commenced. The lander was deployed May 1st 2010, 250 meters south of well head platform B with the sonar system oriented to observe discharged drilling particulates. This was done to clarify to what extent the sonar system was able to track the discharge plume from the platform. For this campaign the lander was deployed as a standalone system without the communication buoy, since it was in a temporary position. Deployment was carried out by the vessel “7 Oceans”, which at the time was participating in the installation work at Peregrino.

Two major problems occurred during the first field campaign. Drilling operations, and thereby cuttings discharges, were delayed, and did not start until after the lander was retrieved for battery shift in October 2010. As a result no cuttings discharges were present in the field during the deployment period. The second problem occurred party because the lander was damaged during handling onboard the vessel. The cable and connector to the power supply unit was damaged during lifting. Repair was attempted prior to deployment and appeared successful, but the system probably short-circuited and drained the
batteries for power after a few weeks. When the lander was retrieved, sea water was found both in the battery containers and the GPT container (computer container). Data was only gathered for about 4 weeks.

Field campaign 2

After repair and battery replacement the lander was again deployed in January 2011, this time from “Maersk Attender”, a crane vessel participating in the installation work at Peregrino. A position 1.4 km southwest of well head platform B, at the edge of the CA bank was chosen. The plan was to also deploy the communication buoy during this campaign, but this was postponed because the fiber cable between the buoy and the lander broke during the preparations for deployment. An unsuccessful attempt to repair was made onboard the vessel.

This time, the system worked better, but the batteries were drained after 4 months. The systems still had problems with corrosion of stainless steel connectors, and this led to higher energy consume than expected. The light sensor did not work during the campaign and the images were of very poor quality, mainly due to overexposure (high flash intensity). A large number of the acoustic files were ‘corrupted’ for reasons unknown, indicating a certain degree of instability in the set up and systems.

Some major changes were necessary based on the experience so far. A technical audit and risk assessment was carried out between Statoil subsea installation experts and METAS, where all aspects of the equipment and operation were reviewed. The lander was therefore sent to Sao Paulo for repair and service, the major adjustment was that all stainless steel connectors were replaced by titanium to avoid corrosion. A comprehensive set of tools and spare part was purchase to always be available during the field campaigns.

For the retrieval of the lander in campaign 2, Statoil supply vessel “Skandi Peregrino” was upgraded to host a work class ROV for the purpose of participating in the PEMCA project. The vessel and the ROV was hired from Fugro, responsible for the remaining campaigns.

Field campaign 3

During field campaign 3, from November 2011 – April 2012, the buoy and anchor were deployed. Because of the periodically very strong current in the field, the buoy came under very strong pressure and almost lay flat in the sea surface. This made the communication even from very close range unstable. After less than 24 hours the weak link between the buoy and the anchor broke, and the buoy had to be rescued by “Skandi Peregrino”. A possible reason for this can be interaction with fishing vessels using the buoy as mooring. There is, however, no clear evidence for this. Since a real-time solution was not essential for the project and due to a cost/benefit consideration the buoy concept was abandoned for the PEMCA project after this.

Data collection on the 3rd campaign was more successful, all sensor systems except the light meter worked. The turbidity sensor failed after about 3 months and the image quality was still reduced due to overexposure or too strong flash. The camera house was also exposed to biofouling. After three months this started to impact the quality of the images. Except for these minor to moderate issues, all systems operated satisfactory.

Field campaign 4

Also the 4th and final campaign, July 2012 – January 2013, was successful, but the light sensor failed also this time. This in spite it had been returned to the manufacturer after the previous cruise, repaired and tested. Apart from this all systems worked well and collected data for the whole period. The images were this time of much better quality and biofouling did not seem to be a significant problem, probably since the sampling took place during the winter and spring season.

General learning from the field campaigns

One of the most challenging issues for the PEMCA project was the logistics and solutions related to vessel capacity and quality. When the project was initiated, “Skandi Peregrino” was planned to carry a work class ROV or at least work class ROV platform, but this was not installed. A ROV platform was installed on “Skandi Peregrino” in 2011 and thereafter used for deployment and retrieval of the equipment.

In general, the initial PEMCA ocean observatory system did not represent a good design with respect to robustness and handle-ability. Only after major improvements did the lander work properly and in combination with anchor, buoy and satellite it represents a system which is very challenging to handle in the field. As a result of the experiences from PEMCA, and other campaigns, has the lander design been changed considerably.

Utilizing seabed based observatory or a stand alone landers for environmental observations is not a new concept. For the oil industry, however, limited experience in this area is present, meaning that the suppliers of this technology are not familiar with
working with offshore requirement’s and level of quality control needed. The PEMCA project has from this viewpoint contributed significantly to develop this experience for all involved parties.

**Sediment traps campaigns**

Three sediment traps were purchased for the PEMCA project in order to monitor natural sedimentation and potential input from discharges of drill cuttings in the area. In general, this equipment is reliable and easy to handle. It can be deployed and retrieved without use of ROV or heavy lifting equipment. The traps are simply dropped from the surface attached to a weight; they sink calmly to the seabed and are retrieved by releasing the trap from the weight by an acoustic signal. Figure 3 shows a photo of a sediment trap under deployment.

![Figure 3: Deployment of sediment trap](image)

Table 3 gives an overview over the sediment trap sampling campaigns. The sediment traps were deployed and retrieved by the supply vessels “Anita”, “Carolina” and “Skandi Peregrino”. Campaigns 1 and 2 were complete, while campaign 3 only included 1 trap. A technical problem led to that one trap could not be redeployed after campaign 2. In addition failure of the acoustic release system made one trap impossible to retrieve and deeply again for campaign 3. This could have been avoided by installing a double acoustic release system. This trap was later retrieved by an ROV. In addition, one trap was destroyed by the vessel during retrieval after campaign 4, so from the 5th campaign only two traps were available.

<table>
<thead>
<tr>
<th>Campaign</th>
<th>Period</th>
<th>Trap 1</th>
<th>Trap 2</th>
<th>Trap 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19.06.2010 - 21.08.2010</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>28.10.2010 - 16.01.2011</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>07.04.2011 - 26.06.2011</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>16.08.2011 - 17.11.2011</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>22.03.2012 - 17.06.2012</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>01.07.2012 - 01.10.2012</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The funnels for sample collection on the sediment traps were located 10 m above the seabed. Ideally, a location closer to the seabed would be preferable since the results are to be compared with sedimentation on the seabed. Since the sediment trap has positive buoyancy in the water column it is sensitive to strong currents. This may influence its ability to sample realistically since the angle of the funnel opening may tilt away from the current direction. The present solution is therefore not optimal for an area with strong currents such as the Peregrino field.

**Sampling locations**

As described above, the lander was during the first campaign located 250 m south of the Peregrino well head platform B, while it for the following three campaigns was located approximately 1.5 km southwest of the platform. The sediment traps were placed in three different positions, 500 m southwest of well head platform B, close to the lander and approximately 4 km southwest of platform B. The latter position was expected to represent an area outside the potential influence area of cuttings.
discharges. When the number of traps was reduced to two, as described above, the two latter positions were maintained. Figure 4 shows the positions of the sampling equipment in an infrastructure and seabed structural map of the Peregrino field.

Figure 4: The Peregrino infrastructure and location of the lander and the three sediment traps and a map showing the area with high density of calcareous algae rhodoliths (pink dotted area)

Overall results of the monitoring campaigns

The present paper focuses on the development, implementation and qualification of monitoring technology for the Peregrino seabed environment. However, to complete the picture reflecting the outcome of the PEMCA project, this section addresses the results of the observations and measurements made through the sampling program of the project. Eide et al (2013) and Nilsen et al (2013) have described the analysis of the sampling campaigns and the risk assessment, respectively. Eide et al. (2013) performed correlation studies and multivariate analysis of the sampling results from the lander and sediment trap campaigns, the discharge logs from the two well head platforms and the dispersion of drill cuttings in the Peregrino seabed modelled by the DREAM model. The intention with the correlation study was to document the distribution of drill cuttings in the area and to identify any potential impact of this on the CA community. Also, the goal of these analyses was to identify which of the sensor and sampling systems contributes significantly to the understanding and documentation of fate and effects of drill cuttings discharges in the area. Eide et al. (2013) showed that no evidence of drill cuttings exposure was present for the sampling sites in the area of the fields hosting the CA habitat, and thus, no effects were observed. The results from the modelling and sampling were in agreement on this point. However, the study by Nilsen et al. indicated the presence of a significant environmental risk of impact to the CA in the outer boundaries of the CA bank, also in the area where the lander was located. The reason for this disagreement lies in the conservative nature of the DREAM model, only reflecting the build-up of drill cuttings in the sediment over the whole discharge period. The sampling campaigns, on the other hand, reflect a more realistic dynamic situation where natural processes of sediment turbation are evident. It was suggested by Nilsen et al. (2013) that the model should be developed further to include this aspect by introducing a time variable sediment reworking function. From the image analysis of photos collected by the lander, Elbe et al. (2013) has determined an average movement frequency of CA rhodoliths. This may be utilised in the risk assessment model to account for the self-cleaning ability of the CA.

A new monitoring approach for the CA community

Technology approach

Based on the experience from use of ocean observatory technology in several environmental monitoring programs over the past years, with Peregrino as the major contributor, a new technical solution for the purpose of seabed based monitoring platforms, or landers, has been developed. The solution attempts to meet and solve the challenges met in the PEMCA project, related to robustness, reliability and logistics. A major priority was to decrease the weight and the size of the sensor platform to increase flexibility and ease the handling during field operations. Another major objective was to enable deployment and retrieval without the need for work class ROV. Figure 5 shows an illustration of a stand-alone lander designed and built by METAS, meeting these criteria. The unit has a total weight of 800 kg and is tailor suited for environmental monitoring in the Peregrino field, with a built-in sediment trap and the sensor package described below. This 2nd generation Peregrino lander is designed as a drop unit with inflectable flotation cells that can be activated by a remote acoustic signal. Alternatively, it can be built with positive buoyancy and connected to drop weights that can be released acoustically to make it surface again. It can also be deployed and retrieved by a special carrier frame with small electrical trustees for positioning. This stand-alone unit can also be integrated in an ocean observatory system and has been tested and qualified by Statoil. It has already found several applications in environmental monitoring programs on the Norwegian shelf.
Alternative monitoring approach for the CA habitat in Peregrino

Based on the results from the PEMCA project and the development of a new lander structure, an alternative approach to environmental monitoring of drill cuttings discharged in the Peregrino field has been designed. The approach has a special focus on the potential impact of the discharges to calcareous algae habitat, but is also aimed to replace the traditional sediment monitoring regime for the field. The program includes two main elements:

- Field sampling campaigns
- Cuttings dispersion and risk assessment modeling

By combining these elements the program aims to improve understanding, management and documentation of the fate and effect of drill cuttings discharges to the Peregrino seabed. The potential for improvement is significant based on the results from PEMCA and the first two years of traditional environmental monitoring. Field sampling will be carried out by use of two separate stand-alone landers, designed as described above, so they can be operated from any of Statoil’s supply vessels at Peregrino. The landers will hold the following sensor and sampling systems, based on the results from the PEMCA field campaigns, as summarized by Eide et al. (2013) and the observations from the image analyses described by Elbers and Sumida (2013).

- Sediment trap for analysis of particle flux, organic carbon, hydrocarbons, metals and isotopes
  These measurements will enable documentation of sediment fluxes and contribution from natural sources vs cuttings discharges. The results can also be used directly for validation of dispersion modeling
- Turbidity sensor
  Will be used for correlation of particles in the near sediment water column with the discharge log, sediment trap results, current and dispersion model results
- Bottom current profiler
  Will be used as input to the modeling and for correlation with sediment traps results, turbidity and discharge log
- Water column current profiler (ADCP) if not obtained from WHB
  As above
- 2 time lap cameras
  Based on the laboratory studies and image analyses from PEMCA, field images will be used to identify impact of sedimentation (natural and drill cuttings) to the CA. Further, the images will be used to validate the risk and dispersion modeling results by applying colour change and movement as variables.
- Battery power and data storage system

The ambition of the proposed monitoring program is to combine field campaigns with dispersion and risk/impact modeling, and thereby present an overview over the environmental status of the Peregrino seabed environment. The results from the model will be visualized by a map over the field where areas are colored related to the risk of impact from the discharges as shown Nilsen et al. (2013). Distribution of drill cuttings will also be visualized by the model. The field sampling campaigns will partly provide input to the model, partly serve to validate the model and also stand alone to document the environmental status of selected locations in the field. In addition, the monitoring program will make it possible to distinguish between natural sedimentation and contamination due to drilling activities. The principle is to run 3 – 9 weeks sampling campaigns where the landers are placed on different locations of the field to give a best possible fundament for modeling and
documentation. As the quality of the modeled results improves and are better documented through field validation, the frequency of the sampling campaigns will be reduced.

Table 3 outlines how the alternative monitoring program can be carried out for the remaining drilling period of Peregrino (updated plan from May 2013) with respect to campaign frequency and modeling. To also cover the need for monitoring the close area of the platforms, conventional grab/box corer sampling campaigns are included at the end of the drilling activities for each platform.

Table 3: Alternative monitoring program for Peregrino field (updated plan from May 2013)

<table>
<thead>
<tr>
<th>Activity / Year</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field sampling campaigns</td>
<td>2 2 1 1 1 1 1</td>
</tr>
<tr>
<td>Modelling</td>
<td>1 1 1 1 1 1</td>
</tr>
<tr>
<td>Sediment sampling campaigns</td>
<td>1 1 1</td>
</tr>
</tbody>
</table>

Cost benefit evaluation

To generate a basis for evaluation of cost for the proposed monitoring program, a request was presented to four potential suppliers of a modified lander system. The suppliers were asked to independently propose a design and estimate production and operational costs for building two lander systems as described above, and make these available for Statoil Brazil. Both local Brazilian and international companies were included in the survey. Re-use of the sensor systems from the PEMCA project was not considered in the request, but it was assumed that the PEMCA sediment traps can be reused as a part of the lander system. The estimates from the four potential suppliers varied significantly, but an average of the three lowest estimates was applied for the overall program cost estimation. Costs related to field work, sample analyses, modelling and reporting were estimate based on experience from the PEMCA project and other environmental monitoring programs conducted in Brazil by local suppliers. Vessel costs assumed the use of Statoil hired supply vessels, using daily rates as basis for the estimate.

By summarizing the investment costs and the costs related to field campaigns, modeling, sample analyses and reporting for the planned drilling period in the Peregrino field (Table 4), a total expected cost of the alternative monitoring program can be established. This figure can be directly compared to the expected cost of the traditional monitoring program required by Brazilian pollution control authorities (IBAMA) and presently implemented in the Peregrino field. The expected costs were estimated to 2.2 and 2.5 million USD, respectively. These figures are of the same order of magnitude, in fact the difference is relatively low. However, over the remaining planned period of drilling the alternative monitoring approach will accumulate to a lower total cost than the on-going conventional program. Because of the up-front investment in equipment the alternative approach will be more expensive than the on-going for the initial four years, but after this period the total cost will be lower for the PEMCA based alternative. If the drilling program is extended, which is not unlikely, this difference will increase. In conclusion, the results indicate that a program using the technology developed can be more cost efficient than the current sediment sampling methodology demanded by Brazilian authorities.

In addition to the expected cost reduction, the alternative program represents a clear improvement in quality of the information obtained through the environmental monitoring campaigns, with respect to documenting the presence or absence of impact of drill cuttings discharges to the CA community. This is simply not possible with the on-going conventional monitoring program. The alternative approach may also represent a significant step in the direction of better control and environmental management for other areas where special focus is needed on sensitive seabed habitats. Further use and thereby increased experience with this type of environmental monitoring may also contribute to cost reductions in the equipment applied.

A general criticism towards environmental monitoring by the traditional grab sampling approach is that the methodology itself poses certain harm to the seabed environment, by disturbing the habitat when removing samples of this for further analysis. As shown during the baseline environmental survey, the only efficient way to sample CA rodoliths is to dredge the seabed surface. This approach to monitoring will pose significant impact on the habitat, since relatively large areas will be affected. The monitoring approach presented in the present paper eliminates this problem, since it is based on passive observation of the seabed environment, with minimum collection of physical samples, e.g. insignificant disturbance on the ambient environment
Aknowledgements

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Paper IV

The effect of sediment mimicking drill cuttings on deep water rhodoliths in a flow-through system: Experimental work and modeling

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1. Introduction

Rhodolith beds are benthic communities dominated by calcareous red algae (Rhodophyta: Corallinales and Sporolithales) which build calcified nodules (rhodoliths) (Resence, 1983; Foster, 2001). Rhodoliths with multi spherical structures are classified within the morphological group “boxwork” (Basso, 1998). Due to the structure, the rhodoliths are inhabited by other organisms increasing the biodiversity of soft-bottom communities (Borbohore et al., 2003; Steller et al., 2005; Figueiredo et al., 2007; Harvey and Bird, 2008; Sciberras et al., 2009) and therefore they play an important ecological role in coastal areas (Hall-Spencer, 1998; Ávila and Riosmena-Rodriguez, 2005; Steller et al., 2009; Riosmena-Rodriguez et al., 2010). The largest occurrence of rhodolith beds in the world are found in the southwest Atlantic along most of the Brazilian continental shelf (Kempf, 1970; Foster, 2001; Lavrado, 2006; Amado-Filho et al., 2012). Calcareous algae are found down to approximately 250 m depth (Littler et al., 1986, 1991). These communities may be disturbed and have a potential to get buried due to natural sedimentation and anthropogenic activities such as fish-trawling and mining (Nelson, 2009). Rhodolith beds are increasingly exposed to discharges of drill cuttings from oil and gas activities, for instance in the Gulf of Mexico and on the Brazilian shelf (Davies et al., 2007). It has been demonstrated that fine sediments (<250 µm grain size) may reduce the photosynthetic activity of coralline algae to a larger extent than coarse calcareous sediments from shallow nutrient-rich estuarine and coastal environment (Wilson et al., 2004; Harrington et al., 2005; Riul et al., 2008) as well as deep rhodolith soft-bottoms (Villas-Bôas et al., 2014). The ability to withstand sedimentation varies greatly among calcareous algae species (Harrington et al., 2005; Villas-Bôas et al., 2014). Different species may have different survival strategy towards sedimentation, for example slow growth and low metabolic demand, shooting branches above thallus surface, translocation of photosynthesis through cell-fusions from healthy to damaged area of thallus, or tilting (Steneck, 1986; Dethier and Steneck, 2001).
The purpose of the present study was to measure the possible impact of sediment coverage on two rhodolith-forming calcareous algae species collected at approximately 100 m water depth at the Peregrino oil field off the coast of Brazil.

Due to the slow growth of the calcareous algae (Adey and Macintyre, 1973; Foster, 2001), photosynthetic efficiency (maximum quantum yield of charge separation in photosystem II, \( \Phi_{\text{PSII}} \)) was selected as endpoint. A decrease in photosynthetic efficiency is generally considered to be a response to environmental stress (Genty et al., 1989; Wilson et al., 2004; Evertsen and Johnsen, 2009).

Natural sediment mimicking drill cuttings with respect to size distribution was used in the study. Although water based drilling fluids consist of water soluble and non- or low-toxic components (Bakke et al., 2013) some laboratory studies on single species (Larsson and Purser, 2011; Larsson et al., 2013) and soft bottom seafloor communities (Trannum et al., 2010; Bakke et al., 2013) have shown larger effects of drill cuttings (water based) compared to natural sediments. However, initial short- and long-term toxicity testing with the algae species used in the present work verified that there was no significant difference in photosynthetic efficiency when comparing sediment and drill cuttings from Peregrino (Reynier et al., in press). It was therefore assumed that this sediment was considered relevant as a surrogate for the drill cuttings from Peregrino. Besides, discharge of drill cuttings from the laboratory experiments would not be permitted.

Sediment coverage and photosynthetic efficiency were studied as functions of light intensity, flow rate and added amount of sediment for nine weeks in an experimental flow-through system especially built for the experiments. Statistical experimental design and multivariate data analysis and statistics have been useful in previous toxicological and environmental studies (Eide and Johnsen, 1998; Søfteland et al., 2009) and were used to obtain multivariate regression models. These models were subsequently used to establish exposure–response relationship for photosynthetic efficiency as function of sediment coverage. In addition, color changes indicating stress or mortality of the calcareous algae were recorded.

2. Material and methods

2.1. Sampling site

The organisms used in the present study were collected at the Peregrino oil field 80 km off the coast of Brazil, in the Campos Basin area. Drilling started in November 2010 and the field came in production in May 2011. The water depth in the area is approximately 100 m. The seabed sediments consist in general of sand and silt with a hard surface (Salgado et al., 2010). In order to avoid impact of drilling activities to the calcareous algae habitat, the drilling platform and the discharge were located approximately 1.5 km away from the habitat.

2.2. Species and their environment

A field assessment was carried out at the Peregrino oil field to identify rhodolith-forming species (Tånega et al., 2013). Rhodoliths and the associated fauna were collected by dredging 22 sampling sites at 94–103 m depth in June and November 2010 and April 2011. For species identification, a selected number of the calcareous algae samples were preserved in 10% formalin solution, and associated fauna samples were preserved with magnesium chloride (8%) for 30 min and then fixed in \( \geq 70\% \) alcohol. The main organisms identified were the long lived encrusting calcareous algae and bryozoans.

The choice of species for the experiments was based on their ecological importance and abundance at the Peregrino oil field, their resistance to sampling, and survival under laboratory conditions. For species identification the calcareous algae were sectioned using histological techniques for optical microscopy according to Moura et al. (1997) and identification followed descriptions of Woelkerling (1988). Two of the most abundant species of encrusting calcareous algae covering rhodoliths were chosen. Organisms for the exposure studies were kept alive in a flow-through system under controlled levels of temperature and light intensity (15 °C and 15 μmol m\(^{-2}\) s\(^{-1}\), respectively) similar to natural conditions.

2.3. The calcareous algae

The two dominant species of calcareous algae, Mesophyllum engelhartii (Foslie) Adey and Lithothamnion sp. (Figueiredo et al., 2012), were chosen for the exposure studies. Rhodoliths free of epibionts and with the most common size (40–60 mm in average diameter) and shape (compact-bladed to bladed) were selected and tagged with numbers glued by epoxy putty (TUBOLIT MEN) to their surface. The calcareous algae used in the exposure studies were healthy specimens, purple to pinkish in surface color with bleached spots.

2.4. Sediment

Natural sediment mimicking drill cuttings with respect to size distribution was used in the study. Composition of the sediment grain size was based on sieving analysis of drill cuttings from one of the wells at the Peregrino oil field (well A-18).

The dominant drill cutting particle size is medium to fine (63–250 μm). Natural sediment was sieved and the fine and coarse fractions were mixed at a ratio of 3:1 in order to mimic drilling particles. Initial toxicity testing verified that this natural sediment and the drilling particles from Peregrino had comparable effects on the two calcareous algae species (Reynier et al., in press).

2.5. The flow-through system

A novel large-scale flow-through system was designed to test the effects of particles on selected species as a function of added sediment amount, light intensity, water flow rate and exposure time. The entire flow-through system consisted of four units with eight loops in each unit placed in a rack system. Each loop consisted of an exposure chamber where the organisms were positioned. The water movement was driven by a propeller as illustrated in Fig. 1. Water flow could be varied within each of the four units. Light intensity and added amount of sediment could be varied independently within each loop. Each exposure chamber was optically shielded from its neighbors and was illuminated by three blue diodes (peak wavelength 465 nm) of the Lambertian type (Seoul Semiconductor type B42182). The entire experimental system of four units, each with eight loops, was placed inside a temperature regulated chamber with the same temperature as the inlet water to avoid temperature fluctuations. A cooling system with the capacity to cool 2 L min\(^{-1}\) of sea water to 15 °C was established outside the cooled room. In addition to a biological filter the water was mechanically filtered using 25 μm and 5 μm filters in series. A 20 L seawater reservoir for the chilled water was placed inside the cooled room.

2.6. Statistical experimental design

Photosynthetic efficiency and sediment coverage were studied as function of the three design variables light intensity, flow rate

\[ C = \frac{l}{C_0} \]

\[ \frac{l}{C_0} \]

\[ \frac{l}{C_0} \]
and added amount of sediment in addition to exposure time. In order to perform the experiments as efficient as possible, and to enable regression modeling to describe possible non-linear relationships and interactions, the predictor variables were combined as a full factorial design (Central Composite Face, CCF) with center points as shown in Table 1 (Box et al., 1978). Replicates (same conditions in parallel loops) are indicated in the table and the legend.

The light levels were 3, 6.6, and 10 μmol m$^{-2}$ s$^{-1}$, the latter corresponding to light intensity at 100 m water depth at the Peregrino field where the calcareous algae were collected. The different flow rates were 0.04, 0.07, and 0.09 m s$^{-1}$, higher flow rates caused too much turbulence in the flow-through system. The added amounts of sediment were 600, 900 and 1200 g per chamber. Introductory studies had shown that the range 600–1200 g resulted in 0–100% coverage.

The full factorial design gave 15 combinations of light intensity, flow rate and sediment amount (Table 1). In addition there were a number of replicates (same conditions in parallel loops) and parallel rhodoliths within each loop (exposure chamber). In the first experimental series there were six parallels (rhodoliths) within each loop, one loop for each of the 15 combinations plus six replicates, giving a total of 21 loops and 126 individual rhodoliths with each of the algae species. In addition there were 16 controls of each species. Three rack units were used in the first trial, and all four were used in the second trial; the intermediate flow rate was used in two of the rack units resulting in a larger number of replicates in the second trial.

The controls were placed in loops distributed between the different units (and hence different flow rates). The controls were neither exposed to light nor sediment and were used to evaluate how long the algae could live in darkness without deleterious effects (Wilson et al., 2004).

Photosynthetic efficiency was measured prior to the addition of sediment, and both photosynthetic efficiency and sediment coverage were measured each week for nine weeks implying that also exposure time was a predictor variable in addition to flow, light and sediment amount.

2.7. Photosynthetic efficiency measurement and color evaluation of calcareous algae

Once a week during nine weeks (T0–T9), except the first week of the first trial due to technical problems, all rhodoliths were taken out of the flow-through system to measure photosynthetic efficiency as maximum quantum yield of charge separation in photosystem II ($\Phi_{\text{PSII}}$) in dark acclimated algae in vivo. Each rhodolith was placed in sterilized sea water at 15 °C and carefully brushed to remove biofilm and sediments. Prior to the measurements the rhodoliths were transferred to a box for dark acclimation for 20 min. Three readings of photosynthetic efficiency were taken randomly from each rhodolith in complete darkness. The measurements were done using a Diving-PAM fluorometer and Win-Control software (Walz GmbH, Effeltrich, Germany). A blue measuring light with a wavelength of 470 nm was used. The saturating pulse was 0.6 s and saturation intensity 150–200 μmol m$^{-2}$ s$^{-1}$, gain 3 μmol m$^{-2}$ s$^{-1}$ and dumping 3 μmol m$^{-2}$ s$^{-2}$. To ensure that the readings always were taken at a distance of 3 mm to the algae surface, a plastic spacer were attached to the fiber optic sensor (2 mm diameter) (Harrington et al., 2005). The average of the three measurements made on each rhodolith was used in the data analysis. After the photosynthetic efficiency readings all rhodoliths were returned to the exposure chambers. $F_0$, the ground fluorescence, and $F_m$, the maximum fluorescence were measured. The variable fluorescence was calculated as $F_v = (F_m - F_0)$. The photosynthetic efficiency was calculated according to the following equation: $\Phi_{\text{PSII}} = F_v/F_m = (F_m - F_0)/F_m$.

<table>
<thead>
<tr>
<th>Flow</th>
<th>Light</th>
<th>Sediment</th>
</tr>
</thead>
<tbody>
<tr>
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<td>3</td>
</tr>
<tr>
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</tr>
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<tr>
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<td>0.04</td>
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</tr>
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<td>6.6</td>
</tr>
<tr>
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<tr>
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<tr>
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<tr>
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</tr>
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<td>10</td>
</tr>
<tr>
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<td>0.09</td>
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</tr>
<tr>
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<td>3</td>
</tr>
<tr>
<td>15</td>
<td>0.09</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Fig. 1. The loop design.
In addition to the photosynthetic efficiency measurement, changes in color tone and intensity of the calcareous algae were evaluated by visual inspection according to a standard color chart (Figueiredo et al., 2000; Villas-Bôas et al., 2014). Furthermore, health status was evaluated according to a classification scheme (Figueiredo et al., 2000). Data on photosynthetic efficiency corresponding to color tone and intensity were organized in a table in order to relate these parameters to health status and stress levels (Table 4).

2.8. Sediment coverage measurement

Sediment coverage was calculated from photos taken of each rhodolith at the beginning of the experiment and each week for nine weeks. To avoid disturbing the sediment, seawater was slowly drained off before taking the rhodoliths out for measurements. Photos were taken at a standard distance with a measuring scale close to each rhodolith. To ensure a constant distance from the rhodolith, a digital camera (Canon G12) was fixed on a frame. Sediment coverage (%) was calculated by outlining the border of each rhodolith image and estimating the covered area by using the software ImageJ (National Institutes of Health, Bethesda, Maryland). After the measurements were completed, the rhodoliths were brought back to their original position in the exposure chambers and sediment was added to replace the amount that was lost when draining off the water.

2.9. Multivariate data analysis

Multivariate regression was performed with partial least squares (PLS) (Martens and Naes, 1993; Wold et al., 1983) using Simca-P+ 11.5 (Umetrics, Umeå, Sweden). The purpose was to relate the predictor variables (X matrix) to the measured responses (Y-matrix). Prior to the PLS-regression, the data were scaled to unit variance and mean centered. The PLS models were validated with respect to explained variance, goodness of fit ($R^2$) and prediction (shown as $Q^2$), the latter obtained after cross-validation (Wold, 1978).

Introductory, the PLS-regression was carried out for each trial and each algal species separately and with all individual observations in order to verify repeatability in the measurements and to identify possible outliers (not shown). Subsequently, averages of parallels (six in each loop in the first trial, and four for each algal species in the second trial) were calculated. However, still there were replicates (same conditions in parallel loops) as described in Section 2.6 and Table 1. The averages were used in the next PLS analyses which were carried out for each trial and each algal species separately and also on the combined data from both trials and both algal species. The combined data matrix with averages had 21 rows (observations) from the first experimental series with Mesophyllum, and from the second experimental series, 28 rows with Mesophyllum and 28 with Lithothamnion resulting in a total of 77 rows for each sampling time. The X-matrix had four columns, one per predictor variable (light, flow, sediment amount and time), and the Y-matrix had one column per response variable (photosynthetic efficiency and sediment coverage).

The PLS-model was subsequently used to predict photosynthetic efficiency and sediment coverage at fixed levels of light intensity, flow rate and time in order to provide data for exposure–response curves for photosynthetic efficiency as function of sediment coverage at different scenarios. The controls were treated separately since they were neither exposed to light nor sediment; these data were analyzed in two different ways: (1) PLS regression of photosynthetic efficiency of controls as function of flow and time (light and sediment amount constant at zero). (2) Linear regression of average values for photosynthetic efficiency, one for each algae, trial and flow, as function of time.

3. Results

3.1. Controls

Fig. 2 shows the result of the linear regression using average values for photosynthetic efficiency in controls as function of time for each algae, trial and flow rate. The regression line has a correlation coefficient of 0.40. There is an indication of larger variability at T9. Performing linear regression from T0 to T8 gives a regression line slightly less steep with a correlation coefficient of 0.56. Although the correlation is not strong, the data indicate a slight decrease in photosynthetic efficiency in controls from 0.49 to 0.43.

Creating nine regression lines (not shown), one for each trial, species and flow rate, gives correlation coefficients of 0.1–0.6. There is no systematic variation of photosynthetic efficiency of controls in relation to flow rate, species or trial. This is also confirmed by PLS-regression (not shown) of photosynthetic efficiency of controls as function of flow rate and time (light and sediment constant at zero). The PLS-models had goodness of fit and prediction of only 0.28 and 0.23, respectively, implying weak correlation and low predictive property.

3.2. PLS modeling of photosynthetic efficiency and sediment coverage as function of predictor variables

Table 2 summarizes the results of the PLS-regression of photosynthetic efficiency and sediment coverage as function of the four predictor variables.

![Figure 2](image_url)

**Fig. 2.** Photosynthetic efficiency ($\Psi_{\text{Imax}}$) in controls from T0 to T9 for the first trial with Mesophyllum (diamonds) and for the second trial with Mesophyllum (dots) and Lithothamnion (squares). Controls were distributed among the different flow rates 0.04 (blue), 0.07 (red) and 0.09 m s$^{-1}$ (green). Lower regression line T0–T9 ($R^2 = 0.40$). Upper regression line T0–T8 ($R^2 = 0.56$).

<table>
<thead>
<tr>
<th>Time (weeks)</th>
<th>Photosynthetic efficiency ($\Psi_{\text{Imax}}$)</th>
<th>Sediment coverage</th>
<th>$R^2$</th>
<th>$Q^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0–T8</td>
<td>0.42</td>
<td>0.51</td>
<td>0.62</td>
<td>0.56</td>
</tr>
<tr>
<td>T0–T9</td>
<td>0.40</td>
<td>0.40</td>
<td>0.60</td>
<td>0.55</td>
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</tbody>
</table>

**Table 2** Goodness of fit ($R^2$) and goodness of prediction ($Q^2$) for photosynthetic efficiency and sediment coverage with flow, light, added sediment amount and time as variables. Data from the first trial with Mesophyllum and the second trial with Mesophyllum and Lithothamnion were analyzed separately and also merged into one matrix and analyzed combined.
predictor variables. Data from the first trial with Mesophyllum and the second trial with Mesophyllum and Lithothamnion were analyzed separately and also merged into one matrix and analyzed combined. The regression models are very good in terms of goodness of fit and prediction. The correlation coefficients ($R^2$) are generally slightly better when analyzing each trial and species separately. However, the prediction properties ($Q^2$) are generally better when analyzing the data combined. Using all data in the same regression model makes the model more generic and robust.

The best model was achieved with one square term in the polynomial that describes photosynthetic efficiency as a non-linear function of added amount of sediment, light intensity, flow rate and time. Table 3 shows the PLS regression coefficients and corresponding 95% confidence limits for the four different models. The table illustrate that the polynomials describing photosynthetic efficiency and sediment coverage as functions of the predictor variables are very similar, confirming that the combined model summarizes all data from both trials and species. Fig. 3 illustrates the regression coefficients for the combined model (same data as in the five last rows in Table 3) and clearly show that added amount of sediment is the major factor reducing photosynthetic efficiency and increasing sediment coverage. Flow rate, light intensity and time had minor impact in the flow-through system within the experimental domain described by the chosen levels of the predictor variables.

### 3.3. PLS modeling of photosynthetic efficiency as function of sediment coverage

The combined PLS-model was subsequently used to predict photosynthetic efficiency and sediment coverage by varying the added amount of sediment at fixed intermediate levels of light intensity, flow rate and time. These three parameters were kept constant since they had minor impact on the responses. The predicted values for photosynthetic efficiency and sediment coverage were then used to create exposure–response curves for photosynthetic efficiency as function of sediment coverage. Fig. 4 shows the exposure–response curve obtained from the regression model. For example, a 50% reduction in photosynthetic efficiency is observed at 70% sediment coverage already after 1–2 weeks of exposure.

### 3.4. Photosynthetic efficiency measurements and color evaluation

Throughout the experiment the two calcareous algae species changed from a healthy purple to pinkish color with bleached spots.

---

**Table 3**

Partial least squares regression coefficients and 95% confidence interval for the four PLS models. The major and significant regression coefficients bolded.

<table>
<thead>
<tr>
<th></th>
<th>Photosynthetic efficiency</th>
<th>Sediment coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mesophyllum</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st trial</td>
<td></td>
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<tr>
<td>Flow</td>
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<td>0.39</td>
</tr>
<tr>
<td>Sediment</td>
<td>-0.82</td>
<td>0.19</td>
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<tr>
<td>Time</td>
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<td>0.11</td>
</tr>
<tr>
<td>Sediment2</td>
<td>-0.50</td>
<td>0.31</td>
</tr>
<tr>
<td>2nd trial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow</td>
<td>0.03</td>
<td>0.32</td>
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<td>0.38</td>
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<tr>
<td><strong>Lithothamnion</strong></td>
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<td></td>
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<tr>
<td>Flow</td>
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<td>0.13</td>
</tr>
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<td>0.13</td>
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<tr>
<td><strong>Combined</strong></td>
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</tr>
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<td>Light</td>
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<td>0.10</td>
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<td>Sediment</td>
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<td>0.07</td>
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<tr>
<td>Time</td>
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<td>0.17</td>
</tr>
<tr>
<td>Sediment2</td>
<td>-0.54</td>
<td>0.10</td>
</tr>
</tbody>
</table>
at the beginning of the experiment (T0), to a stressed pale color after one week when completely buried (1200 g sediment) and later also when partially buried (900 g sediment). By the end of the experiments (T9) there were larger areas of white calcareous algae thallus judged already dead under complete burial and increased patchy white areas due to partial burial. High stress levels were observed by an orange color of thallus and low readings of photosynthetic efficiency ($\Phi_{PSII,max} = 0.16–0.25$). In the most severe cases dead white areas of thallus were observed, consistent with low readings ($\Phi_{PSII,max} \leq 0.15$) of photosynthetic efficiency. Less frequently, whitish patches and areas with pale color were observed in the treatment with the lowest amount of sediment (600 g). No bleaching or color change was observed in the controls kept in darkness without sedimentation during the experimental period of nine weeks. Photosynthetic efficiency of the controls was 0.49 at T0 classifying the algae in the “no stress” category (Table 4). Photosynthetic efficiency decreased slightly to 0.43 at T9 classifying the controls in the “low stress” category (Table 4 and Fig. 2). A computational approach to quantitatively extract size and color features from images is in preparation and will be published in a separate paper.

### 4. Discussion

A major finding from the present study is the statistically significant relationship between the exposure of two species of calcareous algae to particulate matter and the decrease in photosynthetic efficiency which is regarded as a parameter for environmental stress. An exposure–response relationship describing the observed effect on the calcareous algae as function of sediment coverage has been established. For example, at 70% sediment coverage the photosynthetic efficiency was reduced 50% already after 1–2 weeks of exposure. The new insight in the impact of sedimentation on two species of calcareous algae can be used to establish threshold levels and impact categories in environmental monitoring of calcareous algae. Establishment of impact categories will be presented in a separate paper.

The multivariate data analysis showed that the major contributor to sediment coverage and reduction in photosynthetic efficiency was the added amount of sediment (positive and negative correlations, respectively), while flow rate, light intensity and time had minor and mostly insignificant impact on the response parameters within the experimental domain described by the chosen levels of the predictor variables. Although flow rate did not influence sediment coverage in these experiments, flow rate is an important factor to take into consideration because it also affects the supply of oxygen and nutrients. The fact that flow rate and also light had minor impact on photosynthetic efficiency implies that sediment coverage was the major contributor, probably due to reduced gas exchange. This assumption is supported by the controls kept in darkness without sedimentation where no bleaching or color change was observed. Furthermore, both algae species used in the present study were incrusting and unbranched growth-forms which also support the assumption that the measured stress was due to oxygen depletion and accumulation of metabolic products like carbon dioxide caused by the sediment coverage. Reduced gas exchange due to burial of fine sediments is consistent with previous findings (Wilson et al., 2004; Harrington et al., 2005).

No visual changes of the controls were observed during the nine weeks experiments. However, the photosynthetic efficiency measurements decreased slightly from 0.49 at T0 to 0.43 at T9 and may be interpreted as an incipient light limited impact on the calcareous algae.

The handling procedures of the algae are not expected to have significant effect on the photosynthetic efficiency. The removal from the exposure chamber and light source was too short to influence on photosynthetic efficiency. This is confirmed by the controls kept in darkness where only a minor effect was seen even after nine weeks. The 20 min dark acclimation ensured that all reaction center were open for the determination of ground fluorescence ($F_o$). The brushing and replacing of sediment were carried out very carefully in a standardized way. Although calcareous algae are generally considered to be rather robust (Steneck, 1986), initial measurements of photosynthetic efficiency were carried out before and after brushing to ensure that the brushing did not influence the results.

Although the impact of light intensity is shown to be insignificant during the nine week period, the regression coefficient in Fig. 3 and the exposure–response curve (Fig. 4) indicate that low levels of sediment coverage on the calcareous algae may produce a negative effect on photosynthetic efficiency. Photosynthesis of photosystem II has been demonstrated previously (Aro et al., 1993). This indicates that the calcareous algae are well adapted to low light levels and also, to some extent, prefer some light reduction. Similar responses have been found for color patterns of the outermost pigmented layer of the calcareous algae (Villas-Bôas et al., 2014). The assumptions are also supported by environmental monitoring carried out on the Peregrino field demonstrating high degree of natural sedimentation (unpublished data).

The present study has been performed with calcareous algae on an individual level. Possible impact of discharges on population level has not been investigated. However, using all data from both trials and both species in the same regression model makes the model more generic and robust. On a habitat level, large proportions of white dead patches have been attributed to a reduction of rhodolith bed vitality (Harvey and Bird, 2008). In addition to reduced survival as response to smothering and burial, also reduced recruitment of calcareous algae on coral reefs has been documented (Steneck, 1997; Figueiredo and Steneck, 2002).

As already described, one of the main intentions with the present study has been to use the new insight in the calcareous algae tolerance levels to sedimentation to develop threshold levels for calcareous algae use in risk assessment. Risk models incorporating physical disturbances such as burial (Johnsen et al., 2000; Rye et al., 2008; Smit et al., 2008) can utilize these species specific threshold levels instead of the generic set of threshold levels derived from the literature. A similar approach has previously been used for the cold water coral Lophelia pertusa (Purser and Thomsen, 2012; Larsson et al., 2013). It is emphasized that although sediment coverage can be modeled in the experimental flow-through system, these data are not expected to be used to model sediment coverage at sea floor. The environmental relevance of the data is first of all related to the reduction in photosynthetic efficiency as function of sediment coverage. Using the experimental results in risk assessment may require a conversion to sediment thickness although sediment coverage (in %) was considered to be more suitable in the present work since the experiments were carried out with calcareous algae living
on rhodoliths with varying surface structure and porosity. The strong correlation (critically validated) between sediment coverage and photosynthetic efficiency implies that sediment coverage is a valid parameter, and also a parameter that can be measured in the field e.g. by imaging. As a consequence, the results are relevant for environmental monitoring and risk assessment and the results are valid for two important calcareous species.

5. Conclusions

The results from the present study are unique with respect to demonstrating the relationship between exposure of deep water calcareous algae to particulate matter and the photosynthetic response. The statistical approach for the experimental design and interpretation of the sampled data secures the high reliability and significance of the results. This enables establishment of exposure–response relationship describing photosynthetic efficiency of the calcareous algae as function of sediment coverage. The exposure–response relationship can be used to establish threshold levels and impact categories for environmental risk assessment of drill cuttings discharges to the Peregrino and other calcareous algae habitats. Although the present results are of a conservative nature due to the design of the experiments, they provide a more realistic basis for risk assessment than generic effect data which are usually applied.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.marpolbul.2015.04.040.

References


Paper V

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Computational Visual Stress Level Analysis of Calcareous Algae Exposed to Sedimentation

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Abstract

This paper presents a machine learning based approach for analyses of photos collected from laboratory experiments conducted to assess the potential impact of water-based drill cuttings on deep-water rhodolith-forming calcareous algae. This pilot study uses imaging technology to quantify and monitor the stress levels of the calcareous algae *Mesophyllum engelhartii* (Foslie) Adey caused by various degrees of light exposure, flow intensity and amount of sediment. A machine learning based algorithm was applied to assess the temporal variation of the calcareous algae size (*mass*) and color automatically. Measured size and color were correlated to the photosynthetic efficiency (maximum quantum yield of charge separation in photosystem II, $\Phi_{PSII_{max}}$) and degree of sediment coverage using multivariate regression. The multivariate regression showed correlations between time and calcareous algae sizes, as well as correlations between fluorescence and calcareous algae colors.

Introduction

Increasing anthropogenic activities in marine areas call for a holistic environmental monitoring approach using new and more sophisticated models and sensor systems that enable predictions and measurement of impact on organisms of interest [1]. One important input to modeling is knowledge generated through laboratory experiments, determining various levels of stress on the organisms of interest. A common way to measure stress is through visual documentation of behavioral changes, change in abundance [2–4], change of the spectral response [5] or change of the visual appearance [6, 7] of organisms.

The investigated calcareous algae species, *Mesophyllum engelhartii* (Foslie) Adey, belongs to the *Phylum Rhodophyta* under the Order *Hapalidiales*. Calcareous algae play an important ecological role in coastal habitats [8–10] contributing to the formation of rhodoliths. Rhodoliths are made from dead calcareous algae and other calcifying organisms [11]. These multi-
spherical structures are creating a habitat for other organisms living on, between and in the structures [12]. Calcareous algae are found down to about 250 meters water depth [13–15] and the largest occurrence of rhodolith beds are found in the southwest Atlantic on the Brazilian continental shelf [16–18]. These algae communities may be disturbed by natural sedimentation and/or sedimentation from anthropogenic activities such as fish-trawling, mining [19] and discharges of drill cuttings from oil and gas drilling activities [20].

In a previous study the impact from sedimentation of drill cuttings on live calcareous algae was studied by measuring sediment coverage (SC) and photosynthetic efficiency (P) [6]. The study was part of the Peregrino Environmental Monitoring Calcareous Algae Project (PEMCA). Rhodoliths, partly covered with calcareous algae, were collected from the Peregrino oil field off the coast of Brazil. The impact of sedimentation was investigated in a laboratory flow-through system, varying light exposure (L), flow rate (F), amount of sediment (S) and time (T). Photosynthetic efficiency (P) was measured as maximum quantum yield of charge separation in photosystem II, \( \Phi_{PSII_{max}} \). These results have been published elsewhere [6].

The present paper describes a new method to extend the observed impact variables (SC, P) by measurements of size and color of calcareous algae in digital photos recorded during the experiments.

Using photos for environmental monitoring generates a large number of images implying that a manual evaluation is extremely demanding regarding time and resources and requires a careful and professional execution, as for instance outlined in [21].

To support the evaluation and labeling of the photos performed by marine biology experts different software tools have been proposed such as Coral Point Count with Excel extensions (CPCe) [22]. Recently, web-based image annotation and labeling systems have been proposed to support web-based sharing of photos and collaboration, such as BIIGLE (Benthic Image Indexing, Graphical Labeling and Exploration) [23], which was successfully applied in [4, 24–28], and CoralNet [29], the latter one providing for instance an automated point classification for corals as well.

Since humans have a limited capability to quantify visual features, such as color change, in an objective way, we propose a machine learning based approach to compute size and color of the calcareous algae from photos recorded at different time points. A machine learning algorithm is trained with a number of manual image annotations. The trained classifier is applied for the full automatic segmentation of the calcareous algae, enabling the quantification of the calcareous algae size and color over time. To learn the classification function a H2SOM (Hierarchical Hyperbolic Self-Organizing Map) [30] algorithm was applied. This unsupervised learning algorithm has previously been used for cold-water coral segmentation in ROV video frames [24] and for poly-metallic nodule segmentation [31, 32]. Nevertheless, the integration of the basic algorithm into an image analysis pipeline needed to be modified substantially regarding pre-processing, feature computation, pixel classification function and post-processing.

A simplified overview of the whole impact quantification process is given in Fig 1.

### Material

Samples of live calcareous algae *Mesophyllum engelhartii* (Foslie) Adey were collected from 94–103m water depth at the Peregrino oil production field (23°13'28.34"S, 41°50'55.73"W) located off the Brazilian Atlantic coast [11]. Light intensity (L), flow rate (F) and sediment amount (S) could be varied independently as described in [6]. In order to optimize the experiment, the three predictor variables \( L, F, S \) were combined according to a Central Composite Face (CCF) design with center point [33]. This enables regression modeling to describe linear...
and non-linear relationships and interactions between the variables. The full factorial design gives 15 combinations of $L$, $F$, and $S$. Two of these combinations were duplicated and two were triplicated (i.e. technical replicates). Using the 15 combinations and technical replicates resulted in a total of 21 experiments which were carried out in 21 chambers (Table 1). In addition controls were kept in complete darkness and without sediment. The area of the chamber bottom was approximately 0.06 m$^2$ and the height was 0.1 m resulting in a volume of approximately 6 L. The light levels ($L$) used in the exposure studies were 3, 6.6, or 10 $\mu$mol m$^{-2}$ s$^{-1}$, the latter value corresponding to measured light conditions at the sea floor on the Peregino field. The flow rates ($F$) used were 0.04, 0.07, or 0.09 m s$^{-1}$. The amounts of sediment ($S$), applied at the beginning of the experiment (T0), were 600, 900, or 1200 g per chamber. The chosen amounts resulted in a sediment coverage (SC) of the calcareous algae ranging from uncovered to completely covered, implying that also non- and very low sediment covered calcareous algae are included in the analysis. Six parallels (i.e. biological replicates) of rhodoliths

Fig 1. A simplified illustration of the impact quantification process. The process is starting on the upper left with the laboratory experiment, continuing with the image recording, the labeling by the experts, the application of the unsupervised machine learning algorithm (see Machine Learning section for details) and ending with the image segmentation and the measuring of size and color of the segmented area.

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covered with healthy calcareous algae were placed in each chamber, so each of the 21 experiments were conducted with six samples.

In addition to the measurements reported in [6], photos of the calcareous algae samples were taken for purpose of the present paper during the weekly examination. For image-acquisition, the calcareous algae rodoliths were removed from their chambers and manually placed in a transparent, water-filled cylinder together with a color reference plate (Figs 2 and 3A). The reference plate, essential for a comparative study of the color over time, can be seen in the upper part of the images (Fig 3 upper left). The photos were taken with a Canon PowerShot G10, which was placed on a tripod to control the distance (15 cm) between camera and samples. The camera was in automatic mode with macro function and internal flash on. To eliminate light refractions and reflections samples and camera, the latter protected by a waterproof housing, were placed underwater inside the cylinder (Fig 2). The digital images had a resolution of 3456 × 2592 pixels. Each week 63 images (21 chambers × 3 images, 2 samples per photo), were taken summing up to \( N = 630 \) images for the whole experiment \((T0, \ldots, T9)\).

In order to collect a set of image annotations for training and testing the machine learning algorithm, the recorded images were uploaded to BIIGLE. With this online image annotation tool, biological experts from the Instituto Biodiversidade Marinha were manually labeling photo regions (pixel) as “live” calcareous algae (2404 labels), “stressed” calcareous algae (2834 labels), “dead” calcareous algae (4358 labels) and “bare substratum” (43 labels) on all \( N = 630 \) images. For the annotation, the experts were allowed to select single point label or customizable frame labels (Fig 4). These labels provided examples for the later machine learning training

<table>
<thead>
<tr>
<th>Chamber</th>
<th>( L ) ([\text{mm}] )</th>
<th>( F ) ([\text{ml/s}] )</th>
<th>( S ) ([\text{g}] )</th>
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<tr>
<td>18</td>
<td>6.6</td>
<td>0.07</td>
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<tr>
<td>19</td>
<td>6.6</td>
<td>0.07</td>
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<td>20</td>
<td>6.6</td>
<td>0.07</td>
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<tr>
<td>21</td>
<td>6.6</td>
<td>0.07</td>
<td>900</td>
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The configurations for the 21 chambers for light intensity \( L \), flow rate \( F \), and sediment amount \( S \) are displayed. Replicated configurations are grouped.

Table 1. Chamber configurations for the CCF design.

doi:10.1371/journal.pone.0157329.t001
step (see Machine Learning section below). The labeling strategy was chosen to reduce the time needed for the labeling and simultaneously cover the whole variation between and within each label category over time. The "live" and "stressed" calcareous algae labels represent the so-called "positive" class in the segmentation and the "dead"- and "bare substratum"-labels represent the so-called "negative" class. All images and labels can be accessed via BIIgLe (https://ani.cebitec.uni-bielefeld.de/biigle/). To browse the data, a login with username pemca and password pemca is required. The data is stored in the project Pemca3rd, with the transects T0, . . . , T9. Image material is also published under DOI 10.4119/unibi/2775316.
Methods

The permission to collect the calcareous algae samples for the experimental study described in the Material section was granted by the Chico Mendes Institute for Biodiversity Conservation SISBIO license n 20820-2 and 20826-1. The experimental study did not involve endangered or protected species.

The basic idea of the computational calcareous algae segmentation is to classify each pixel in each image to be i) “live” or “stressed” calcareous algae or ii) other, including “dead” calcareous algae. A pixel classifier is trained using data collected from the annotations provided by the experts (see Material section). From the pixel-wise classification, the regions of “live”/“stressed” calcareous algae are determined for each sample at each time point. The results are analyzed in
combination with the previously measured parameters photosynthetic efficiency ($P$) and sediment coverage ($SC$) using multivariate analysis. The individual steps for image processing, pixel classification and final data analysis are described in detail in the following sections.

**Pre-Processing**

Before the feature extraction and the machine learning can be applied, the recorded images need to be pre-processed.

**Illumination Correction.** In order to compensate illumination fluctuations in the images the local space average color scaling [34] is used on each image individually. The local space average color image is computed using a Gaussian blurring with $\sigma = 0.093 \cdot \max(I_{\text{height}}, I_{\text{width}})$. 

![A screenshot of the BIIGLE system in a web-browser.](https://i.imgur.com/3Q6Q5.png)

The images of the calcareous algae were examined and labeled using the BIIGLE system. Images can also be zoomed to examine more details. The experts were allowed to select single point label or customizable frame labels. The single point labels are represented as filled colored circles, the customizable frame labels are represented as white outlined rectangles with a filled colored circle in the upper left corner of the individual rectangle. The colors of the filled circles indicate the class of the individual label. Red is representing “live” calcareous algae, yellow “stressed” calcareous algae, green “dead” calcareous algae and Pink “bare substratum”.

*Fig 4. A screenshot of the BIIGLE system in a web-browser.* The images of the calcareous algae were examined and labeled using the BIIGLE system. Images can also be zoomed to examine more details. The experts were allowed to select single point label or customizable frame labels. The single point labels are represented as filled colored circles, the customizable frame labels are represented as white outlined rectangles with a filled colored circle in the upper left corner of the individual rectangle. The colors of the filled circles indicate the class of the individual label. Red is representing “live” calcareous algae, yellow “stressed” calcareous algae, green “dead” calcareous algae and Pink “bare substratum”.

doi:10.1371/journal.pone.0157329.g004
As the images were captured in sRGB [35], which assumes a gamma correction of 1/2.2, the images are gamma corrected and then divided pixel- and channel-wise (c) by the corresponding Gaussian filtered image $G^{(n)}$:

$$\hat{i}_{x,y}^{(n)} = \left(\frac{(I_{x,y}^{(n)})^{1/2.2}}{\tau - G_{x,y}^{(n)}}\right)^{1/2.2}$$

$\tau$ is a scaling factor and set to $\tau = 2$ in the whole study. An example for an illumination corrected image is displayed in Fig 3 (upper right).

**Reference Plate Detection, Color and Zoom Correction.** The first step in the color correction is the detection of the color circles in the reference plate using a Hough circle transformation [36]. The Hough transform computes a list of circle candidates and those that show a low color variance inside are selected taking the spatial layout of the color plate into account as well. The identified six color circles $C_i (i = 1, \ldots, 6)$ of each $I^{(n)}$ are then used to calculate one RGB color triplet $c^{(i)}$ for each circle over all its pixels $p_{(x,y)}$.

$$c^{(i)} = \left(\text{median}_{(x,y)\in \text{circle}_i} P_{(x,y),\text{red}}^{(n)}\right)$$

$$\text{median}_{(x,y)\in \text{circle}_i} P_{(x,y),\text{green}}^{(n)}$$

$$\text{median}_{(x,y)\in \text{circle}_i} P_{(x,y),\text{blue}}^{(n)}$$

In addition, overall median color references are computed for each of the six color circles (Eq 3) of all images (Fig 5).

$$c = \left(\text{median} c^{(i)}_{\text{red}}\right)$$

$$\text{median} c^{(i)}_{\text{green}}$$

$$\text{median} c^{(i)}_{\text{blue}}$$

For each image $I^{(n)}$ and color channel $c \in \{\text{red}, \text{green}, \text{blue}\}$, the individual, channel-wise gamma correction is calculated using the color RGB triplet $c^{(n)}$ (Eq 2) of the individual image.

![Fig 5. The average color reference plate. This reference is computed by averaging over the detected reference plates from all images used in this study (see text for details). Colors are referring the RGB triplets (left to right) (181,185,100), (147,179,200), (146,173,106), (173,101,147), (183,67,80), and (69,88,154).](https://doi.org/10.1371/journal.pone.0157329.g005)
and the overall median color references (Eq 3).

$$g_n = \text{median}_j \left( \frac{\log \frac{c_n}{p(x,y)}}{\log \frac{c}{p(x,y)}} \right)$$

This image specific gamma correction is applied channel-wise to all the images resulting in a new set of color corrected images (Fig 3 lower left)

$$f_{(x,y),c}^{(n)} = \left( f_{(x,y),c}^{(n)} \right)^{g_n}.$$  

A difference image \(f^{(n)} - f^{(r)} / 2 + 128\) is presented in Fig 3 (lower right) to demonstrate the impact of the described illumination and color correction.

The layout of the reference plate is also used to correct zoom variations, which occurred for a significant number of images. The average distance \(d\) between the neighboring color circles (e.g. green and magenta) on each plate is evaluated from the five Euclidian circle distances \(d_{i,i+1}\)

$$\tilde{d} = \frac{1}{N} \sum_n \frac{1}{5} \sum_{i=1}^5 d^{(n)}_{i,i+1}.$$  

The difference between the average distance and the observed individual distances in image \(f^{(n)}\) is used to rescale each image individually.

**Segmentation**

Unsupervised learning is applied to learn a vector quantization of the image feature space (see Machine Learning section). Vector quantization fits a set of so called prototype vectors iteratively to a data set of feature vectors from the images describing pixel features. After the training step is finished, each prototype represents a group of pixels sharing similar features, i.e. a dense cloud in the feature space. The prototypes are assigned to the classes “live / stressed calcareous algae” and “other”, including “dead calcareous algae” and “bare substratum”, and are applied to classify all image pixel (see Prototype Label Mapping section). For the final segmentation result the classified image is post-processed (see Post Processing section).

**Feature Extraction.** One important step in vector quantization-based image segmentation is the selection of appropriate features and the collection of a training set. To collect a training set for the vector quantization learning, a selection of image pixels \(p\) from a subset of all \(N\) images are chosen and their feature vectors \(x^{(i)}\) are computed. Here, Median RGB values extracted on a \(11 \times 11\) pixel neighborhood \(p_{(11)}\) for each color channel, are used as features since we observed such a representation to be sufficient for the initial task of calcareous algae segmentation by pixel classification.

$$x^{(i)} = \left( \begin{array}{c} \text{median} \left( x_{(i,y)\text{Red}} \right) \\ \text{median} \left( x_{(i,y)\text{Green}} \right) \\ \text{median} \left( x_{(i,y)\text{Blue}} \right) \end{array} \right)$$
To reduce the computation time, features are only extracted for pixels in a 2 × 2 grid resolution collecting a training set of about 2.5 million feature vectors \( \mathbf{x}^{(i)} \).

**Machine Learning.** To perform vector quantization on the training data the unsupervised machine learning algorithm H^2SOM [30] is applied.

H^2SOMs with different parameter settings, like the number of prototypes, were trained and the best parameter set was determined using a customized criterion described in (SI Text). A training set of feature vectors generated from 12.5% of the pixels chosen from a small subset (2%) of the entire image collection is used to construct the H^2SOM with the best segmentation results. The H^2SOM is trained using \( 30 \times |\{\mathbf{x}^{(i)}\}| \) iterations, an exponentially decreasing learning rate of \( \alpha = [0.99, 0.1] \), an eight-neighbor topology and three rings and therefore is consisting of 161 prototypes.

**Prototype Label Mapping.** The next step is to build a pixel classifier out of the trained H^2SOM, using the feature vectors \( \mathbf{x}^{(i)} \) of all images \( f^{(i)} \). We distinguish between feature vectors \( \mathbf{x}^{(i)} \) used for the H^2SOM training and feature vectors \( \mathbf{x}^{(i)} \) from all images, but of course both are computed as described in Eq 7. The expert labels "live" and "stressed" from BIIGLE are used to build the classifier as follows. In general, we have observed that a differentiation between the categories "live" and "stressed" is problematic regarding the reproducibility of the results of the visual assessment. As a consequence a discrimination between these two categories has been neglected. The fused category is referred to as "live calcareous algae".

First, a label \( y_p \) is assigned to each feature vector \( \mathbf{x}^{(i)} \)

\[
y_p = \begin{cases} 
1, & \text{if the pixel was labeled as "live"/"stressed" calcareous algae} \\
0, & \text{else}
\end{cases}
\]  

Second, each feature vector \( \mathbf{x}^{(i)} \) is assigned to one of the H^2SOM prototypes \( \mathbf{u}^{(j)} \) (\( j = 1..161 \)) that represents the features of \( \mathbf{x}^{(i)} \) in the best possible way. This prototype is selected by the so called Best Matching Unit (BMU) criterion, that selects the prototype with the minimal Euclidian distance to \( \mathbf{x}^{(i)} \) in the feature space. Next, all cluster prototypes are investigated in order to classify them. The prototypes constitute a Voronoi tessellation of the feature space

\[
V_j = \{\mathbf{x}^{(i)} | j = \arg\min_{j} \text{euclid}(\mathbf{u}^{(j)}, \mathbf{x}^{(i)})\}
\]  

with \( q_j = |V_j| \) as the number of feature vectors that have been assigned to \( \mathbf{u}^{(j)} \) and therefore are located in \( V_j \). In each Voronoi cell \( V_j \) we now analyze how many feature vectors stem from pixel, labelled as "live" or "stressed":

\[
V_j^* = \{\mathbf{x}^{(i)} | j = \arg\min_{j} \text{euclid}(\mathbf{u}^{(j)}, \mathbf{x}^{(i)}) \land y_p = 1\}
\]  

with \( q_j^* = |V_j^*| \) as the number of feature vectors in \( V_j \) that are labeled as "live"/"stressed" calcareous algae. The relation \( s_j = q_j^*/q_j \) quantifies how well a prototype \( \mathbf{u}^{(j)} \) resembles the features of live calcareous algae. Since we do not expect all \( \mathbf{x}^{(i)} \) with \( y_p = 1 \) to be perfect representatives, only prototypes \( \mathbf{u}^{(j)} \) with a high \( s_j \) will represent the positive class (presence of live calcareous algae).

Next the relation values \( s_j \) are sorted in descending order:

\[
s_j \rightarrow s_i, \text{ with } s_i > s_{i+1}\forall i.
\]  

From this list, the first \( L \) prototypes \( \mathbf{u}^{(i)} \) are chosen as a model for typical live calcareous algae color features. \( L \) is chosen so at least 80% of the entire positive training data (i.e. \( y_p = 1 \)) is covered. This set of the first 16 "most live calcareous algae-like" prototypes is used for the pixel
classification based segmentation in all images. In each image, each pixel $p$ is mapped to each feature vector $x^p$. The BMU of the feature vector is determined and if this unit is a live calcareous algae-like prototype, as described above, the pixel is labeled as live calcareous algae ($L(x^p) = 1$) or otherwise as background ($L(x^p) = 0$).

**Post Processing.** By classifying all feature vectors $x^p$, binary images are created showing white pixels on live calcareous algae classified positions and black pixels otherwise. These binary images are post-processed with an opening filter mask [37] of a size $10 \times 10$ pixels to remove small areas of false positive classifications. The post-processed binary images represent the final segmentation result.

**Multivariate Data Analysis**

To analyze the possible biological impact of sedimentation on calcareous algae, the size and the color of the segmented areas in the images are computed. (Fig 6). The size ($A$) of the live calcareous algae area is measured as the amount of segmented pixels per image $f^{n}$. It is weighted by the ratio of the average color circle distance of circle centers $d$ and the average circle center distance $d_c$ of the color reference plate from the Image $f^{n}$.

$$A = \text{size} \cdot \frac{d}{d_c}$$

(12)

The relative size $\hat{A} = \frac{A}{A_0}$, with $A_0$ being the live calcareous algae size at the first measurement, is finally used as one variable. The HSV (hue, saturation, value) color space is used for measuring the color. Note that we use a different color space here than the one we used for the segmentation. Averages of hue (averaging is applied with respect that it is a circular quantity) ($\bar{h}$), saturation ($\bar{s}$) and value ($\bar{v}$) of all segmented pixels per image $f^{n}$ are computed of the segmented pixels. These four variables are combined to one measurement for the image $n$:

$$\mathbf{f}^{(n)} = (\hat{A}, \bar{h}, \bar{s}, \bar{v})^T$$

(13)

All calcareous algae samples from the same chamber are exposed to the same treatment parameters. On each image two samples were captured. To avoid the need of a colocation of the samples as well as taking into account that all rhodoliths are different, averages of size and color within each chamber are used. The dataset can be found in S1 Table.

Multivariate regression is performed with partial least squares (PLS) [38, 39] on the live calcareous algae area measurements $f^{n}$, using Unscrambler X 10.3 (CAMO Software, Oslo, Norway) to correlate the predictor variables ($X$ matrix) to the measured responses ($Y$ matrix). The previously published data (first experimental series with *M. engelhartii* in [6]) on $P$ and SC are included in the data matrix for the regression analysis. To match $f^{n}$ also data for $P$ and SC were averaged chamber wise (six parallels). The final data matrix has 168 rows (21 chambers $\times$ 8 time-points) (observations), four columns for the four predictor variables ($C$, $F$, $S$ and $T$), and six columns for the response variables ($\hat{A}$, $\bar{h}$, $\bar{s}$, $\bar{v}$, $P$, SC). Prior to the multivariate data analysis, the data are mean centered and scaled to unit variance. The models were evaluated with respect to explained variance, and goodness of fit and prediction, the latter obtained after cross validation [40, 41].

In addition to the PLS regression, a traditional statistical analysis was conducted by performing ANOVA, MANOVA and pairwise correlation analysis. These results are presented in the supplementary (Table A, Table B, Table C in S2 Text and Fig A, B, C in S3 Text). In the following we will concentrate on the results of the PLS regression as it takes all variables into
Fig 6. Example of one pair of calcareous algae samples. In the top row the original images recorded at T2, T5 and T9 are shown. In the middle row the segmentation results are highlighted and in the lower row the live calcareous algae relative size (\(A\)) and hue (\(h\)), starting from 10 (slightly orange red) to 0 (red), are presented. The samples were exposed to \(S = 900\) g (a partially covered sample), \(L = 6.6\mu\text{mol m}^{-2}\text{s}^{-1}\) and \(F = 0.07\text{m s}^{-1}\).

doi:10.1371/journal.pone.0157329.g006
consideration simultaneously and gives a better understanding of the relative importance and the significance of all variables.

**Results**

**Pre-Processing**

Fluctuations in sample illumination are a well-known problem in computational image analysis and the majority of the $N = 630$ images $I^{(n)} (n = 1, \ldots, N)$ suffered at least partially from it. The procedures described above compensated this effect (Fig 3(B)).

In 15% of the images used in the analysis, the reference color circles could not be detected automatically. In these images the circles were marked manually or only a subset of detected circles was used for the color correction. Although reflections were avoided on the calcareous algae samples, serious reflection problems were observed on the color reference plates in some of the images. The images from T0 and T1 had to be excluded from further analysis because of this problem.

Visual inspection showed that the channel-wise gamma correction produced robust results. The pre-processing stages described above could be computed all together in about three minutes per image.

**Segmentation**

The segmentation results were reviewed by comparing the human expert labels with the segmented areas of all images using standard measures for image analysis accuracy assessment like recall (or sensitivity), precision (or positive predictive value) and false positive rate (FPR). The recall is the percentage of all pixels labeled “live” or “stressed” $p^{(+)}$ that have been segmented correctly as live calcareous algae by the algorithm.

$$\text{recall} = \frac{|(p^{(+)} \cap (p^{(s)})|}{|p^{(s)}|}$$

The precision is the percentage of all pixels segmented as live calcareous algae $(p^{(s)})$ that have been segmented correctly by the algorithm.

$$\text{precision} = \frac{|(p^{(+)} \cap (p^{(s)})|}{|p^{(+)}|}$$

From the segmentation results we computed a recall value of 0.89 and a precision of 0.03. Since the manually labeling did not attempt to measure the precise live calcareous algae extent in each image, also the “dead” and “bare substratum” labels were used to review the segmentation results. The false positive rate (FPR) was used to measure the number of pixels that were segmented to be “live” or “stressed” $p^{(+)}$ but were labeled “dead” or “bare substratum” $p^{(-)}$.

$$\text{FPR} = \frac{|(p^{(-)} \cap (p^{(+)})|}{|p^{(+)}|}$$

The FPR was very low compared to the recall. Looking at the false positive rates in detail it should be noted that the FPR for the “bare substratum” is higher than the one of the “dead” labels (Table 2). Segmentation results are also displayed in Fig 7.

**Multivariate Data Analysis**

The best PLS regression model was obtained after expansion with one square term $(S^2)$ in the polynomial describing the relationship between predictors ($L, F, S$ and $T$) and responses.
A significant outlier was identified and removed from the data set, as it appeared that the segmentation failed in the corresponding image (no "live" or "stressed" calcareous algae were detected). Fig 8 shows the correlation loading plot obtained from the PLS-regression. The outer circle represents 100% explained variance and the inner circle 50% explained variance for the different variables.

SC and P, were both positively and negatively (respectively) correlated with amount of sediment (S) with excellent goodness of fit and prediction. Also the HSV-variables (h, s, v) extracted with our approach, were correlated with S. Goodness of fit and prediction, the latter obtained after cross validation, are summarized in Table 3. Furthermore, there were inter-correlations between the response variables: the HSV-variables were inter-correlated with SC, and inversely correlated with P. The predictor parameters F and L had low influence on the measured responses. Time (T) showed no correlation with P, SC, or HSV, but was well explained and inversely correlated with relative size (A). This implies that there are two major directions in the data reflected in the loading plot. The first (horizontal) PLS-component describes S and measured P, SC and the HSV-variables. The second PLS-component (vertical) describes T and A, which are not correlated with the other variables shown in the loading plot.

The apparent inverse correlation between photosynthetic efficiency (P) and the HSV-variables suggests an alternative PLS-regression with HSV-variables as predictors and P as response. Fig 9 shows the resulting loading plot obtained after PLS-regression with linear relations. Goodness of fit and prediction were both 0.82, enabling prediction of photosynthetic efficiency from HSV-values.

Discussion
The use of BIIGLE enabled a flexible and swift exchange of data between the researchers involved in this interdisciplinary study, independent of their geographical location.

The selected strategy for the manual labeling in this study was to apply an "example based" labeling approach, rather than to fully outline the different calcareous algae regions. The rationale behind the chosen strategy was that color changes were expected to be time and/or treatment related and that the use of a "example based" annotation approach (rectangles and points) would balance the time spent on labeling and the amount of training data needed. Due to this approach, no representative ground truth for the negative class, i.e. pixel regions that show no calcareous algae, existed. In principle the negative class could have been constructed by a random selection from the unlabeled regions of the images. However this random selection might have introduced some false-negatives to the negative class. This motivated us to apply an unsupervised learning approach. The prototype label mapping in the H²SOM followed a conservative strategy to classify only 80% of the positive training data as "live"/ "stressed" calcareous algae. Despite of this strategy, our segmentation result showed a high

(Å, h, s, v, P, SC). One significant outlier was identified and removed from the data set, as it appeared that the segmentation failed in the corresponding image (no "live" or "stressed" calcareous algae were detected). Fig 8 shows the correlation loading plot obtained from the PLS-regression. The outer circle represents 100% explained variance and the inner circle 50% explained variance for the different variables.

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<table>
<thead>
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<th>Recall</th>
<th>Prec.</th>
<th>FPR</th>
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<td>0.89</td>
<td>0.03</td>
<td>0.02</td>
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<td>0.05</td>
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The very low values for precision were expected, since a realistic quantification of the FP is not possible in our dataset (see text for details). The low FPR though indicates that the segmentation generates low FP in the "dead" or "bare substratum" labeled regions.
Fig 7. Examples of manually labeled rhodoliths (left) and the corresponding segmented rhodoliths (right). White rectangles with a green dot mark “dead” calcareous algae labeled regions and rectangles with a yellow dot mark “stressed” calcareous algae labeled regions. The pixel regions of “live” or “stressed” calcareous algae are marked red.

doi:10.1371/journal.pone.0157329.g007
 recall of 0.89. Based on the selected "example based" manual labeling strategy the precision was low, as we were expecting. The rationale behind the chosen strategy was that color changes were expected to be time and/or treatment related and that the use of a "example based" annotation approach (rectangles and points) would balance the time spent on labeling and the amount of training data needed. A posterior visual inspection of the results showed that the selected approach produced many false positives that actually turned out to be true positives. Computing the precision as defined in Eq 15 was therefore not a reasonable assessment for the

Fig 8. The correlation loading plot obtained after PLS-regression. It was computed with light (L), flow rate (F), amount of sediment (S, S'), and time (T) as predictors (blue dots), and HSV-variables (h, s, v), relative size ($\hat{A}$), photosynthetic efficiency ($P$) and sediment coverage (SC) as responses (red dots). The outer circle represents 100% explained variance and the inner circle 50% explained variance for the different variables.

doi:10.1371/journal.pone.0157329.g008
accuracy of our segmentation system (Fig 7). The FPR scores should be low, as an indication of the effect, that almost none of the pixels labeled as “dead” or “bare substratum” were segmented into “live” or “stressed” calcareous algae regions. The FPR for the “bare substratum” is noticeable, but was interpreted as still low and does not seem to have a significant effect on the evaluated colors.

The PLS regression showed that the photosynthetic efficiency is correlated ($R^2 = 0.82$) to the HSV-values, implying that it is possible to predict the photosynthetic efficiency from the color (Fig 9). The segmented images indicate that the area of live calcareous algae decreases with time during the exposure study. However, the correlation of $P$, $SC$ and the color ($h$, $s$, $v$) with time was low, as goodness of fit and prediction are 0.39 and 0.35, respectively (Fig 8). Only the relative size ($\hat{A}$) seemed to be associated with time although the correlation was relatively weak. According to Table 3 goodness of fit and prediction were 0.5 for $\hat{A}$ as a function of all predictor variables, including time. Performing linear regression with $\hat{A}$ as a function of time alone gave a correlation coefficient of $R^2 = 0.4$. The latter low correlation could have been caused by rotations of rhodoliths around an axis not perpendicular to the image plane between the different time points of the images (Fig 10).

The results of the pre-processing steps show that the illumination fluctuations could be reduced significantly. Furthermore, the reference plate enabled us to achieve color constancy and to correct camera zooming for all images. Although we were able to design a pre-processing pipeline to enhance the image quality and to compensate feature shifts caused by the experimental set up, some experimental steps can still be improved. For instance, in most of the excluded images, the color reference plate showed strong reflections due to a suboptimal material surface and the angle between camera and reference plate. Hence, the circle detection failed or the gamma correction produced wrong corrections if the reflection influenced too many circles. The strong reflections that appeared in the color reference plate may be avoided by selecting a material that gives minimal reflections. Also using an imaging setup where the location and angle of the reference plate are fixed and optimized to avoid strong reflections will improve the image quality. Furthermore using a camera with manual settings enables the use of a fixed white balance that reduces possible fluctuations in color. The necessity to apply illumination correction could maybe be avoided using an optimized stable light setup system with artificial light sources only. Reference plate and sample should be illuminated evenly throughout the whole image. By experience even in laboratory studies these conditions are often hard to achieve throughout the whole experiment. The presented semi-automated software solution can be used to evaluate the images even if not recorded under the optimized conditions, as shown here.

At this state the whole automated segmentation progress takes about 4 minutes for each image, where most of the time is spent on the pre-processing stage. As shown by [31] a significant saving of processing time is achievable by code optimizations and the use general-purpose...
computing on graphics processing units (GPGPU). A similar acceleration can be expected for our approach, as no code optimization and no GPGPU has been applied for this study.

In comparison to this laboratory study, the analysis of underwater images recorded in the field is even more challenging for the issues discussed above as the levels of the inherent optical properties (IOP) will affect the image quality. Various concentrations of phytoplankton (Chl a), colored dissolved organic matter (cDOM) and total suspended matter (TSM) will alter the

![Correlation Loadings (X and Y)](image-url)

Fig 9. The correlation loading plot for the photosynthetic efficiency ($P$). It was obtained after PLS-regression with the HSV-variables ($h$, $s$, $v$) as predictors (blue dots), and photosynthetic efficiency ($P$) as response (red dot). The outer circle represents 100% explained variance and the inner circle 50% explained variance for the different variables. The plot showed that the predictor variables are highly correlated to the response variable. A prediction of the photosynthetic efficiency using the HSV-values is therefore possible for our experiment.
contrast, sharpness and colors of objects due to absorption and/or scattering of light [42, 43]. In shallow waters, (0–20 m depth) reflection from the seafloor and varying light conditions related to the cloudiness and flickering effects (focusing/defocusing due to wave effects) would add even more challenges that should be considered [44]. Therefore, it must be expected that image (pre-)processing will be needed when operating under field conditions. As both the calcareous algae and sediments at the Peregrino field moves quite extensively (unpublished results), the monitoring should focus on measurements of possible color change of the segmented (visual) calcareous algae present in the image over time.

Furthermore, we believe that this methodological approach has the potential to be applied to studies with other species where color change is a stress indicator, e.g. tropical corals [7]. However, as individual species have species specific features (color, structure, shape, etc.) and their surroundings differ, species specific adjustment for computational analysis may be required.

**Conclusion**

This pilot study has shown that impact of sedimentation on calcareous algae samples can be detected by the presented computational approach for automatic size and color measurement from photos.

In addition to the previously published correlation between photosynthetic efficiency and sediment coverage [6], the present multivariate regression showed correlations between time and calcareous algae size, as well as correlations between fluorescence and calcareous algae color. Furthermore, we have shown that the use of an unsupervised learning algorithm is a promising attempt to create a classifier out of a sparsely labeled dataset. The chosen approach of an automatic assignment of the H2SOM prototypes was successful. The results of this pilot
study will enable researchers to conduct more studies in the future with different parameteriza-
tions and samplings to improve calcareous algae stress models.

The observed correlation between photosynthetic efficiency and the HSV-values is highly
interesting for field studies, since photosynthetic efficiency measurements are impractical to
perform manually in deeper waters. Color measurement in images has therefore the potential
to play an important role in future field calcareous algae monitoring systems.

Supporting Information
S1 Text.
(PDF)
S2 Text.
(PDF)
S3 Text.
(PDF)
S1 Table.
(CSV)

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Author Contributions
Conceived and designed the experiments: JO IN IE MAOF FTST TWN. Performed the experi-
ments: JO IN IE MAOF FTST TWN. Analyzed the data: JO TWN IE IN. Contributed reagents/
materials/analysis tools: JO IN IE MAOF FTST TWN. Wrote the paper: JO IN IE MAOF FTST
TWN.

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Integrated Environmental Monitoring and Multivariate Data Analysis—A Case Study

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ABSTRACT

The present article describes integration of environmental monitoring and discharge data and interpretation using multivariate statistics, principal component analysis (PCA), and partial least squares (PLS) regression. The monitoring was carried out at the Peregrino oil field off the coast of Brazil. One sensor platform and 3 sediment traps were placed on the seabed. The sensors measured current speed and direction, turbidity, temperature, and conductivity. The sediment trap samples were used to determine suspended particulate matter that was characterized with respect to a number of chemical parameters (26 alkanes, 16 PAHs, N, C, calcium carbonate, and Ba). Data on discharges of drill cuttings and water-based drilling fluid were provided on a daily basis. The monitoring was carried out during 7 campaigns from June 2010 to October 2012, each lasting 2 to 3 months due to the capacity of the sediment traps. The data from the campaigns were preprocessed, combined, and interpreted using multivariate statistics. No systematic difference could be observed between campaigns or traps despite the fact that the first campaign was carried out before drilling, and 1 of 3 sediment traps was located in an area not expected to be influenced by the discharges. There was a strong covariation between suspended particulate matter and total N and organic C suggesting that the majority of the sediment samples had a natural and biogenic origin. Furthermore, the multivariate regression showed no correlation between discharges of drill cuttings and sediment trap or turbidity data taking current speed and direction into consideration. Because of this lack of correlation with discharges from the drilling location, a more detailed evaluation of chemical indicators providing information about origin was carried out in addition to numerical modeling of dispersion and deposition. The chemical indicators and the modeling of dispersion and deposition support the conclusions from the multivariate statistics. Integr Environ Assess Manag 2016;12:000–000. © 2016 SETAC

Keywords: Drill cuttings Principal component analysis (PCA) Peregrino Partial least squares regression Sediment traps

INTRODUCTION

New technology has led to new opportunities for a holistic and integrated environmental monitoring approach in offshore petroleum exploration and production operations. It has also led to new challenges associated with the interpretation of vast amounts data (Nilssen, Ødegård et al. 2015). Sensor-based environmental monitoring has during the past years been used as alternative or supplement to conventional sampling-based monitoring campaigns (Godø et al. 2014; Bagley et al. 2015). An integrated environmental monitoring approach comprises selection of parameters, sensors, sensor platforms, data collection, storage and interpretation, the latter requires advanced analytical methodology (Nilssen, Ødegård et al. 2015). Multivariate data analysis has successfully been used in several marine environmental studies for the interpretation of large data sets, for example on heavy metals and biomarker response (Rodríguez-Ortega et al. 2009), on spatial and temporal distribution of heavy metals in seawater and sediments (Lin et al. 2013), on element release from sediments (Muñoz et al. 2015), on PAH in marine and freshwater sediments (Neff et al. 2005; Eide et al. 2011), and to predict toxicity from sediment chemistry (Alvarez-Guerra et al. 2010).

The present work demonstrates the use of multivariate data analysis within the integrated environmental mapping and monitoring concept using data from the Peregrino oil field in Brazil as a case study. Multivariate data analysis was used to interpret the large data sets comprising oceanographic data, sediment trap data, chemical and physical environmental parameters, and also discharge data from offshore drilling obtained during long-term environmental monitoring. Because of the variability of the sampling frequency and the number of variables per sensor system, routines for preprocessing and combining data were established. Principal component analysis (PCA) was used as an exploratory approach to evaluate similarities between campaigns and samples (Jackson 1991). Partial least squares (PLS) regression was used to reveal correlation between predictors and responses (Wold et al. 1984).
The Peregrino oil field

The Peregrino oil field is located 80 km off the coast of Brazil, southeast of Cabo Frio, in the Campos Basin area. The field consists of 2 fixed wellhead platforms named A and B (WHP A and B) for drilling of production and water injection wells, and 1 floating production storage and offloading unit (FPSO). A map and a table with positions are available in the Supplemental Data (Figure 6 gives an overview). Drilling at Peregrino began November 9, 2010 and the field came in production April 9, 2011. The water depth in the area varies from 90 to 120 m, and seabed sediments consist, in general, of sand and silt with a relatively hard surface (Salgado et al. 2010).

The shallower part of the Peregrino seabed hosts a calcareous algae community (Salgado et al. 2010, Figueiredo et al. 2015). Calcareous algae are regarded as important for the ecosystem, as they create a habitat for other species living between, on, and in the calcareous algae structures (rhodoliths) (Basso 1998). These communities can be disturbed by natural sedimentation and anthropogenic activities, for example discharges of drill cuttings (Villas-Bôas et al. 2014, Figueiredo et al. 2015). The drilling fluid used at Peregrino is water-based, which generally is non- or low-toxic (Bakke et al. 2013). The concern related to the discharge of drill cuttings is related to the physical effect of burial and reduced light and gas exchange (Figueiredo et al. 2015). Because of the prevailing currents from WHP B toward the calcareous algae bank (Nilssen, Santos et al. 2015), field campaigns during 2010 to 2012 were carried out to monitor if drill cuttings could be detected in the vicinity of the Peregrino calcareous algae community.

Sediment traps and lander campaigns

One sensor platform (lander) and 3 sediment traps were placed in predefined positions on the seabed (Figure 6, details in the Supplemental Data). The first of the 7 campaigns was carried out before drilling and thus represents baseline (Table 1). The prevailing current direction in the area is toward the southwest from WHP B toward traps 1 and 3 and the lander (Nilssen, Santos et al. 2015). Trap 2 was located in an area not expected to be influenced by the discharges. The major area with calcareous algae is located approximately 1.3 km south-west of WHP B (see the map in the Supplemental Data). The sediment traps and the lander are described in more detail by Salgado et al. (2010) and Johnsen et al. (2014). The funnel of the sediment traps was 10 m above the seabed. Each trap captured 20 samples of sediment during periods of 3 to 4.5 d (fixed time intervals within each campaign) implying that each sediment trap campaign lasted for approximately 60 to 90 d. After completing the 20 samples, the traps were retrieved, and the sediment samples were analyzed in the laboratory.

In addition to the sediment traps, data were also available for campaigns 5 and 7 from the lander located roughly between traps 1 and 3. The lander was equipped with sensors providing data on current speed (CS) and current direction (CD) at 10 depth (every 10 m) measured every 10 min. Temperature, pressure, conductivity, and turbidity were measured every 5 min. Details on sensors are available in the Supplemental Data. Data on discharges of water-based drilling fluid and cuttings were provided on a daily basis for WHP B for the 5th and the 7th campaign. The discharges were directed vertically downward 50 m below sea surface.

Analyses of sediment trap samples

The sediment trap samples were used to determine suspended particulate matter (SuspPM) and a number of chemical compounds as briefly described below. The details are available in the Supplemental Data. Analyses of 26 individual alkanes (n-C12 to n-C35 and pristane and phytane) and 16 PAHs (US Environmental Protection Agency [USEPA] priority list) were carried out in accordance with UNEP (1992) with minor modifications. PAH data were not available for the first campaign, the methodology was not sufficiently sensitive but was improved before the subsequent campaigns.

Terrestrial-aquatic ratio (TAR) was determined according to Bourbonniere and Meyers (1998). Carbon preference index (CPI) was calculated to evaluate the possible petroleum source of n-alkanes (Aboul-Kassim and Simoneit 1996). Isomeric ratios for different PAH were calculated according to Yunker et al. (2002).

Carbon (13C and 14C) and N (14N and 15N) analyses were carried out as described by Thornton and McManus (1994) and Zhou et al. (2006) with a few modifications. The analyses provided data on organic C (Corg), total N (Ntot), organic C and N as percentages of SuspPM (CORG% and NTOT%), and bulk C to N (C:N). Carbon (12C and 13C) and N (14N and 15N) and organic C (12C and 13C) were used to calculate the bulk organic proxies δ13C and δ15N (Meyers 2003). CaCO3, CaCO3 was determined gravimetrically (campaign 2-7). Barium analysis was based on the procedure described in the SW 846 (USEPA 1996).

Preprocessing

As the variables were recorded at different time intervals, the data were preprocessed in various ways to match the variables with the lowest temporal resolution before the multivariate analysis. For multivariate data analysis including sediment trap data, the average for the corresponding time intervals (3-4.5 d) were also calculated for the other parameters. Models with turbidity, temperature, conductivity, and current were based on common interpolation of data to 10-min intervals. The data for CS and CD at 10 different depths were used in different ways in the analyses:

- As CD (angle relative to north) and CS (corresponding horizontal speed)
- As “effective current” (CD, CS) calculated from CS and CD according to the following procedure: calculation of the angle (in degrees) between CD and the direction from WHP B to the lander. This angle will be referred to as “relative current angle.” The “effective current” is obtained by multiplying CS with cosine of the relative current angle. A histogram for the frequency of effective current was calculated from all the individual observations for the time intervals corresponding to the sediment trap data.
- As score vectors obtained from PCA based on CS, CD, and effective current histograms (PCA described in next section)
The rationale behind “effective current” is that discharged particles are assumed to be transported in the direction of the lander and sediment traps 1 and 3. Using the average current speed, it takes approximately 6 h for discharged drilling particles to travel 1436 m from WHP B to the lander, and this delay was used when matching the discharge data to the lander data before the data analysis. This delay was also used for sediment trap 3 and was considered sufficiently accurate because sampling periods were 3 to 4.5 d. With this approach, any perpendicular current direction will not contribute to the effective current. The direction from WHP B to the lander is 221° (north is 0°). The dominating current direction was between 180° and 240°, confirming that the lander was located downstream of WHP B.

**Multivariate data analysis**

PCA (Jackson 1991) was used to evaluate similarities and differences between samples and for tracking changes, for example between campaigns, traps, and samples. This is achieved by evaluating all variables simultaneously, obtaining the structured information in the data, and visualizing the result in score and loading plots. Multivariate regression was carried out with PLS (Wold et al. 1983; Martens and Næs 1993) because it overcomes the problem of intercorrelated predictor variables and also takes into account relationships between response variables.

The sensors for turbidity and current were placed on the lander, and PLS-regression was done in an attempt to relate turbidity to CS and CD. As the lowest sampling frequency for these variables was 10 min, turbidity was also calculated every 10 min after interpolation. A total of 8267 observations for campaign 5 were included in the model.

PLS-regression was also carried out for the 5th and the 7th campaigns using discharge data and score vectors from individual PCA models for CS, CD, and effective current and histograms, CD, CS (described in previous section) as predictors, and SuspPM, Ba, and turbidity as response variables. The PCA models were calculated independently for campaigns 5 and 7 implying 6 individual PCA models (not shown) providing score vectors for the PLS model. The score vector approach was chosen because the high number of variables would make the interpretation difficult and the plots overloaded. Furthermore, the score vectors represent trends in current speed as function of depth. All data were adjusted to the sediment trap sampling intervals. The score vectors were combined with individual parameters in a multiblock model. All score values are available in the Supplemental Data.

**Dispersion and deposition modeling**

The numerical simulations of the horizontal and vertical dispersion in the water column and the deposition of the drilling discharges on the seabed during campaigns 5 and 7 were carried out using the dose-related risk and effect assessment model (DREAM) (Rye et al. 2008; Singsaas et al. 2008; Durugut et al. 2015). DREAM uses discharge characteristics and environmental data such as current, wind, etc. to predict the behavior of the discharge plumes in the water column and the deposition on the seabed. Particle size distribution of drill cuttings from the Peregrino oil field was obtained from sieving analyses. Volumes of discharged drill cuttings and drilling fluids with a temporal resolution of 24 h were obtained from the platform drilling logs. The total amount of solids in the water-based drilling fluid was calculated in accordance with the bulk density of the drilling fluid through the given drilling operation period at Peregrino. Because of the temporal 24-h resolution of the discharge log, the model was run in daily sequences, enabling a daily overview of the accumulation of the deposition. More details on the numerical modeling is described in Nilsen, Santos et al. (2015) who modeled deposition from WHP B over a 2-y period.

**RESULTS AND DISCUSSION**

**PCA on data on alkanes and PAHs from all sediment trap samples (all campaigns)**

An initial PCA was carried out to evaluate grouping and covariance of the individual hydrocarbons. PAH data were not available for the first campaign and the PCA was carried out for campaigns 2 to 7. The correlation loading plot in Figure 1 shows 2 groups of alkanes, and all alkanes except pristane and...
n-C25 vary systematically and are well explained. PC-1 and PC-2 explain 31% and 20% of the variation, respectively. PC-3 and PC-4 explain 11% and 6%, respectively. For PC-5 and onward, no individual variable is explained to more than 15%. The variance in PC-3 is, in essence, due to 1 sample from sediment trap 2. However, a third PCA was carried out for campaigns 2–7 including CaCO3 and sum PAH because these data were not available for campaign 1. A PCA without the 2 extreme samples (ST3-7-14 and ST3-7-21) gives essentially the same conclusions, i.e. the same explained variance and correlation between variables (score and loading plots not shown). However, Ba and HMWHC are better explained but are not correlated with SuspPM. Barium, 

![Figure 1](image1.png)

**Figure 1.** Correlation loading plot obtained after PCA on all data on 26 alkanes and 16 PAHs from the sediment traps, campaigns 2–7. The outer circle represents 100% explained variance and the inner circle 50% explained variance. The full names of Benz[g,h,i and Inden[1,2,3-c,d]pyrene, respectively.

![Figure 2](image2.png)

**Figure 2.** Score plot (A) with Hotelling’s F2 ellipse and correlation loading plot (B) obtained after PCA on all data from the 3 sediment traps, all 7 campaigns (data on CaCO3 and PAH not included because they were not available for the first campaign). The alkanes were summarized into LMWHC and HMWHC based on the initial PCA (Figure 1). The notation is ST1–ST3 for the 3 sediment traps, followed by 1–7 for each of the 7 campaigns, and the last digits are sample number (20 samples in each trap each campaign; some samples had to be combined to provide sufficient sample material for the analyses). Legend shows symbols and colors for each of the 7 campaigns. The intercorrelations between Ntot, Corg, and SuspPM are illustrated by the blue circle. The approximate location of PAH after PCA of data from campaigns 2–7 is indicated.
which is an indicator of drilling activity, is high in a few samples, particularly in ST1 and ST3 from the 2nd campaign and also in 1 sample from ST2, 5th campaign. A few samples from ST2 2nd campaign (samples 3–10) have a relatively high content of HMWHC. The elevated concentrations cannot be explained by drilling discharges from WHP B because ST2 is located 4 km away from WHP B and in a direction not expected to be influenced by discharges from the platform. The PCA for campaigns 2 to 7, including CaCO3 and sum PAH (missing for campaign 1), does not change Figure 2 or the conclusions (not shown, however, the approximate location of PAH after PCA of data from campaigns 2–7 is indicated in the loading plot in Figure 2).

CPI and TAR values support that the sedimentation is of a natural and biogenic origin (Eglinton et al. 1962; Volkman et al. 1992; Meyers 1997; Hostettler et al. 1999). The TAR values generally indicate terrestrial organic matter (TAR > 1). At some periods, lower TAR values were observed (TAR < 1) due to an increase in the relative contribution of nC15 and nC17 (algae-derived n-alkanes). As a result, TAR values decrease indicating an increased relative contribution of marine organic matter on SuspPM. CPI and the general predominance of odd-to-even C-numbered n-alkanes indicate terrestrial sources of n-alkanes, possibly due to riverine input (Eglinton et al. 1962; Bi et al. 2005; Zhang et al. 2006); however, the source could also be maritime traffic (Deyme et al. 2011). n-Alkanes originating from petroleum usually show a wide C chain length distribution but no predominance of odd-to-even C number (Volkman et al. 1992).

PAH isomeric ratios (Yunker et al. 2002) are shown in the cross-plots in Figure 3. PAH sources are most likely related to pyrogenic sources, based on BaA/228, IP/IPþ and Fl/Flþ values. Nevertheless, there is contribution from direct input of petrogenic sources, as shown by Ant:178 ratios. Therefore, there are mixed sources of PAH to SuspPM at the Peregrino oil field. The relative abundance of LWMPAH and HMWPAH, with relative predominance of HMWPAH confirms the mixed sources of PAH in this area (Neff et al. 2005; Deyme et al. 2011).

**PLS with current speed and direction as predictors and turbidity as response**

PLS with current speed and direction and discharge data as predictors and turbidity as response was carried out for campaigns 5 and 7 because lander data were only available for these 2 campaigns. The loading plot in Figure 4 based on data from campaign 5 shows that turbidity is not well explained and is independent on CD and CS and cannot be related to currents from WHP B. The explained variance for turbidity after 2 factors was 27% and 15% for calibration and validation, respectively, implying that there is no predictive ability in the model. However, Figure 4 shows that CS and CD follow very systematic patterns. CS varies with depth and the correlation changes accordingly. CD for all depths is correlated showing that the current is homogeneous for all depths. Turbidity does not correlate with CD or CS. On the other hand, CD is well explained for all depths. CS is relatively well explained for the depths 16 to 76 m above seabed, whereas the 3 points representing CS at 86 to 106 m above seabed are inside the 50% explained variance circle in Figure 4. It is emphasized that the depth values (16–106 m) refer to the distance from the seabed, not from the sea surface.

**PLS-regression with data from campaign 7 based on 13 236 observations (not shown) gives essentially the same result as campaign 5 (Figure 4).**

**PLS using score vectors for CS, CD, and effective current**

PLS-regression with discharge data, temperature, conductivity, and scores for CS, CD, and CD CS as predictor variables, and SuspPM, Ba, and turbidity as response variables was carried out with data from campaigns 5 and 7, sediment trap 3. Sediment trap 3 was used because it was located downstream from the discharge (data were not available for sediment trap 1).

The first model for the 40 observations corresponding to the sediment trap intervals for campaigns 5 and 7 indicated 2 outliers, ST3-7-14 and ST3-7-21 with very high values for SuspPM. These 2 samples were also extreme in the previous PCA (Figure 2) but were not considered as outliers as the pattern among the variables did not change when these 2 samples were excluded from the model. In the PLS-regression, however, they are outliers because they significantly influence the parameters in the regression model if they were included. This means that they are influential, but the extreme values for
Discharges of drilling fluid and cuttings from WHP B. A correlation loading plot obtained after PLS with turbidity as x-variable as the current derived variables are inside the normal range for these 2 samples. The correlation loading plot in Figure 5 shows that SuspPM does not correlate with any of the other variables. Furthermore, although goodness of fit (explained calibration variance) for turbidity is 41% and Ba 30% with 2 PLS factors, the model is not stable and lacks prediction power (evaluated by cross-validation). This implies that SuspPM, turbidity, and Ba cannot be explained by transport of drilling discharges from WHP B to the lander or sediment trap 3.

Dispersion and deposition modeling

For comparison, numerical modeling with DREAM was carried out to describe dispersion and deposition of the discharges of drilling fluid and cuttings from WHP B. A corresponding 2-y modeling has previously been published (Nilssen, Santos et al. 2015), however, the modeling in the present work was carried out for campaigns 5 and 7 specifically because lander data were available for these 2 campaigns. The purpose was to evaluate whether established numerical models would support the observation that the drill cuttings did not settle in the sediment traps or increase turbidity at the lander position. Figures 6A and 6B show the deposition of discharged drill cuttings and solids in drilling fluid. The lower limit of deposition was set to 50 g m\(^{-2}\) corresponding to 0.05 mm thickness. The deposition figures demonstrate that these amounts of drill cuttings and drilling fluid solids hardly reach sediment trap 3 during campaigns 5 and 7. Obviously, the position for sediment trap 3 was not optimal for capturing drill cuttings and fluid solids from the discharges during campaigns 5 and 7. Furthermore, the deposition is closer to sediment trap 2 than expected.

Table 2 shows the predicted accumulated sedimentation from the discharges during the 2 campaigns compared to the larger measured sedimentation in sediment traps 2 and 3. The difference further supports the conclusion that the major part of the sediment collected in the traps had another origin than WHP B. Furthermore, it is generally assumed that DREAM overestimates sedimentation (Rye et al. 2012), implying that the modeled deposition should probably be even lower than shown in Table 2.

Figure 6C shows a representative snapshot of the horizontal and vertical dispersion plume in the water column from the discharge of drill cuttings and drilling fluid solids. The lower limit is 0.05 ppm of particles in the water column. The horizontal dispersion shows that the plume goes in the direction of the lander and to some extent to sediment trap 3. The vertical cross section shows that there is a significant deposition close to the platform, whereas the plume continues at intermediate water layers and will not have any significant impact on turbidity at the lander position. This may explain the lack of relationship between turbidity and discharges (Figure 4).

CONCLUSION AND FUTURE PERSPECTIVES

The present article demonstrates the essential benefit of multivariate data analysis for optimized data interpretation in integrated environmental monitoring. The multivariate data analysis integrates a high number of variables and vast amounts of data. Principal component analysis was used to evaluate similarities and differences among samples and correlations between variables. Partial least squares regression was used to obtain correlations between predictors and responses. Because of the variability of the sampling frequency and the number of variables per sensor system, a multiblock modeling approach was applied for the final PLS-regression.

The different multivariate models support each other and are also supported by chemical indicators and numerical modeling of dispersion and deposition using DREAM.

In a future perspective, data from biosensors, images, spectra, etc., may be integrated in the multivariate data analysis in addition to the parameters described in the present work. A further step in integrated environmental monitoring is the integration of multiple sensors, online transmission of data and automated multivariate statistics for real-time monitoring and integration in operational systems. In addition to providing a better basis for rapid mitigation in case of incidences or undesired impact from planned discharges, a monitoring...
system integrated as part of the daily industrial operations will, in most cases, be cost-efficient. The large amount of data generated from real-time measurements represents a major challenge both with respect to transmission to, and interpretation by the end user. Multivariate data analysis is capable of handling both these challenges by reducing the magnitude before the data are transmitted and through the capability of identifying patterns in huge data sets. Software for online multivariate data analysis is already installed at the Lofoten-Vesterålen Ocean Observatory, Norway (http://love.statoil.com). Results and experiences from this online multivariate data analysis will be published later.

Figure 6. Accumulated deposition of drill cuttings and drilling fluid solids in g m$^{-2}$ at the Peregrino seabed predicted by DREAM during campaigns 5 (A) and 7 (B). Lower limit of sedimentation is set to 50 g m$^{-2}$ (0.05 mm thickness). Snapshot (C) of horizontal and vertical dispersion of drill cuttings and drilling fluid solids in the water column after discharge from WHP B. Arrow indicates prevailing current direction.
Table 2. Predicted (by DREAM) accumulated sedimentation from the discharges compared to the measured accumulated sedimentation in sediment traps 2 and 3 during campaigns 5 and 7 (g m⁻²).

<table>
<thead>
<tr>
<th>Campaign 5 ST2</th>
<th>Measured</th>
<th>Predicted</th>
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<tbody>
<tr>
<td>134</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>Campaign 7 ST2</td>
<td>28</td>
<td>25</td>
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<td>126</td>
<td>48</td>
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<tr>
<td>Campaign 7 ST3</td>
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<td>17</td>
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Data availability—All raw data will be made available upon request from the authors.

SUPPLEMENTAL DATA
Table S1. Table with positions.
Table S2. Table with descriptive statistics of hydrocarbons.
Table S3. Table with all data used in the multivariate data analyses.
Figure S1. Map.
Data S1. Text with methods details and additional results.

REFERENCES


Assessing the potential impact of water-based drill cuttings on deep-water calcareous red algae using species specific impact categories and measured oceanographic and discharge data

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Modelling

Abstract
The potential impact of drill cuttings on the two deep water calcareous red algae Mesophyllum engelhartii and Lithothamnion sp. from the Peregrino oil field was assessed. Dispersion modelling of drill cuttings was performed for a two year period using measured oceanographic and discharge data with 24 h resolution. The model was also used to assess the impact on the two algae species using four species specific impact categories: No, minor, medium and severe impact. The corresponding intervals for photosynthetic efficiency (\(F_{\text{PSII}}\)) and sediment coverage were obtained from exposure–response relationship for photosynthetic efficiency as function of sediment coverage for the two algae species. The temporal resolution enabled more accurate model predictions as short-term changes in discharges and environmental conditions could be detected. The assessment shows that there is a patchy risk for severe impact on the calcareous algae stretching across the transitional zone and into the calcareous algae bed at Peregrino.

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1. Introduction

The calcareous red algae, Mesophyllum engelhartii (Foslie) Adey and Lithothamnion sp. are encrusting species growing on different hard substrates such as rhodoliths. Rhodoliths are calcified multi-spherical structures of different sizes made of dead calcareous algae and other calcifying organisms such as bryozoans and different species of polychaetes (Tamega et al., 2013) (Fig. 1). These multi-spherical structures are regarded as important for the ecosystem, creating a habitat for other taxa living between, on and in the rhodolith structures (Basso, 1998). Rhodoliths are found down to 250 m (Henriques et al., 2014; Littler et al., 1991, 1986), and the largest occurrence is discovered along the Brazilian Continental Shelf (Amado-Filho et al., 2012; Foster, 2001; Kempf, 1970). The knowledge about growth, sensitivity to environmental stressors and ecological importance of the deep water rhodolith communities is rather sparse (Henriques et al., 2014; Steller et al., 2009, 2007). However, these communities may be disturbed and buried due to natural sedimentation and anthropogenic activities such as fish–trawling and mining (Nelson, 2009). Burial may result in reduced photosynthetic activity due to reduced gas exchange (Figueiredo et al., 2015; Harrington et al., 2005; Wilson et al., 2004). It is also demonstrated that fine particles (<63 \(\mu\)m grain size) may reduce the photosynthetic efficiency of coralline algae to a larger extent than coarse calcareous and nutrient-rich shallow estuarine sediments (Figueiredo et al., 2015; Harrington et al., 2005; Riul et al., 2008; Wilson et al., 2004).

Furthermore, rhodolith beds are increasingly exposed to discharges of drill cuttings from oil and gas activities, for instance in
The Peregrino oil field, located 80 km off the coast of Brazil, south of Cabo Frio, in the Campos Basin area, is located close to a rhodolith bed (Fig. 9). The calcareous algae Mesophyllum engelhardtii (Foslie) Adey and Lithothamnion sp. are among the most abundant algae species present in the area (Figueiredo et al., 2015; Salgado et al., 2010; Tamega et al., 2013). Drill cuttings with residues of water-based drilling fluids are discharged from the drilling activities at Peregrino. Drill cuttings are formation rock particulates generated during drilling (Neff, 2008). The water-based drilling fluid discharges only contain residuals of water soluble and none or low toxic components such as barite, clay, salts and calcium carbonate (Bakke et al., 2013; Frost et al., 2006; Neff, 2008). Barite is a weighting agent in drilling fluids and one of the most abundant solid in drilling fluids (Neff, 2008). Laboratory tests verified that the residuals of water-based fluid from the Peregrino oil field are not toxic to Mesophyllum and Lithothamnion (Reynier et al., 2015). However, as calcareous algae have no individual motion and since the rhodoliths they are living on are expected to have low motion capabilities (Fig. 1), these discharges may have a physical impact on the test organisms through sedimentation of particles. Reduced production of oxygen and reduced in vivo photosynthetic efficiency, reported by Reynier et al. (2015) was primarily physical and due to the burial with drill-cuttings. Also sediment mimicking drill cuttings from the Peregrino oil field resulted in reduced in vivo photosynthetic efficiency in Mesophyllum and Lithothamnion (Figueiredo et al., 2015; Villas-Boas et al., 2014). Photosynthetic efficiency was measured as in vivo Chlorophyll a fluorescence kinetics of dark acclimated cells (ΦPSII_max). A decrease in photosynthetic efficiency is regarded as a response to stress (Genty et al., 1989).

Modelling is frequently used to assess potential risk or impact of discharges to sea from oil and gas exploration and production. Environmental risk assessment based on the PEC/PNEC approach is commonly used by offshore operators in Europe, and the principle is accepted by the Oslo Paris Commission (OSPAR) as a basis for environmental management of produced water discharges (OSPAR, 2012a, 2012b). One example of such a model is the Dose-related Risk and Effect Assessment Model (DREAM) (Beyer et al., 2012; Durgut et al., in press; Johnsen et al., 2000; Rye et al., 2008; Smit et al., 2008). DREAM predicts dispersion and potential environmental risk based on the PEC/PNEC approach for discharges of produced water and drill cuttings to the marine environment. A major criticism against this approach has been the lack of ecosystem relevance as the PNEC levels derived from the literature may not be representative for local species. This is especially of concern when operating in areas considered as particularly vulnerable or housing species or habitats of particular interest. This situation is indeed valid for the Peregrino field, housing a deep water calcareous algae community. However, DREAM also allows the use of species specific effect data as an option to the more generic PNEC approach, giving a risk or impact assessment targeted at selected species.

The aim of the present study was to assess the potential impact of drill cuttings discharges on the dominating species of calcareous algae at the Peregrino oil field. Furthermore, the purpose was to verify that the assessment of the potential impact as performed by DREAM provides valid and reliable information for environmental management. This was achieved by:

1) establishment of species specific impact categories for the calcareous algae Mesophyllum engelhardtii (Foslie) Adey and Lithothamnion sp. based on exposure studies performed in a flow-through system (Figueiredo et al., 2015) and
2) modelling the potential impact on the two calcareous algae species using the established impact categories together with measured current velocity and direction and actual drill cutting discharges with high temporal resolution.

2. Methods

The methodological approach in this study is based on the principles outlined by Nilsen et al. (2015) for integrated environmental mapping and monitoring, describing a flexible approach for optimised knowledge gathering through combined use of laboratory experiments and measured field and discharge data with modelling. To enable the link between the impact categories obtained from the flow-through exposure studies (Figueiredo et al., 2015) and the dispersion modelling, sedimentation experiments were performed to convert sediment coverage (%) to sediment deposition (kg m⁻²). A flow chart of the different elements used to perform the assessment of potential impact on the two calcareous algae species is illustrated in Fig. 2.

2.1. The Peregrino area

The Peregrino oil field consists of two fixed well head platforms (WHP) for drilling of production and water injection wells, and one floating production storage and offloading unit (FPSO). The WHPs are located 10 km apart with the FPSO in between. Drilling at the Peregrino field commenced in November 2010 and until May 2013,
30 wells were drilled. The field came in production in May 2011. The well streams are transported to the FPSO through subsea pipelines, while produced water (water that is produced together with the hydrocarbons from the reservoir) is routed back to the WHPs and re-injected to the reservoir. Drill cuttings with residuals of water-based drilling fluid are discharged to the sea, while cuttings from the hydrocarbon containing reservoir section are sent to shore for disposal (Johnsen et al., 2014).

The water depth at Peregrino varies from 90 to 120 m and seabed sediments consist in general of sand and silt with a relatively hard surface (Johnsen et al., 2014; Salgado et al., 2010). The rhodolith bed is found in the shallow part of the Peregrino seabed (<110 m).

### 2.2. Dispersion modelling

The numerical simulations of the dispersion and deposition of the drilling discharges over a two years period were carried out using the DREAM model (Beyer et al., 2012; Durgut et al., in press: Johnsen et al., 2000; Rye et al., 2008; Singsaas et al., 2008). DREAM uses discharge characteristics and environmental data such as current, wind, etc. to estimate the behaviour of the discharge plumes in the water column and the deposition on the seabed, the predicted exposure concentration (PEC). Due to the temporal 24 h resolution of the discharge log the model was run in daily sequences, enabling a daily overview of the accumulation of the deposition.

#### 2.2.1. Field data

The environmental variables used were bathymetry, sea temperature, salinity, speed and direction of wind and currents, the latter being the most complex and crucial for reliable outputs from modelling of cuttings deposition. Despite the 4-D behaviour (3 spatial dimensions and time) of a cuttings discharge plume, from near the sea surface to settling on the seabed, the horizontal scale of the plume is expected to be much smaller than the horizontal variability of the currents. It was therefore presumed that the vertical profile of the currents in the vicinity of the operation is representative for the currents for the whole area of interest.

The vertical profile of the currents was obtained from an Acoustic Doppler Current Profiler (ADCP) moored in the vicinity of WHPB. Current velocity and direction were measured every 10 m from 14 m below the sea surface to 104 m water depth. The dispersion modelling was carried out for the time period 10th November 2010 to 29th November 2012. Measured data were lacking in the period of 10th November to 26th January 2011, 16th August to 21st November 2011 and 25th April 2012 to 2nd July 2012. These gaps were filled by model outputs from the MyOcean project (Dombrowsky et al., 2013). This project uses the Nucleus for European Models of the Ocean (NEMO) to assimilate current data, sea surface height and sea temperature measurements derived from satellites. The complete current time series used in the study is presented in Fig. 3. Current velocities varied between 0 and 1.01 m s⁻¹ at about 10 m above the seabed.

Both modelled and measured current velocity and direction showed a barotropic behaviour from surface to bottom, mainly flowing south-westwards. Inversion on the current direction was observed most frequently in the autumn/winter period (from May to August). This behaviour is explained by the Brazil Current, a western boundary current flowing towards high latitudes along the continental shelf break (Evans and Signorini, 1985). Its intensity and direction may be modified by cold front passages (Stech and Lorenzzetti, 1992).

#### 2.2.2. Discharge data

Particle size distribution of drill cuttings from the Peregrino oil field (well A-18) was obtained from sieving analyses. Volumes of discharged drill cuttings and drilling fluids with a temporal resolution of 24 h were obtained from the platform drilling logs. The total amount of solids in the water-based drilling fluid was calculated in accordance with the bulk density of the drilling-fluid through the given drilling operation period at Peregrino.

### 2.3. Effect data and impact categories

Stress on calcareous algae is traditionally categorised by visual inspection, using charts for colour tone and intensity (De O. Figueiredo et al., 2000; Villas-Boas et al., 2014) (Table 1). Figueiredo et al. (2015) related the categorised stress levels to corresponding photosynthetic efficiency in their study with sediment coverage on Mesophyllum and Lithothamnion. The photosynthetic efficiency was measured as in vivo maximum quantum yield
lishing the following four species: *Mesophyllum* and *Lithothamnion*. The corresponding sediment coverage intervals were obtained from the exposure study (Figueiredo et al., 2015). Photos were taken of each rhodolith each week through the experimental period (T0–T9). The borders of the each rhodolith were outlined before and after removal of sediment for the photosynthetic efficiency measurements. Sediment coverage was calculated from these images. The corresponding *ΦPSII* values are 0.46–0.55, 0.36–0.45, 0.26–0.35 and <0.26, respectively, implying that the two most severe stress levels were merged into one category. The corresponding sediment coverage intervals were obtained from the combined exposure–response relationship for photosynthetic efficiency as function of sediment coverage for the two algae species as described by Figueiredo et al. (2015). Sediment coverage and photosynthetic efficiency were measured in a flow-through system varying light intensity, flow rate and added amount of sediment once a week for nine weeks. Statistical experimental design and multivariate data analysis provided statistically significant regression models which subsequently were used to establish the exposure–response relationship.

All calcareous algae used in the experimental work were classified as healthy, “no stress” (*ΦPSII*max ~ 0.46–0.55) at the beginning of the experiment (T0). This is a conservative approach and it is expected that lesser healthy individuals to a lesser extent would tolerate the sediment exposure during the experiment.

### 2.3.1. Sedimentation experiments

The DREAM dispersion modelling provides sedimentation of the discharges in kg m⁻². In order to relate modelled sedimentation to sediment coverage (%), as provided by the exposure study (Figueiredo et al., 2015), sedimentation experiments were performed (Fig. 2). The flow-through system used by Figueiredo et al. (2015) for the exposure studies was also used in the sedimentation experiments, however, without rhodoliths in the chambers.

Three series of experiments were performed with five different sediment amounts added to the chambers under three different flow conditions. The flow rates were 0.04, 0.07, and 0.09 m s⁻¹, identical to those used in Figueiredo et al. (2015) and the amount of sediment added were 600, 750, 900, 1050 and 1200 g.

A Plexiglas tray with the size of 80.34 cm² was placed horizontally at the bottom of each exposure chamber (approximately 6 L) in the flow-through system to collect the deposited sediments. Each experiment lasted 60 min, which was appropriate for the particles to settle. After settlement, the flow was stopped and the remaining seawater was slowly drained off the exposure chambers to prevent loss of deposited sediments, to minimise the amount of salt in the sediment and to reduce the drying process. The sediment

### Table 1

<table>
<thead>
<tr>
<th><em>ΦPSII</em>max</th>
<th>Colour (Tone)</th>
<th>Colour (Intensity)</th>
<th>Stress level</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.015</td>
<td>0–1</td>
<td>0–2.25</td>
<td>Dead</td>
</tr>
<tr>
<td>0.16–0.25</td>
<td>1.1–2.0</td>
<td>2.26–3.25</td>
<td>High stress</td>
</tr>
<tr>
<td>0.26–0.35</td>
<td>2.1–3.0</td>
<td>3.26–5</td>
<td>Intermediate stress</td>
</tr>
<tr>
<td>0.36–0.45</td>
<td>3.1–3.75</td>
<td>5.1–6</td>
<td>Low stress</td>
</tr>
<tr>
<td>0.46–0.55</td>
<td>3.76–4.25</td>
<td>6.1–7</td>
<td>No stress</td>
</tr>
</tbody>
</table>

Fig. 3. Time series of current velocity and direction at Peregrino used in the DREAM simulations. The ADCP data (measured) is represented by black arrows and MyOcean data (modelled) by red arrows. The timeline indicated on the x-axes equals the aggregated deposition modelled after 6, 12, 18 and 24 months presented in Fig. 4a and b (24 months), respectively. Prevailing current direction is south-westwards. Measured current velocities were 0–136 m s⁻¹ (all depths).
covered Plexiglas trays were removed from the exposure chambers and dried in air for 24 h before the sediments were transferred to metal trays and oven dried for another 24 h before dry weight measurements.

The amounts of sediment deposited in the three sedimentation experiments were averaged and converted to kg m\(^{-2}\). Corresponding data for sediment coverage (%) were obtained from the exposure study (Figueiredo et al., 2015). The relationship between sediment coverage (%) and deposition (kg m\(^{-2}\)) was obtained by regression modelling.

In addition, sediment deposition (kg m\(^{-2}\)) was converted to sediment thickness (mm) using an initial density of drill cuttings of 2.65 kg L\(^{-1}\) which was reduced to 1.06 kg L\(^{-1}\) using a porosity index of 60% for the deposited cuttings. The porosity index is commonly applied for deposition at this water depth (Bryant et al., 1981).

2.4. Impact assessment

In addition to dispersion modelling, the DREAM model was used for the assessment of the potential impact of the drilling

Fig. 4. Deposition of drill cuttings at the Peregrino seabed predicted by DREAM. a) Aggregated discharges from WHPB after 6, 12 and 18 months and b) total discharges from WPHA and WPHB aggregated after two years. Prevailing current direction is south-westwards. Lower limit of sedimentation is set to 1000 g m\(^{-2}\) (~1 mm thickness).
discharges on the two species of calcareous algae, *Mesophyllum engelhartii* and *Lithothamnion sp.* One of the modules in DREAM covers thresholds for physical disturbances on organisms, including burial, oxygen depletion and change in grain size for discharges from drilling activities. DREAM uses, as a default, a generic set of effect threshold levels for impacts derived from literature studies (PNECs) (Rye et al., 2008; Smit et al., 2008). The PNEC for the nontoxic stress from burial have been derived by use of a Species Sensitivity Distribution (SSD) approach from available chronic data (NOEC) (Smit et al., 2008). SSDs can be applied in risk modelling by predicting the potentially affected fraction of species at a certain level of exposure. The 5% affected fraction is in general regarded as representative for the PNEC (Harbers et al., 2006) and this is also used in the DREAM model. However, when species specific knowledge is regarded as crucial, specific values for effects derived from laboratory studies can be used instead of generic PNECs as input to the model.

In the present study, the species specific impact categories described in section 2.3 were used as input to the DREAM simulations. This provides an impact assessment analogous to the assessment of physical disturbances of drill cuttings on the reef building cold and deep water coral *Lophelia pertusa* (Det Norske Veritas, 2013).

3. Results

3.1. Dispersion modelling

The results from the dispersion modelling of drilling discharges from the first two years of drilling at the Peregrino field are presented as deposition maps of different colours as function of time, represented by the deposition after 6 months (May 2011), 12 months (November 2011) and 18 months (May 2012) (Fig. 4a) and the total aggregation over the two years period (Fig. 4b), respectively. As expected, deposition is following the ocean current pattern and is concentrated in the south-west/north-eastern direction. However, periods with divergent current directions occur, as shown after 18 months in Fig. 4a (grey lines).

Examples of aggregation of sedimentation at two different geographical positions over time are presented in Fig. 5. Fig. 5a shows the aggregation in a position near the discharge point (WHPB), while Fig. 5b presents the deposition for a position further southwest, close to the calcareous algae rhodolith bed. As expected, deposition of discharges is higher close to the discharge point, while areas further away are expected to receive less amounts and the deposition therefore increases more gradually that in the immediate vicinity of the discharges.

3.2. Effect data and impact categories

Four species specific impact categories for *Mesophyllum* and *Lithothamnion* were established in section 2.3: No, minor, medium and severe impact. The corresponding *ΨPIImax* values are 0.46–0.55, 0.36–0.45, 0.26–0.35 and <0.26, respectively. The corresponding sediment coverage intervals were obtained from the combined exposure–response relationship for photosynthetic efficiency as function of sediment coverage for the two algae species as described by Figueiredo et al. (2015). The result is shown in Fig. 6.

The variability in the exposure–response curve ($Ψ_{PIImax}$=0.06) is illustrated by the dotted lines (Figueiredo et al., 2015). These take into account the contribution from the other factors that were varied in the exposure studies, namely flow rate, light intensity and time. However, the contribution of each of these factors is minor and the dotted curves represent the extreme upper and lower limits when all three factors contribute simultaneously in the same direction, each on its maximum level. The solid exposure–response curve has flow rate, light intensity and time at intermediate levels. Due to the fact that other factors may contribute, the sediment coverage intervals corresponding to the established $Ψ_{PIImax}$ levels are rounded off to the nearest 10% value. The following categories were established for possible impact of sediment coverage (%) on the two species of calcareous red algae at the Peregrino field:

- **No impact**: 0–30% sediment coverage
- **Minor impact**: 30–50% sediment coverage
- **Medium impact**: 50–70% sediment coverage
- **Severe impact**: >70% sediment coverage

3.2.1. Sedimentation experiments

The results from the sedimentation experiments are presented in Table 2. The amounts of sediment deposited in the three sedimentation experiments were averaged and subsequently converted to kg m$^{-2}$. Corresponding data on sediment coverage (%) obtained from the exposure studies (Figueiredo et al., 2015) are presented in the last column of Table 1.

Average sediment deposition as a function of added sediment amount and flow rates are presented in Fig. 7. The data points for the two highest current velocities (0.07 and 0.09 m s$^{-1}$) are overlapping, indicating that sedimentation will probably not increase beyond these velocities.

In order to establish the correlation between sediment deposition (kg m$^{-2}$) and coverage (%) corresponding data from Table 2 were used. The best regression model was obtained with an exponential curve ($R^2=0.85$) presented in Fig. 8.

![Fig. 5. Aggregated deposition of drill cuttings over the two years drilling period](image-url)
3.3. Impact assessment

The established impact categories and corresponding photosynthetic efficiency ($\Delta F/\Delta phi$) as function of sediment coverage for *M. engelhartii* and *Lithothamnion* sp. Green: no impact; yellow: minor impact; orange: medium impact; red: severe impact. The curve is based on regression modelling of data from laboratory experiments (Figure modified from Figueiredo et al. (2015)).

![Graph](image)

Fig. 6. Established impact categories based on exposure–response curve for in vivo photosynthetic efficiency ($\Delta F/\Delta phi$) as function of sediment coverage for *M. engelhartii* and *Lithothamnion* sp. Green: no impact; yellow: minor impact; orange: medium impact; red: severe impact. The curve is based on regression modelling of data from laboratory experiments (Figure modified from Figueiredo et al. (2015)).

### Table 2

<table>
<thead>
<tr>
<th>Flow (m s$^{-1}$)</th>
<th>Sediment added (g)</th>
<th>Sediment deposited (average g/side)</th>
<th>Sediment deposited (kg m$^{-2}$)</th>
<th>Sediment coverage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>600</td>
<td>692 ± 7.5</td>
<td>8.6</td>
<td>7.3</td>
</tr>
<tr>
<td>0.04</td>
<td>750</td>
<td>890 ± 2.3</td>
<td>11.1</td>
<td>11.4</td>
</tr>
<tr>
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<td>900</td>
<td>997 ± 7.9</td>
<td>12.4</td>
<td>21.4</td>
</tr>
<tr>
<td>0.04</td>
<td>1050</td>
<td>1024 ± 6.7</td>
<td>12.7</td>
<td></td>
</tr>
<tr>
<td>0.04</td>
<td>1200</td>
<td>1345 ± 3.2</td>
<td>16.7</td>
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<tr>
<td>0.07</td>
<td>600</td>
<td>621 ± 10.4</td>
<td>7.7</td>
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<td>0.07</td>
<td>750</td>
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<td>9.8</td>
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<td>1200</td>
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<tr>
<td>0.09</td>
<td>1200</td>
<td>1160 ± 11.3</td>
<td>14.4</td>
<td>96.3</td>
</tr>
</tbody>
</table>

* Numbers from Figueiredo et al. (2015).
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would be presented. The PEC/PNEC approach of DREAM includes a generic PNEC for sediment species related to the effect of physical coverage of drill cuttings. The value is derived from SSDs from a comprehensive data set obtained from the literature (Smit et al., 2008). The basis for the SSD approach is NOEC (No Observed Effect Concentration) values of burial of different species, and where the PNEC represents 5% of the potentially affected fraction of the species. In the present study this approach is replaced by the use of impact categories, expressing the potential effect of drill cuttings or sediment burial on the species of interest. The generic PNEC for burial in DREAM equals 6.3 mm sediment thickness (Smit et al., 2008), while the “no impact” interval (<30%) for the impact categories equals a sediment thickness of <10.7 mm (Table 3). These results show that the sensitivity of calcareous algae towards sediment or drill cuttings burial is well within the range of the species represented in the SSD curve presented by Smit et al. (2008) and are not among the most sensitive species (NOEC for calcareous algae > generic PNEC). In the present case with the calcareous algae, the PEC/PNEC approach would have been applicable to assess the possible impact.

However, applying the impact categories reduces the uncertainties of the potential impact of drilling discharges to the two species of calcareous algae. In addition it provides flexibility to the impact assessment. While the generic PEC/PNEC approach in DREAM does not distinguish between levels of risk by using one cut-off PNEC value, the impact categories approach introduces a range of severity (no impact–severe impact) in the risk picture. A species specific impact category approach based on degrees of exposure provides improved management ability adjusted to varying geographical environmental conditions and the species of interest. For instance, field sampling at Peregrino have shown high natural sedimentation (0.4–2.5 g m⁻² d⁻¹) (unpublished results) and Figueiredo et al. (2015) indicated that the calcareous algae at Peregrino is adapted to some degree of natural sedimentation, as the best light conditions for the photosynthetic efficiency were found within the interval 12–14% particle coverage (max light regime used in experiment equals 100% light intensity measured at the Peregrino rhodolith bed). Reduced fluorescence emission from algae due to too high irradiance is also well documented in the literature (Ars et al., 1993; Johnson and Saltzburg, 2007). In field situations, variations of particle loads in suspension and deposited (natural and anthropogenic), current conditions and water depth will determine the potential impact of drilling particulates discharges might have on the calcareous algae. It is expected that areas with low current velocity tolerate less discharges of particulates than areas with stronger currents since stronger currents will give reduced sedimentation by wider dispersion of a discharge and/or increased re-suspension. Due to this considerable influence of environmental factors, the category or interval approach applied in a planning process on a field may open up for a case by case evaluation, adjusting the acceptance intervals to the present geographical environmental conditions. Such an interval approach combining health status or environmental conditions with pre- dicted sedimentation, is aligned with the approach described in the guidelines for cold water corals where an individual classification of health status for each reef is evaluated against the predicted sedimentation (Det Norske Veritas, 2012).

The established impact categories are based on laboratory studies and may be adjusted after experience from environmental monitoring and assessment in the field has been obtained. An
alternative monitoring program, in accordance with the principles of a flexible monitoring program aligned with type of discharges, environmental conditions and organisms of interest (Nilssen et al., 2015) has been proposed by the Peregrino Environmental Monitoring and Calcareous Algae (PEMCA) project (Johnsen et al., 2014). The environmental monitoring focuses on the calcareous algae and possible impact of discharges from drilling activities. It is proposed to combine sediment traps measurements, current velocity and images, in agreement with the integrated approach to verify and improve both the environmental modelling and monitoring (Nilssen and Johnsen, 2008).

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Abbreviations and definitions

DREAM Dose-related Risk and Exposure Assessment Model
FPSO Floating production storage and offloading unit
NOEC No Observed Effect Concentration
PAM Pulse Amplitude Modulated fluorometer
PEC Predicted Exposure Concentration
Phototrophic efficiency In vivo maximum quantum yield of charge separation in photosystem II in dark acclimated cells ($\Phi_{PSII,max}$)

PNEC Predicted No Effect Concentration
PEMCA Peregrino Environmental Monitoring and Calcareous Algae
PLS Partial least squares
PSII Photosystem II (oxygen evolving site)
SSD Species Sensitivity Distribution
WHP Wellhead platform
WHPA Wellhead platform A
WHPB Wellhead platform B

![Fig. 9. Illustration of the potential impact after two years of drilling discharges from WHPA and WHPB, expressed by the established impact categories. Prevailing current direction is south-westwards. Note: The colour coding is not identical to the colour coding used of the impact categories in Fig. 6.](image-url)
A computer vision approach for monitoring the spatial and temporal shrimp distribution at the LoVe observatory

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HIGHLIGHTS

• First computational approach to monitor shrimp populations for long time periods with a camera-equipped observatory.
• Combination of superpixel representations and a new color change feature enables integration of shape and color features of shrimp.
• Shrimp abundance heat maps enable for a first time rapid access to changes in shrimp abundances and spatial distributions in the area.

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ABSTRACT

This paper demonstrates how computer vision can be applied for the automatic detection of shrimp in smaller areas of interest with a high temporal resolution for long time periods. A recorded sequence of digital HD camera images from fixed underwater observatories provides unique opportunities to study shrimp behavior in their natural environment, such as number of shrimp and their abundance at different locations (micro habitats) over time. Temporal color contrast features were applied to enable the detection of the semi-transparent shrimp. To study the spatial–temporal characteristics of the shrimp, pseudo-color visualizations referred to as shrimp abundance maps (SAM) are introduced. SAMs for dif-
1. Introduction

A range of fixed long term underwater observatories (FUOs) equipped with a variety of sensors, e.g. digital cameras, have for some years become increasingly deployed (e.g. NEPTUNE Barnes et al., 2010, FixO3 Observatories, 2015, DELOS Vardaro et al., 2013, and LoVe Godøet al., 2014). FUOs constitute a rich collection of quantitative and qualitative data for high temporal resolution monitoring of smaller areas of interest over longer time periods. Basic knowledge of marine organisms living in their natural environment is scarce and FUOs provide a unique opportunity to gain general knowledge about the present species natural variations related to behavior, describing their spatial and temporal distribution in the various microhabitats covered by the camera frame (approximately 1–20 m²) over time. Information of such natural variation is essential for detecting long-term changes, seasonal fluctuations, sudden events, or possible impact from anthropogenic activities such as oil drilling activities (Nilssen et al., 2015). According to Mortensen and Fosså (2006) the quantitative species composition of a reef-associated fauna is hard to study using the traditional monitoring, where point samples of organisms are brought into the laboratory and individuals are counted. Most mobile species can escape during sampling and transport through the water column. In contrast to this, imaging provides unique non-destructive opportunities for establishment of general knowledge on species specific behavioral variations.

Behavior is commonly used as an impact parameter for organisms (Buhl-Mortensen et al., 2015; Anderson, 2000). Recently Buhl-Mortensen et al. (2015) performed a manual analysis of a limited number (203) of images recorded with a stationary digital camera in a cold-water coral reef to measure possible effects of water flow and drill cuttings particulates on polyp behavior of Lophelia pertusa. The increasing number of images recorded by FUOs, requires automated or semi-automated analytical systems to handle the vast amount of data (Nilssen et al., 2015). While some work has been published about computational segmentation of cold water corals (Purser et al., 2009; Tusa et al., 2014), computational segmentation of the associated fauna is scarce. One group of organisms that are present in high numbers in Norwegian reefs is the shrimp (Purser et al., 2013). Several shrimp species have been identified, dominated by Pandalus spp. (Jonsson et al., 2004; Mortensen and Fosså, 2006; Purser et al., 2013). Despite its documented presence shrimp abundance across microhabitats in cold water coral reefs has not been studied in detail (Purser et al., 2013). In contrast to sessile species (e.g. corals), moving species are more difficult to monitor, either by manual annotation or by computational approaches. Existing studies of image analysis applied on shrimp or morphological related species (Harbitz, 2007; Gorsky et al., 2010; Benfield et al., 2007) have removed the studied species from their natural habitat before imaging to gain optimized imaging conditions. The only paper we are aware of that considers computational in-situ shrimp detection uses shrimp eye reflection from the ROV (remotely operated underwater vehicle) lights in video images as a feature (Purser et al., 2013) and does consider the temporal context. In our study, the shrimp eye reflection approach could not be applied, as in the images of the FUO the shrimp eye contrast is not sufficient. Use of color for shrimp detection is challenging due to the shrimp semi-transparency. However, our temporal color contrast feature driven approach enables to handle the shrimp color variations. The method identifies and maps the distribution of shrimp in the microhabitats of a cold water coral reef automatically. The computed shrimp abundance is visualized as a shrimp abundance map (SAM).

2. Material

The fixed underwater observatory (FUO) LoVe1 (Lofoten—Vesterålen) is located in the north of Norway 22 km off the coast at a depth of approximately 260 m (N 68° 54.474’, E 15° 23.145’). The
The FUO is connected via cable to the mainland allowing a two-way communication (Godø et al., 2014). The connection also provides power supply to the different sensors mounted on the FUO, including a digital camera (Canon EOS 550D in a waterproof housing: METAS DSF5210) with a flash (METAS DSF4365) attached to an adjustable beam allowing to pan and tilt the camera. The camera is orientated to face a *Lophelia pertusa* coral reef with a camera angle of 45°. In European waters *Lophelia pertusa* is commonly the key reef building species (Freiwald et al., 1999). The multi-spherical structure creates niche for other species (Purser et al., 2013). The image frame was selected based on earlier studies (Mortensen and Fosså, 2006; Purser et al., 2013; Jonsson et al., 2004), indicating that the composition of the reef microhabitats (live corals, areas with bigger dead fragments and coral rubble where small coral fragments are mixed with sand). The distance between camera and coral reef is about 2–3 m (Godø et al., 2014). The imaged area is about 10 m², resulting in images with about $2 \times 10^6$ pixel (Godø et al., 2014). The FUO is recording images since September 2013 (Godø et al., 2014), except for a maintenance break from mid-June till the beginning of October 2014. The camera is recording one image every hour (temporal resolution: 1 image h$^{-1}$) with a resolution of $5184 \times 3456$ pixel and 8 bit per color channel. The data recorded by the FUO is publicly available after registration at http://love.statool.com. For our study we choose 1140 images which were collected in within 6 weeks (1st of May 2014 0:17:19 till 18th of June 2014 08:17:19). An example image is shown in Fig. 1. A small subset of $N = 80$ of these images was uploaded to the Bio-Image Indexing and Graphical Labeling Environment (BIIGLE) (Ontrup et al., 2009; Schoening et al., 2009) platform. Using BIIGLE on these $N$ images the positions of shrimp were manually marked with point labels using a computer mouse. These labels were used as a training set for our computational shrimp detection algorithm (see Chapter 3). Annotations are publicly accessible via https://ani.cebitec.uni-bielefeld.de/biigle/ with the username shrimp and the password shrimp under the area ”love” and transect ”May June Selection”. The annotators were allowed to place more than one point annotation on each shrimp, so that many shrimp are represented by a small cloud of marked points (Fig. 4). In total 3459 shrimp point annotations were made on the 80 images. In a previously performed experiment the intra observer agreement of one annotator was estimated. The annotator had to re-label 20 images after a time gap of four days, resulting in an agreement of 0.66 estimated on in total 3503 shrimp point annotations. This low agreement again motivates the need for an automation of the detection. Nevertheless, it indicates that shrimp can be identified in the images, as otherwise this agreement would have been much lower.

3. Methods

The different steps of the shrimp detection and location analysis presented in Fig. 2 are described in detail in the following subsections. After aligning the images spatially in the pre-processing (Section 3.1.1) temporal color contrast features are computed from the superpixel representation of the original image (Section 3.1.2). Using these features (Section 3.2), a supervised learning algorithm is trained using the 80 example images (Section 3.3). A pseudo color heat-map, referred to as shrimp abundance map (SAM) (Section 3.5), is derived from the positions found in all 1090 images to allow a first impression of the dynamics of shrimp positions.

3.1. Image pre-processing

In general, pre-processing of underwater images is essential, as these type of images often show a noticeable variation in illumination caused by changes in the camera–object distance. A variation in the object–camera distance will also affect the color of the objects in underwater images as the light attenuation is wavelength dependent. In this study no illumination or color correction was applied as

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2 The operation mode of the camera was changed for the second deployment and is now recording raw image data with 14 bit per color channel.

3 21 images of this time period had to be excluded or were not recorded.

4 The first 50 images of the 1140 images were only used to compute the first shifting median image, see Section 3.1.2.
Fig. 1. Example image collected at the 1st of May 2014 0:17:19. The camera is facing towards a cold water coral reef with a horizontal angle of 45° and is pointing 60° north. In the upper left part of the image mostly live corals can be found, in contrast to the lower right part where mostly dead corals appear. The three blurry patches in the right upper quadrant and in the lower middle were caused by biofouling, which stayed constant during the actual period.

Fig. 2. The computational shrimp detection and shrimp location analysis. Starting in the upper row from left with the image collection at the LoVe Barbados, image registration (Section 3.1.1) and shrimp annotation within BIBIGLE. Continuing with superpixel segmentation (Section 3.1.3), feature extraction (Section 3.2), machine learning (Section 3.3) (middle row), automated shrimp detection (Section 3.4) and visualization of the spatial shrimp distribution over time in a shrimp abundance map (Section 3.5) (lower row).

The image collecting setup is stable in this regard. The object–camera distance is steady and relatively short, i.e. 2–3 m (Godø et al., 2014) (Fig. 1). The artificial illumination is evenly distributed throughout the whole image and for the total set of images. In order to use the high likeliness of shrimp movement between two images (i.e. one hour time lag) as a feature for discrimination between shrimp and non-shrimp.
shrimp, all images need to be registered (i.e. spatially aligned) as the camera is slightly shifted by the present current speed and direction.

3.1.1. Image registration
All 1140 images (height \( H = 5184 \) pixels, width \( W = 3456 \) pixels) are registered to the first image \( I^{(0)} \), the so called reference image, collected on 1st of May 2014 0:17:19 to compensate the small camera shiftings. \( I^{(0)} \) is initially cropped by 50 pixels on all four image borders, allowing a shift of maximal 50 pixels in all four directions for the following images, the so called moving images. The best alignment shift is computed, using the Canny edge (Canny, 1986) map \( E^{(n)} \) of image \( I^{(n)} \) with a low threshold of 30 and a high threshold of 90. Each image \( I^{(n)} \) is transformed to a new registered version \( \hat{I}^{(n)} \) using a transform function \( \psi \), i.e.

\[
\hat{I}^{(n)} = \psi(I^{(n)}; (x^{\text{best}}_n, y^{\text{best}}_n)),
\]

using a transform function \( \psi \), i.e. \( \psi(I; x, y) = A \in \mathbb{R}^{(W-100) \times (H-100)} \) with \( A_{j,k} = I_{50+j,x-50+k-y} \) that (i) reduces the width and height of the image (see cropping instructions above) and (ii) shifts all pixels by the vector \((x, y)\). The optimal shifting parameters \((x^{\text{best}}_n, y^{\text{best}}_n)\) are computed as

\[
(x^{\text{best}}_n, y^{\text{best}}_n) = \arg \max_{(x,y) \in (-50,...,50)^2} \left\{ \sum_{j,k} (\psi(E^{(n)}, x, y))_{j,k} \cdot (\psi(E^{(n)}, 0, 0))_{j,k} \right\}.
\]

3.1.2. Temporal color contrast features
Shrimp are semi-transparent, which causes a color variation of the individual shrimp dependent of the background color. To enhance the contrast between shrimp and background we propose to include this in a feature representation at a pixel \((x, y)\), the temporal color contrast feature \( C_{(x,y)}^{(n)} \) is computed for each pixel in the CIELab color space (Schanda, 2007) by \( C_{(x,y)}^{(n)} = \hat{I}_{(x,y)}^{(n)} - \hat{I}_{(x,y)}^{(0)} \),

\[
(2)
\]

where \( \hat{I}_{(x,y)}^{(n)} \) is the floating median image.

The floating median image \( \hat{I}^{(n)} \) is also computed in the CIELab color space, resulting in an image including only sessile objects and thereby an image without shrimp (Fig. 3, lower left).

\[
\hat{I}_{(j,k)}^{(n)} = \hat{I}_{(j,k)}^{(0)},
\]

where the position of the median computed on the luminance part of the CIELab color space gives the image pixel \( \hat{I}_{(j,k)}^{(0)} \) used as the pixel \((j, k)\) for the median image:

\[
m_{j,k} = \arg \max_{m=50,...,50} \left\{ \hat{I}_{(m,k)}^{(0)} \right\}.
\]

The result can be visualized as a contrast map \( C^{(n)} \) by computing

\[
C^{(n)} = \frac{\hat{I}^{(n)} - \hat{I}^{(0)}}{2} + 127 (\text{Fig. 3, lower right}).
\]

3.1.3. Super-pixel segmentation
All images \( \hat{I} \) are pre-segmented using the SLIC (Simple Linear Iterative Clustering) superpixel algorithm (Achanta et al., 2012) with a feature weight of 40 and a step size of 20 pixels, as shown in Fig. 4. The superpixel segmentation enables a reduction of the number of feature extraction points. Instead of extracting features on e.g. overlapping quadratic regions, image information of local pixel similarities is used to find regions for feature extractions. The superpixel size was optimized to cover the size variation of the shrimp, resulting in a size of one superpixel for the smallest shrimp.
Fig. 3. Visualization of the pre-processing steps from the original image to the shrimp contrast map. In the upper left the original image $I$ can be found. In the upper right the registered image $\tilde{I}$ (see Eq. (1)) is displayed, which is slightly shifted. In the lower left the median image $\hat{I}$ (see Eq. (3)) is shown, where no moving objects like the shrimp can be found. In the lower right the shrimp contrast map $C$ (see Eq. (4)) is displayed.

Fig. 4. SLIC (Simple Linear Iterative Clustering) superpixel segmentation is applied and shown for one example image. White contours outline the superpixel areas. In the zoomed area examples for annotations of a shrimp (blue color) can be found, visualizing multiple annotations per shrimp. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Table 1 Description of the features.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\bar{I}_a), (\bar{I}_b)</td>
<td>Lab mean values computed from (I)</td>
</tr>
<tr>
<td>(h_{a,0}, \ldots, h_{a,15})</td>
<td>Lab 16 bin histogram values computed from (I)</td>
</tr>
<tr>
<td>(\bar{C}_a), (\bar{C}_b)</td>
<td>Lab mean values computed from (C)</td>
</tr>
<tr>
<td>(h_{c,0}, \ldots, h_{c,15})</td>
<td>Lab 16 bin histogram values computed from (C)</td>
</tr>
</tbody>
</table>

Fig. 5. Illustration for the post-processing of the output of the Random Forest (RF) shrimp classification. (a) has a superpixel size of one and will therefore be excluded. (b) has a superpixel size of five and therefore fulfills the size criteria while (c) will be excluded as it is too big (11 superpixels).

3.2. Feature extraction

Features are extracted for each superpixel \(s_i\) on \(I^{\text{sh}}\) and corresponding \(C^{\text{sh}}\) represented by a feature vector \(\mathbf{x}_i\). These 38 features are mean values and histogram values (16 bins) in the CIELab color space (see Table 1). A label \(l_i \in \{1 = \text{shrimp}, -1 = \text{no shrimp}\}\) is assigned to each feature vector \(\mathbf{x}_i\) referring to the corresponding superpixel. All 38-dimensional \(\mathbf{x}_i\) are thus either labeled shrimp if one or more shrimp point labels were placed in the area of the corresponding superpixel or not shrimp otherwise.

3.3. Machine learning

For the automated detection of shrimp the supervised classification algorithm Random Forest (RF) (Breiman, 2001) was selected. The algorithm allows to use a smaller training set, compared to e.g. the Deep Learning algorithms like Convolutional Neural Networks (LeCun et al., 1998). Furthermore it is very robust against overfitting and can also be used to compute the feature importance (Fig. 14). The RF is trained and tuned using a stratified four-fold cross validation (Kohavi, 1995). Therefore the set of 80 annotated images is divided into four different sets of training and test images. The RF is trained on the labeled feature vectors \((\mathbf{x}_i, l_i)\) of the training set of images. The training parameters of the RF are tuned on feature vectors and their corresponding label belonging to the test set of images and were varied for the maximum tree-depth \(5, 10, 20, 50, 100, 150\), the maximum number of trees in the forest \(100, 500\) and the minimum sample count \(5, 10, 20\). The class-weights for the shrimp class were also varied \(2, 5, 10, 100\). Other parameters were not varied, resolving in a training of in total 144 different RFs.

3.4. Post-processing

To optimize the classification performance the classification output is post-processed using a size criterion. Connected superpixels, referred to as regions \(r_i^{\text{sh}}\), that are all classified to be shrimp forming a shrimp region of size \(|r_i| = \# \text{connected superpixel}\) are filtered to be in range of \(|r| > 1\) superpixel, \(|r| < 11\) superpixel, excluding very small \(|r| = 1\) and very large regions \(|r| > 10\) of shrimp classifications (Fig. 5).
3.5. Shrimp abundance map

The shrimp abundance map (SAM) visualizes the spatial distribution of the shrimp over a defined time-period $T$. The cold water coral reef scene is divided into a grid of equal sized quadrants $q$ (width = 120 pixels, height = 120 pixels). For the quadrants $q_n$, the relatively shrimp abundance $\alpha$ is visualized using a heated object color scale with 9 levels (9-class VIOOrd (Brewer, 2013, 1999)). The color scale is starting at dark red for the lowest abundance and ending at a light yellow for the highest abundance (e.g. Fig. 10, on the right). The relative shrimp abundance is computed as

$$\alpha_n = \log_2 \left( \frac{\gamma_n - \min_{n'} \gamma_{n'}}{\max_{n'} \gamma_{n'} - \min_{n'} \gamma_{n'}} + 1 \right),$$

where $\gamma_n$ is the shrimp abundance for the quadrant $q_n$

$$\gamma_n = \sum_{n \in T} |o_i| \text{ with } s_i \cap q_n \neq \emptyset.$$  

An average image of the images of the visualized time-period is used as a background image (Fig. 10).

3.6. Accuracy assessment

The assessment of an image analysis system’s accuracy can be a complex subject. In general manual annotations of image samples are compared with classification outputs obtained for the same data and grouped into true positives (TPs), false positives (FPs), false negatives (FNs) and true negatives (TNs). In this two-class classification problem, here shrimp vs. not shrimp, matches of positive manual annotations and positive classifications are counted as TPs, positive manual annotations with a negative classification output are counted as FNs and positive classification outputs which were not annotated (i.e. not shrimp label) are counted as FPs. True negatives are not considered as no manual negatives (i.e. not shrimp) were annotated explicitly.

The exact pixel location of the annotation (point labels are used in this study) though is more or less random in a certain extend across the object of interest (OOI), i.e. the shrimp in this case, which is intended to be annotated, as the OOI has a spatial extent, not to mention that the use of a computer mouse also comes with accuracy limitations. This brings up the problem that a classification output can be counted as a FP and the annotation as a FN, although both are located on the same OOI, but not on the exact same pixel location. For the purpose of identifying the spatial distribution of shrimp over time, it is sufficient enough to detect only parts of a shrimp, as long as for each shrimp a part e.g. the tail is detected. A solution can be to allow limited distances between annotations and classification output, allowing a neighboring positive annotation to count as a true positive (TP) (Fig. 6(b)).

We therefore create a binary mask image $B_{oi}^{nm}$ from the labels $l_{oi}^{nm}$ and a separate one $B_{qi}^{nm}$ from the positive RF outputs $q_{oi}^{nm}$ and compare them to determine TP, FP and FN counts.

$B_{oi}^{nm}$ is a binary image, where pixel values are set to $B_{oi}^{nm} = 1$ if the corresponding superpixel label holds $l_{oi}^{nm} = 1$ (i.e. a shrimp label) and $B_{oi}^{nm} = 0$ otherwise. $B_{qi}^{nm}$ is a binary image, where pixel values are set to $B_{qi}^{nm} = 1$ if the classification output holds $q_{oi}^{nm} = 1$ for the corresponding superpixel (i.e. shrimp) and $B_{qi}^{nm} = 0$ otherwise. The morphological image-dilation function $\phi$ is applied to $B_{oi}^{nm}$ allowing a neighboring positive annotation to count as a true positive (TP) (Fig. 6(b)). The $B_{qi,0}^{nm}$ is evaluated for all connected regions $r_{oi}^{nm}$. Each connected region $r_{oi}^{nm}$ is counted as a TP, if parts of it are marked in $B_{qi,0}^{nm}$...
Fig. 6. Patches from an evaluation image \( B^n_O \) computed for the accuracy assessment of the shrimp detection. (a), (b) displaying both true positives (TPs). Please note that (b) is counted as a TP due to the dilation rule (see text for details). (c) is displaying a false positive (FP) and (d) a false negative (FN). Pixel values are coded in red for pixels only marked in the binary classification output image \( B^n_O \), in blue for pixels only marked in the binary label image \( B^n_L \) and in pink for pixels marked in both. White contours illustrate the superpixel areas. The effect of the dilation function is also visible as a small border around the superpixel classified as shrimp. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and \( \phi(B^n_O) \), as a false positive (FP) if the region is only marked in \( \phi(B^n_O) \) and as a false negative (FN) if \( r^n_m \) is only marked in \( B^n_O \) (Fig. 6).

TP, FP, and FN are finally used to calculate the precision and the recall for the shrimp classification system. The precision is measuring the number of correct identified shrimp over all shrimp detections:

\[
\text{precision} = \frac{\text{TP}}{\text{TP} + \text{FP}}. \tag{6}\]

The recall is measuring how many of the annotated shrimp are correctly identified to be shrimp by the Random Forest (RF):

\[
\text{recall} = \frac{\text{TP}}{\text{TP} + \text{FN}}. \tag{7}\]

The \( F_1 \) score is computed and used to optimize the classification system, to weight precision and recall equally, i.e. the harmonic mean between both:

\[
F_1 \text{ score} = 2 \cdot \frac{\text{precision} \cdot \text{recall}}{\text{precision} + \text{recall}}. \tag{8}\]

Based on the assumption that the ground truth is correct, i.e. no shrimp are overseen and no “none shrimp area” is labeled as shrimp, the best accuracy would be a precision of 1 and a recall of 1 resulting in an \( F_1 \) score of 1.

4. Results

The results of the applied previous described methods are presented in the following sections.

4.1. Registration

The registration was evaluated by visual inspection of a rendered time-laps video. This showed that the registration process reduced the shift between the images, even though the applied method does not correct for a rotation.

4.2. Superpixel segmentation

The superpixel segmentation was evaluated manually using visual inspection. Most of the shrimp were segmented into several superpixels (Fig. 4) and only a few very small shrimp were covered by only one superpixel. In a re-inspection of these one superpixel sized shrimp we observed a low level of reproducibility in the manual annotation of the shrimp-like objects. Shrimp positions were marked in the training set to consider this phenomenon in the following accuracy assessment.
The parameters of the Random Forest classifier are optimized using a stratified four-fold cross validation. The results averaged of the four-fold cross validation for training and test image sets are given here. The performance of the Random Forests is measured by recall, precision and $F_1$ score using the assessment method presented in Section 3.6.

<table>
<thead>
<tr>
<th></th>
<th>Precision</th>
<th>Recall</th>
<th>$F_1$ score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training</td>
<td>0.48</td>
<td>1</td>
<td>0.64</td>
</tr>
<tr>
<td>Test</td>
<td>0.69</td>
<td>0.52</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Table 3: Results of the manual re-evaluation of the test images (Re-ev. test), including the results from the previous automated evaluation of the test images (Test). The manual re-evaluation was performed with the conservative ground truth (see text for details).

<table>
<thead>
<tr>
<th></th>
<th>Precision</th>
<th>Recall</th>
<th>$F_1$ score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>0.69</td>
<td>0.52</td>
<td>0.59</td>
</tr>
<tr>
<td>Re-ev. test</td>
<td>0.77</td>
<td>0.91</td>
<td>0.84</td>
</tr>
</tbody>
</table>

4.3. Accuracy assessment of the shrimp detection

The accuracy assessment described in Section 3.6 was applied to optimize the training parameters of the RF to give the highest $F_1$ score. In Table 2 averages for precision, recall and $F_1$ score of the four-fold cross validation for the best RF parameters are given. The best $F_1$ score was achieved with a tree-depth of 50, a minimal sample count of 20, 10 active variables, a shrimp class weight of 10, a maximal number of trees of 100 and an out of bag error of 0.001 (the last two both used as termination criteria during the training).

Manual annotation can be very error-prone (Schoening et al., 2012; MacLeod et al., 2010). Some shrimp will be likely to be overseen during the manual annotation process, as it is expected that the performance of the annotator will vary, as we have reported in our intra-observer study (see Section 2). The classification outputs were therefore manually re-evaluated region wise (Fig. 8). Since we observed a rather low reproducibility for a number of small shrimp (see Section 4.2) we re-evaluated the computational results with a second, more conservative ground truth: connected regions in $B^{(n)}$ were excluded if they only consist of one superpixel (Fig. 7). This resulted in an improved $F_1$ score of 0.84 (see Table 3).

4.4. Shrimp abundance maps (SAM)

The number of detected shrimp in each image over the analyzed time period is displayed in the chart of Fig. 9. The locations of the automated detected shrimp in each image were used to generate shrimp abundance maps (SAMs) for different time scales and periods. Fig. 10 displays the relative shrimp abundance of all 1090 analyzed images (3rd of May 2014 02:17:19 till 18th of June 2014 08:17:19). In Fig. 11 a SAM obtained by analyzing images recorded at day time between 8 am and
5. Discussion

A computer vision approach for the automated detection of shrimp in *Lophelia pertusa* reef has been established. The relative spatial abundance of shrimp over time can be visualized in SAMs and allows the identification of behavioral changes in an intuitive way.

The application of superpixel algorithm for pre-segmentation accelerated the automated detection and provided a reasonable criterion (\(|r|\)) to filter manual annotations and automated classifications.
Fig. 10. The shrimp abundance map (SAM) visualizing the spatial shrimp distribution from early May (3rd of May 2014 02:17:19) till middle of June 2014 (18th of June 2014 08:17:19). The color scale is displayed on the right starting with dark red for the lowest relative shrimp abundance $\alpha_m$ (Eq. (5)), continuing to red and orange indicating a higher relative shrimp abundance and ending at a light yellow for the highest relative abundance over time. [For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.]

Fig. 11. Two shrimp abundance maps (SAMs) comparing the relative shrimp abundance at day time between 8 am and 8 pm (left) with the relative shrimp abundance at night time between 8 pm and 8 am (right) for the time period early May till middle of June 2014 (3rd of May 2014 02:17:19 till 18th of June 2014 08:17:19).

Fig. 12. Two shrimp abundance maps (SAMs) comparing the relative shrimp abundance at 11th of May (left) with the relative shrimp abundance at 18th of May (right).

Using the temporal color contrast feature enabled to discriminate between shrimp and not shrimp, as it combines information from previous recorded images with the current image. This improvement of the ability was validated using a method introduced by Osterloff et al. (2014), comparing different
Fig. 13. Two shrimp abundance maps (SAMs) comparing the relative shrimp abundance of the first 3 weeks (3rd of May 2014 02:17:19 till 25th of May 2014 21:17:19) (left) with the relative shrimp abundance of the next three weeks (25 of May 2014 22:17:19 till 18th of June 2014 08:17:19) (right).

Fig. 14. The feature importance for the best Random Forest. The importance for each variable is displayed, differentiating between features computed on $\tilde{I}$ colored in blue and features computed on $C$ colored in green. A slightly higher importance for features computed on $C$ can be observed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

image processing methods, and by evaluating the feature importance of the best RF (total importance of 0.59 for $C$ and total importance of 0.41 for $\tilde{I}$) (Fig. 14). However, features computed on $\tilde{I}$ were not excluded, since it would have lowered the accuracy, as their importance was still high.

The $F_1$ score of 0.84, estimated in the manual re-evaluation, confirms that we established a reliable classification system. During the manual re-evaluation it was also observed that most of the remaining FPs were parts of relatively big objects like legs and body parts of crabs, parts of sea urchins, sea lilies and basket stars. Detection sensitivity is dependent on local image quality. Non illuminated areas of the images like holes or shadows, caused by the multi-spherical structures of the coral reef, lead to a lower detection sensitivity. However, as long as the camera position is fixed, we can presume that this effect is constant over time. Obviously the dark spot areas caused by the multi-spherical structure and light settings, must be handled with care, if someone wants to compare results from different FUs.

The presented system computes shrimp abundance charts for evaluation of the number of visible shrimp per image and SAMs for visualization of the relative spatial abundance in the same images over time. Qualitative differences and similarities can be recognized in an intuitive way e.g. in Figs. 12 and 11, respectively. The visual differences between the relative shrimp abundance of the first three weeks and the following three weeks (Fig. 13), noticed during a manual inspection, were caused by some FP classification of sea lilies, which moved in the field of view in the second time period. Therefore, in the next development stage of the system, a pre-detection of big objects (in relation to the shrimp) is advised. Also, an exclusion of images with very low visibility, e.g. caused by high turbidity, in the
pre-processing would increase the reliability of the system. Furthermore, varying inherent optical properties (dissolved organic material, plankton and inorganic particulates) of the water will change the attenuation of light, impacting color and contrast of the images and might affect the detection sensitivity, as well. Although no such changes were recognized during the analyzed time period, it should be considered in the pre-processing of an improved system. Variations in the inherent optical properties may cause the shrimp to occur over time. The results from the present study show predominantly higher shrimp abundance in the live coral parts compared to the coral rubble or sediment parts of the image. This distribution corresponds to the findings of the study by Purser et al. (2013). The shrimp distribution will be investigated in detail in future studies, following statistical analysis of the manual annotation sensitivity and automated detection performances on both areas. As in the study by Purser et al. (2013), no attempt was made in the present study to identify shrimp down to species level.

Reliable classification of shrimp requires additional physical sampling and no such sampling has so far been performed on the LoVe observatory. Even though a more detailed manual classification of the shrimp from the images might be possible with additional sampling, automatic separation at the present state is not achievable due to shrimp similarity and image resolution.

Knowledge of natural variations is essential to perform a sound environmental monitoring (Nilssen et al., 2015). Our next step will be to apply the method described in the present paper on a larger dataset to investigate possible seasonal and yearly variations in the shrimp abundance. Furthermore, we will try to correlate natural variations with the other measured variables, such as turbidity and current speed and direction, available from the LoVe ocean observatory.

Acknowledgment

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References


Paper IX

Change Detection in Marine Observatory Image Streams using Bi-Domain Feature Clustering

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Abstract—Vision based environmental monitoring using fixed cameras generates large image collections, creating a bottleneck in data analysis. In areas with limited background knowledge of the monitored habitat, this bottleneck can often not be overcome by traditional pattern recognition methods. A new change detection method uses the new Bi-Domain Feature Clustering (BDFC). BDFC integrates the location of a feature vector in the feature space as well as the location in the image into the clustering. First, BDFC is applied to a time dependent representation of the image stream to identify regions of similar change. Secondly it is applied to a time independent representation to group these changes into categories. These categories can rapidly be assessed by a human observer to bypass the time consuming inspection of the whole data set. To make the posterior browsing of detected changes more efficient, a relevance factor computed for each category is proposed.

The approach is demonstrated with experimental runs, using images from the Lofoten Vesteralen ocean observatory, showing the potential to harvest changes of interest and novelties in large image collections.

I. INTRODUCTION

Change detection is a commonly used approach to evaluate images taken from a fixed position, and has already been of great interest in a variety of scientific fields [1] such as video surveillance (e. g. traffic) [2]-[5] and remote sensing [6]-[16] (e. g. deforestation monitoring or monitoring of destruction/construction in urban areas). In the context of underwater imagery applications are still limited [17]-[22]. The two most common change detection approaches are background subtraction (BS) and change vector analysis (CVA). BS aims at building and maintaining a background model of the investigated images and then thresholding the difference between the background model and a target image. Lots of efforts have been put into background maintenance as well as in computing a suitable threshold for the pixel differences. CVA methods basically compute the difference image between two images before analyzing the vectors of the difference image (so-called change vectors). Whereas most change detection algorithms compute a binary output by assigning each pixel to either true or false, indicating that changes have occurred or not, some algorithms subdivide the set of changed-pixels into various subclasses.

In [12] and [13] the authors introduce CVA algorithms detecting and categorizing changes based on the length and the direction of each change-vector, respectively. Other change detection algorithms that do not fall within the two categories described above are for instance based on temporal predictive models [23]-[25], significance tests [26] or slow feature analysis [27]. However, all these methods require a human observer to identify changes of interest in a threshold image or a set of transformed images representing changes.

In recent years, a growing number of fixed long-term underwater observatories (FUO, [28]-[30]) have been deployed to monitor marine habitats. The FUO are in most cases deployed in areas of particular interest, such as areas with high biodiversity. The biological diversity and abundance of species present at these sites represent considerable challenges to a change detection approach:

1. Prior knowledge about which species to find in the monitored areas and/or how they behave is often limited and can therefore not be used in the design of a change detection method.
2. As some species occur and/or move much more frequent than other species, change detection in pixel values only is not sufficient to detect relevant changes in the monitored scene.

The contribution of this paper is to introduce a new approach to detect various changes in an area with very limited a-priori knowledge. The approach includes the concept of super-pixel segmentation in feature space and the new Bi-Domain Feature Clustering (BDFC). In contrast to existing methods, this approach finds regions of similar change patterns, groups all detected regions into categories and ranks the categories according to a proposed relevance based on frequency and pixel differences.

II. METHODS

The aim in the analysis of images from an FUO is the identification of regions of interest as connected components with similar change patterns. As similar changes and patterns are expected at different time-points, the similarity of change features at different time-points must be considered as well. The proposed framework (Fig. 1) integrates these aspects by
computing two feature representations (Section II-B). The new clustering procedure (Section II-A) is used to cluster the time dependent change features and the time independent change features, respectively. Regions showing similar change patterns are identified using the time dependent change features. The regions are assigned to clusters of the time independent features, which represent categories of change.

The method assumes that all images are in CIELUV [31] color space. Moreover, we assume that the images are taken with the same fixed camera at all time-points implying that all color space. Moreover, we assume that the images are taken in independent features, which represent categories of change.

The regions are assigned to clusters of the time dependent change features and the time independent change features, respectively. Regions showing similar change are identified using the time dependent change features and the time independent change features, respectively. Regions showing similar change are identified using the time dependent change features and the time independent change features, respectively. Regions showing similar change are identified using the time dependent change features and the time independent change features, respectively. Regions showing similar change are identified using the time dependent change features and the time independent change features, respectively. Regions showing similar change are identified using the time dependent change features and the time independent change features, respectively. Regions showing similar change are identified using the time dependent change features and the time independent change features, respectively. 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prototype in the H²SOM clustering result:

$$I^B_\ell(p) = \arg \min_{1 \leq \ell \leq L} \{ |F^2_\ell(p) - u^B_\ell| \}$$

A visualization of the H²SOM result can be found in Figure 2.

To take the proximity of cluster indices in $I^B_\ell$ into account during the cluster merging procedure in step (ii), let

$$\Omega_A^\ell = \{ p \in \mathcal{P} | I^B_\ell(p) = \ell \}$$

for every cluster index $\ell$. Let $r \in \mathbb{R}$ with $r \geq 1$ ($r = 10$ in this study). We call two pixels $p, q$ close, if and only if $d_{\infty}(p, q) \leq r$. With

$$\Omega_{A}^{\ell,k} = \{ (p, q) \in \mathcal{P}^2 | p \in \Omega_A^\ell, q \in \Omega_A^k, d_{\infty}(p, q) \leq r \}$$

we define the image proximity of two clusters $\ell$ and $k$ by

$$\phi_A^\ell(k) = \frac{\sum_{(p, q) \in \Omega_{A}^{\ell,k}} 1 - \frac{d_{\infty}(p, q)}{r}}{|\Omega_A^\ell| + |\Omega_A^k|}.$$  \hspace{1cm} (3)

Note that the choice of the parameter $r$ is not crucial for the cluster merging, but the restriction of the sum in the denominator of $\phi_A(k, k)$ increases the computation speed of $\phi_A(k, k)$. We use the parameter $n \in \mathbb{N}$ to control the number of clusters merged in the merging process. In this paper, we set the parameter to $n = 5$. We define three conditions to be fulfilled so two clusters with indices $\ell$ and $k$ are merged:

(A) $\ell$ is neighbor of $k$ in the H²SOM grid-topology, i.e. $\ell \in \mathcal{N}_A(k)$

(B) the Euclidean distance $d_{\infty}(u^A_{\ell}, u^A_k)$ is one of the lowest $n$ distances $d_{\infty}(u^A_{\ell}, u^A_{k'})$.

(C) the image proximity $\phi_A(k, k)$ is one of the highest $n$ image proximities $\phi_A(\ell, \cdot)$

The clusters are merged iteratively, as described in algorithm 1, until no clusters satisfy (A), (B) and (C). A visualization of the final result of the BDFC-algorithm is shown in Figure 2.

**B. Feature extraction**

Let $(I_1, \ldots, I_T)$ be an image sequence and let the mean image $\overline{I} = 1/T \cdot (I_1 + \cdots + I_T)$ model the background of the scene. To compute change features, we compute a new representation $\tilde{J}_t$ from each image $I_t$, encoding the pixel differences to the mean image: $J_t(p) = |\overline{I}(p) - I_t(p)|$ ($\forall p \in \mathcal{P}, 1 \leq t \leq T$). To account for external effects having impact on the whole image (e.g. change in lighting) we standardize each channel $J^c_t$ ($c \in \{1, 2, 3\}$) of an image $J_t$, i.e. we define $\tilde{J}_t^c(p)$ to be the standard score of $J^c_t(p)$.

To separate trend (i.e. long term signal change) from fluctuation (i.e. short term signal change) we apply wavelet transformation [38] using a Daubechies filter [38]. With $W_T$ and $W_F$ the trend and the fluctuation computed by the wavelet transformation and $\tilde{x}$ the concatenation of vectors (i.e. $(x_1, x_2) \rightarrow (x_1, y_2) = (x_1, x_2, y_1, y_2)$), we define the feature map $\mathcal{F}_{\text{map}}$ by

$$\mathcal{F}_{\text{map}}(p) = W_T(\tilde{J}^1(p)) - W_F(\tilde{J}^3(p)) \hspace{1cm} (4)$$

**Algorithm 1:** Clusters are merged until no pair of clusters exists that satisfies the conditions (A), (B) and (C). When $I$ is merged to cluster $k$, $u^B_k$ is set to the weighted mean of the cluster centers. Moreover cluster $k$ absorbs all neighbors of $I$ in the H²SOM-topology as well as all pixels former associated to $I$. 

```plaintext
while found_clusters_to_merge == true do
    found_clusters_to_merge = false
    for 1 ≤ k < l ≤ L do
        if (A) and (B) and (C) then
            found_clusters_to_merge = true
            $u^B_k = \frac{|\Omega_A^l| u^B_l + |\Omega_A^k| u^B_k}{|\Omega_A^l| + |\Omega_A^k|}$
            $\mathcal{N}_A(k) = \mathcal{N}_A(l) \cup \mathcal{N}_A(\ell)$
            $I^B_{\mathcal{N}_A}(p) = k \forall p \in \mathcal{N}_A$
        end
    end
end
```

Fig. 2. The BDFC is illustrated for the time independent feature representation. Features are extracted from an image sequence and clustered by a H²SOM [35]. Pixels belonging to one object (see the magnified starfish) are initially assigned to different clusters, as indicated by nine shades of purple/blue in the visualization ([36], [37], middle). White contours have been drawn between pixels of the starfish that belong to different clusters, to bring out the fragmentation of the starfish. After cluster merging (right) based on proximities in the image and feature domain, most pixels of the starfish belong to one cluster.
regions are classified into categories and since a particular change pattern are computed. These time-points where changes occur are determined for every region in \( R \) is assigned to a change category \( \kappa(R) \) by

\[
\kappa(R) = \arg \max_{1 \leq k \leq K} \left| \{ p \in R | \mathcal{F}_\text{int}(p) = k \} \right|. \tag{7}
\]

Having regions and categories defined, an index is assigned to every category that estimates the degree of importance for a change. Without knowledge about the experts’ preferences, we define the relevance based on frequency and pixel differences. With the mass center \( m \) of the categories defined by

\[
m = \frac{1}{|R|} \sum_{1 \leq k \leq K} \left| \{ R \in \mathcal{R} | \kappa(R) = k \} \right| \cdot u^\text{int}_k \tag{8}
\]

This allows us to rank the categories \( C_k \) according to the computed relevance. To further facilitate the non-automatic posterior browsing, we propose additional filters like the well-defined) pixels in the 8-connected neighborhood from \( p \) that lie on the line through \( p \) perpendicular to \( B \). Note that one of the pixels \( i_p \) and \( o_p \) is inside \( R \) and one is outside \( R \). We define the coherency of \( B \) to \( I \) by

\[
d^{B,I} = \frac{1}{|B|} \sum_{i_p \in B} d_1(I_i(i_p), I_i(o_p)) \tag{9}
\]

In order to find all time-points where changes occur in the region \( R \), we compute a threshold \( \tau \) from the sequence \( d^{B,1}, \ldots, d^{B,T} \). Let \( \sigma_R \) be the permutation that brings the sequence \( d^{B,1}, \ldots, d^{B,T} \) in ascending order, i.e.

\[
d^{B,\sigma_R(t)} \leq d^{B,\sigma_R(t+1)} \quad \forall 1 \leq t \leq T - 1. \tag{10}
\]

With

\[
m = \arg \max_{1 \leq t \leq T-1} d^{B,\sigma_R(t)} - d^{B,\sigma_R(t+1)}, \quad \text{and} \quad \tau = \frac{d^{B,\sigma_R(m)} + d^{B,\sigma_R(m+1)}}{2} \tag{11}
\]

we say change occurs at time-point \( T \), if and only if \( d^{B,T} > \tau \).
III. RESULTS

We evaluate our method on images of the Lofoten-Vesterålen (LoVe) ocean observatory [30]. LoVe is a fixed marine observatory monitoring a coral reef in the Norwegian Sea (N 68° 54.474′, E 15° 23.145′). The observatory that was deployed in October 2013 takes one image every 60 minutes. All images are available online at http://love.statoil.com/. In the present paper, we evaluate the results of the algorithm applied to 6 data sets. Each data set is a sequence of 24 images (one day). We use the same parameter settings for each data set: The superpixel segmentation was performed setting the weight factor (Section II-A) to 8 and the number of superpixels to $M = 12800$ corresponding to a superpixel-size of 80 pixels in average. For the H$^2$SOM clustering, the H$^2$SOM with 3 rings and spread factor 8 was trained with a random set of $0.25 \cdot M$ samples. The tolerance and the radius used during cluster merging (Section II-A) were set to 5 and 10, respectively. For the wavelet transformation in the feature extraction (Section II-B), we use Daubechies Filter of length 6. See Section IV for more information on the wavelet transformation. As proposed in Section II-C, we apply additional filters to the categorized regions: A region $R^i_l$ of pixels mapped to the cluster center $u^i_{tmp}$ is considered in the evaluation if and only if (i) the size of the region is at least 400 pixels and (ii) $|u^i_{tmp}| \geq 0.2 \cdot \max_{1 \leq l \leq L} |u^i_l|$.

As an example Figure 4 shows changes identified by the algorithm in 2 of the six data sets.

Figure 5 shows the precision of the algorithm in 6 data sets, each represented by one graph. Each of the $N$ changes identified by the algorithm was evaluated manually either as relevant or irrelevant. For $1 \leq n \leq N$ we denote by $t(n)$ the number of true positives, i. e. the number of changes within the $n$ most relevant changes that are labeled manually as relevant. The precision is computed as $P(n) = t(n)/n$ and plotted against $n/N$. Note that the recall of the method was not computed, as manual detection of all relevant changes is not feasible due to the high abundance of changes in the given image sequences and the absence of a ground truth. However, most regions of the visual field are considered in the graphs and the method assigns a high relevance factor to most true positives. This indicates that most changes of interest belong to the most relevant changes identified by the proposed method.

IV. DISCUSSION AND CONCLUSION

In this paper we have presented a change detection method including the new BDFC algorithm, which shows the potential to be used in various future image processing tasks. The change detection method categorizes and orders various changes present within a fixed image frame by their relevance. Thereby, the method enables the identification of a variety of different changes such as presence and movements of species within images from a fixed position over time. The


Paper X

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- two case studies from marine sciences and engineering.
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Images in environmental monitoring: Enhanced knowledge through interdisciplinary collaboration
– two case studies from marine sciences and engineering

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Abstract

Images are increasingly being used for documentation of the marine environment. Based on humans shared cognitive capabilities in detecting and classifying objects and movement, we argue that imaging technologies have the potential of acting as a communicative tool (boundary object) for a general understanding of the environment, including communication and collaboration. Solutions on how interdisciplinary collaboration on image processing can contribute to utilise the images inherent knowledge to overcome the human limitations in perceiving objects and movements other than human’s in time and space are proposed. Two case studies from the marine environment are used to illustrate the additional knowledge that can be gained from images through interdisciplinary collaboration. The cases are related to environmental monitoring and modelling, discussing abilities and challenges related to temporal and spatial resolution, respectively. Furthermore, future potential use of images in decision making processes is discussed.

Keywords: Images; environmental monitoring; interdisciplinary approach; communicative tool
1. Introduction

In 1998, Science published an article on the concept of the “third culture”; use of technology stating that “… technology generates opportunities: new things to explain; new ways of expression; new media of communications …” (Kelly, 1998). Furthermore, “The third culture creates new tools faster than new theories, because tools lead to novel discoveries quicker than theories do”. This rapid development of enabling technology gives a possibility to acquire a more holistic understanding of the environment and environmental phenomenon (Nilssen et al., 2015a). On the other hand, according to the technology philosopher Don Ihde, the applied sensor technology used determines what we see (Ihde, 1979; Ihde, 1991). From this perspective the rapid technology developments are challenging the human ability to interpret and understand the data provided in an efficient and effective manner. The limited experience with continuous new types of technologies might therefore affect our ability to integrate and transform all these new measurements into new knowledge, which in its turn is used in applications such as models, risk management or as basis for decisions in general.

The more information gathered with various new technologies and technology applications and the more acquired knowledge, it has become clear that complex environmental problems cannot be solved without an effort from interdisciplinary teams of experts (Brown et al., 2015; Rylance, 2015; Wuchty et al., 2007). This statement is valid for interpretation of complex datasets on the individual level to interpretation of this acquired knowledge into decisions on organisational, national and international decision levels (Leedom et al., 2007). However, interdisciplinary collaboration between disciplines is not new. For instance have archaeologists, geologists and life sciences such as system biology a fundamental commitment and a tradition of working across cultures and disciplines. In interdisciplinary work, the disciplines bring along various preconditions and cultural traditions to solve a given task. Establishment of a sufficient unified understanding among the actors involved is required to enable reasonable actions to be taken. The further divided the disciplines are professionally and the more novel or innovative the task is, the more challenging the establishment of such a sufficient unified understanding is (Carlile, 2004).

With various professional background and experiences among the actors involved, a success criterion for establishment of a sufficiently unified understanding of the given task is to find
mechanisms, or tools, that are recognisable or somehow familiar for all actors involved. In science, for instance, all kind of imaging and visualisation such as graphs, diagrams, table, simulations and photos are used to disseminate results and knowledge (Burri and Dumit, 2008). Due to the human cognitive capability, images should in general have an inherent capacity of being understood by all humans, independent of profession and background. The communicative potential of images has been reflected by growing numbers of professions since the late 1990’s. Computer scientists, graphics designers and cognition scientists have all created new fields such as visualised information, information-graphics and aesthetics, visual diagnostics of methods to process and display, or abstract, data in the most optimal way for the human observer’s cognitive skills and background knowledge (Card et al., 1999; Munzner, 2014; Ware, 2012).

In the marine environment use of digital imaging is a relatively new methodological application for monitoring. While video for habitat mapping has been performed for more than a decade, use of images for monitoring purposes (time-series or repeated measurements) is still fairly new, but increases rapidly. Due to the limited experience with image technology in this environment, there is still a development need for optimised data collection and automated or semi-automated analyses to handle the vast amount of data (Nilssen et al., 2015a), or simply to see and exploit the potential provided by the introduction of images into the marine environmental monitoring. Even though the human brain is good in detecting human motion in time and space, research shows that we perform worse on movements of animals and object that are unlike humans and that we have less experiences with (Shiffrar and Thomas, 2013; Smith and Kosslyn, 2014). Due to the vast amount of images of high temporal and/or spatial resolution gathered from the, relatively little known environment, an interdisciplinary effort is required to exploit the inherent knowledge available in the measurements.

The purpose of this paper is to elucidate why images have the potential of being good communicative and collaborative tools. Furthermore, approaches for how to process the information from images gathered for underwater environmental monitoring are proposed. The author’s hypothesis is that interdisciplinary collaboration on processing and interpreting images has the potential to enhance the knowledge and understanding of the marine environment considerably since this collaboration enables us to utilize the inherent knowledge available also within the temporal and spatial domain. How the temporal and spatial obstacles can be dealt with is exemplified through two interdisciplinary case studies from the marine environment (see
chapter 3 Case studies on images). The first case demonstrates how collaboration between biologists and computer scientists on time series of time-lapse photos from a multi-sensor ocean observatory can be used to monitor biological activities and habitat health state with time. In the second case biologists, information technology personnel, cyberneticists and social scientists contributed to develop a 2D and 3D Geographic Information System (GIS) model visualising, among other thing, topography, resources of interest, current speed and direction, water turbidity and dispersion of discharge from a point source. Models can aid mitigating the human spatial limitations by providing an overview of the spatial extent of a set of given measurements in a defined geographical area simultaneously.

2. Material and Methods

In the following chapter the cognitive advantages with using images in environmental monitoring is explained by (Ihde, 1979) and his theory on instrumental realism. Furthermore, the potential of enhancing environmental knowledge through interdisciplinary collaboration and innovation is elaborated in the context of (Carlile, 2004) and his framework for managing knowledge across boundaries.

2.1. Images and image technology

According to the technology philosopher Don Ihde, our visual perception of what we see is determined by the measuring sensor technology as it transforms the object of interest or phenomenon through a two-sided process where some features are magnified and others are reduced, or even left out (Ihde, 1979; Ihde, 1991). In that sense technologies are non-neutral (Ihde, 1979). This phenomenon is exemplified in Figure 1, where a variety of measurements with different spatial resolution covering different areas of the monitored habitat presents an abstract sketch of various sensors in a habitat. The habitat can for instance be a cold water coral reef where image and Measurement 2 are exemplified by photos of a coral reef area (see also Figure 2 a) and a magnified photo focusing on shrimp (see also Figure 2 b), respectively. Measurement 1 can for instance represent turbidity measurements, while Measurement 3 can be an echogram representing the biomass integrated over a certain area (see also Figure 2 d). However, as Figure
Figure 1 illustrates, neither individual sensors, nor a combination of sensors will cover all aspects of a given habitat completely as different sensors amplify and/or reduce different phenomenon/objects of interests and in most cases these sensors are point samples (Almklov et al., 2014). Being able to describe isolated variables, objects of interest or an entire habitat we are, in most cases therefore dependent of models that can extrapolate the measurements (from a delimited area) to a broader area of comparable composition and environmental condition.

![Figure 1: Schematic illustration of a typical multisensory coverage of an investigated habitat, for instance a cold water coral reef (the habitat is indicated by the irregular outer borders of the figure). The spatial resolution of the individual sensors will vary. The photo (image) will, dependent of the distance from the camera to the object of interest, cover approximately 10 m$^2$ of the reef (see also Figure 2 a). Measurement 1-3 can be turbidity (measurement 1), Measurement 2 can represent a magnified part of the photo, focusing on the presence of shrimp or sponge (see also Figure 2 b) and Measurement 3 can be an echogram (see also Figure 2 d) measuring zooplankton and fish biomass integrated over a given water column (detection distance and taxa identification is dependent of the frequency used) or use of models for extrapolation from the findings in the image to the reef habitat. According to Ihde (1979), also the degree of transformation will vary significantly dependent on the measuring technology. Technology transformation is further exemplified in Figure 2 a-d.](image-url)
Ihde (1979) categorises the technologies (the “instrumental intentionality”) in two dimensions: 1) in accordance to how transformed the measurements are from the human vision (“horizontal” or “vertical instrumental variation”) and 2) the measurements’ degree of magnification and reduction (“high” or “low contrast”). Contrast in this context is referring to what is magnified in the photo and not its technical quality or properties. Representations close to the human vision is categorised as horizontal instrumental variations (Figure 2 a, b), while measurements where the immediate visual recognition have disappeared (Figure 2 c, d) are categorised as vertical instrumental variations (Ihde, 1979). Since the measurements categorised as vertical instrumental variation are highly transformed, they have to be read in a particular scientific tradition (have to be learned) to be interpreted and understood. Furthermore, high contrast measurements are magnification of selected objects of interest or phenomenon in a given image (Figure 2 b, d). For instance in Figure 2 b, the photo is magnified on the present shrimp using their eye reflections for detection and to estimate their abundance. While for the echogram the technology is integrating the biomass present in a given volume of water (up till several hundred meters distance, depending on the echo sounder frequency). Low contrast measurements can for instance be a transformation of the original image (horizontal instrumental variations of low contrast) to a heat map where the shrimps, or other organisms of interest, are presented as coloured pixels reflecting their abundance (Figure 2 c).
Figure 2: Examples of images with different degree of instrumental transformation and different degree of magnification.

Figure 2 a: Photo of cold water coral reef habitat at the Lofoten and Vesterålen (LoVe) ocean observatory. White parts are living *Lophelia pertusa* and grey part is sediments with large amounts of dead *L. pertusa* fragments (Statoil, n.d.). The photo is a representative for images categorised as horizontal instrumental variation of low contrast.

Figure 2 b: Magnified part of photo measuring shrimp abundance by their eye reflections (paired or single yellow dots indicated by arrows) in a cold water coral reef habitat dominated by *L. pertusa*. Image acquisition and computational shrimp detection is explained in Purser et al. (2013). The photo is a representative for images categorised as horizontal instrumental variation of high contrast.
Figure 2 c: Heat map of shrimp abundance at the LoVe ocean observatory where the different colours represent the shrimp density from no shrimp (dark red) to high density (pale yellow). The algorithms for computing the shrimp abundances and heat map computation are explained in Osterloff et al. (In Press-a). The heat map is a representative for images categorised as vertical instrumental variation of low contrast.

Figure 2 d: Echogram (acoustic backscatter) measuring biomass of fish and zooplankton integrated from surface to approximately 250 m depth at the LoVe ocean observatory. The echogram shows aggregations of Northeast Arctic cod (*Gadus morhua*) at 60 – 100 m (depth scale on left) and, presumably, an aggregation of zooplankton underneath (blue-green “cloud”). The echogram is a representative for images categorised as vertical instrumental variation of high contrast. (Image provided by Terje Tornelsen, Metas).
2.2. Interdisciplinary work

To succeed within cross disciplinary collaborations it is essential to find appropriate communicative tools (boundary objects) that are understood by all actors involved (Carlile, 2004). According to Carlile (2004), new knowledge and knowledge development occurs when individual actors use their already existing knowledge and experiences on new tasks. The preconditions to succeed are that 1) the actors manage to identify their initial level of mutual understanding and 2) they, through the development, manage to agree and thereby establish knowledge by bring the task to a level of high confirmation (Figure 3).

Depending on the complexity of a task, Carlile (2004) divides the framework for managing knowledge across boundaries into three levels, syntactic, semantic and pragmatic, mentioned in the order of increased scientific deviation and experiences. When actors are in the syntactic level (lower part of Figure 3) they share a lexicon of concepts and world views and they can therefore easily establish a sufficient unified understanding of the task. In such cases development of a “common language” through transfer of information, orally or for instance by the help of a power point presentation, is sufficient for the actors to establish a mutual understanding of the situation, or as in our case to understand that the given image represents a selected area of a cold water coral reef (see also Figure 2 a). In the semantic area (middle section of Figure 3), the degree of novelty of the task has increased, and thereby decreases the level of confirmation of the task. At this stage the actors are further scientifically divided and more effort is required to establish a sufficient unified understanding of the task. In our case this can be the stage were the biologists and computer scientists need to collaborate to handle the temporal and spatial dimensions of the images, for instance to follow change in shrimp abundance with seasons (see also Figure 2 c and Figure 4). Negotiations between the actors and willingness to change their domain knowledge may be required at this level (Carlile, 2004). Carlile (2004) describes this as the level where knowledge has to be translated between disciplines. In the pragmatic level (upper part of Figure 3) the ability to share and access knowledge between the actors is challenging and a transformation of the domain-specific knowledge is required to establish a sufficient unified understanding between the actors involved. In our case, this stage is represented by interpretation of measured biological activity (documented by the image analysis developed at the semantic
level) with other multisensory measurements and variables such as temperature (time of the year), currents, and discharges (in areas influenced by industrial activities). Furthermore, models can be applied to extrapolate the findings from the delimited area of the image frame to the present habitat in general (Figure 1) or even similar habitats with comparable environmental conditions.

According to Carlile (2004), it is only when the tasks dealt with in the semantic and pragmatic level are pushed down to the syntactic level and has been institutionalised in new methods, tools and representations that innovation has occurred and that new knowledge is established and visible (arrow on the left in Figure 3). In our case, the time-lapse images (dealing with the human’s temporal limitations) and models (dealing with the human’s spatial limitations) are the communicative tools understood by the actors involved based on their low degree of transformation (See section on Images and image technology) that contributes to bring the tasks towards a level of high confirmation. It is emphasised that the transition between the levels characterising the increasing degree of divergence based on scientific background and experiences (syntactic - semantic and semantic - pragmatic) are diffuse.
3. Case studies on images

Based on Ihde (1979) and his theory on instrumental realism, images are to a little degree transformed or manipulated, compared to the human vision and they should therefore be relatively easily understood by humans in general. However, research shows that humans have limitations when it comes to interpreting movements and objects that are unlike humans and that we have less experiences with both in the temporal and spatial domain (Shiffrar and Thomas,
2013; Smith and Kosslyn, 2014). The following two case studies from the marine environment are used to demonstrate how interdisciplinary collaboration, in accordance with (Carlile, 2004) and his framework for managing knowledge across boundaries, can contribute to utilize the inherent knowledge available in the increasingly number of images gathered from mapping and monitoring surveys by overcoming the human brain’s limitations in detection objects and movements in the temporal (Figure 4) and spatial (Figure 5) domain.

3.1. Case study 1; How to overcome human limitations in detecting objects and phenomenon within the temporal domain: interpreting time-lapse photos

In September 2013 the cabled Lofoten and Vesterålen ocean observatory (LoVe) was deployed at a cold water coral area, 20 km off the north western coast of Norway (N 68 °54.474’, E 15 °23.145’) at approximately 260 meters water depth (Godø et al., 2014a). Time-lapse photos (RGB) of the coral habitat, dominated by Lophelia pertusa, are sampled with a temporal resolution of one hour (Figure 4). In addition, key environmental parameters such as temperature, salinity, echograms presenting zooplankton and fish biomass in a given water volume, current speed and direction, sound, concentration of Chlorophyll a, coloured dissolved organic material and total suspended matter are measured (Godø et al., 2014a; Statoil, n.d.). The camera used was a Canon EOS 550D in a waterproof housing (MEATAS DSF5210). The photo covers an area of approximately 10 m² (Osterloff et al., In Press-a). The cold water coral habitat holds a high taxonomic diversity and the selected photo frames covers both an area with live corals and an area with coral rubble. Except from limited long line fishing activities, there is no industrial activity in the area and the long term deployment provides a unique opportunity to establish basic knowledge of natural variations in this undisturbed area documenting species-specific behaviour in their natural environment.

In this case study, the overall aim was to develop algorithms for automatic or semi-automatic detection of biological activity and health status of the habitat documented in the photos in time and space. The overall aim was to interpret these results with other environmental factors affecting species distribution and biomass, such as current speed and direction, temperature (time of the year) and turbidity. Being able to overcome our limitations in observing objects and movements in time and space efficiently with respect to time use and human resources,
development of algorithms is crucial. Such an approach calls for an interdisciplinary collaboration. Furthermore, incorporating images with other multisensory, in this case environmental variables, also call for interdisciplinary collaboration and application of multivariate data analyses.

The need for biologists and computer scientists to work jointly was addressed already in the planning process for the LoVe ocean observatory. To ensure images of such a quality that development of semi-automatic and/or automatic image analysis could be performed, the computer scientists were involved already in the designing process of the camera set-up, facilitating their preferences with respect to distance to object of interest and light conditions. When the observatory came in operation, the biologists and computer scientists used several arenas for cooperation to discuss the photos from face-to-face meetings, via video meetings and to a web based annotation tool (Ontrup et al., 2009). The biologists brought their biological skills and ecosystem knowledge into the discussion and approached the photos from a viewpoint of which organisms that were most interesting, what they expected the photos to show, and what was regarded as unexpected with regards to presence and or behaviour. Examples of the latter are for instance how frequent the Sea lilies moves, the discovery of colour change of *Lophelia pertusa* or the discovery that Tusk (*Brosme brosme*) is stationary. The computer scientists on the other hand approached the images and organisms from a technical and mathematical point of view: Is it possible to develop algorithms enabling automatic or semi-automatic detection of the specific organisms or to track species-specific behaviour pointed out by the biologists? Is the photo quality good enough (e.g. is the spatial resolution sufficient to detect and identify different species or to what extent is the water quality affecting the photos?) and/or are the features of the organisms so distinctive that they can be discriminated from the surroundings?

At LoVe, to date two approaches have been performed to detect organisms of interest and bringing the outcome of the interdisciplinary collaboration down to the syntactic level of understanding and where new knowledge is institutionalised and visible (Carlile, 2004). One of the approaches has been to use unsupervised computer learning to detect and group interesting events, such as presence and behaviour of different species. The methodology is based on species features and change detection (Möller et al., 2015). This approach can for instance be helpful when operating in more or less unknown areas where knowledge about which species to find or to document behaviour for species with infrequent appearance. Examples of the latter at LoVe
are detection of star fish and sea urchins. This method provides the biologist with a set of possible interesting events identified by the computer that they easily can scroll through. Depending of the scope, the organisms’ location on the reef and how frequent they are present can be detected in a time-efficient manner.

The other approach has been to identify behaviour of specific species of interest. Examples of on-going work on natural behaviour of specific species are shrimp abundance (Osterloff et al., In Press-a) and monitoring colour change (Osterloff et al., In Press-b). This approach will for instance be helpful to monitor frequently present or sessile species regarded as key species for a habitat or to monitoring sensitive or threatened species where change in behaviour or colour change (Osterloff et al., 2016) is used as an endpoint in laboratory experiments or to measure anthropogenic impact in the field.

**Figure 4:** Use of algorithms for automatic detection of shrimp abundance on a cold water coral reef and on the coral rubble area beneath over time. Figure based on Osterloff et al. (In Press-a).

### 3.2. Case study 2; How to overcome human limitations in detecting objects and phenomenon within the spatial domain: 3D modelling

In November 2010, the Integrated Environmental Monitoring project was initiated with Statoil, Kongsberg Group (Kongsberg Maritime and Kongsberg Oil&Gas), DNV-GL and IBM as partners. The purpose of this project was to build an overall infrastructure for environmental data, from sensor carrying platforms, sensors, , data transfer/handling/storage and access to
analysis and visualisation of data to end-users, in this case the decision makers (Hepsø et al., 2012; Ulfsnes et al., 2014). Visualisation of important parameters and results, such as topography, presence of resources and dispersion of discharges was developed as part of the visualisation portal. Both a 2D and a 3D model were developed.

One of the purposes by building the GIS portal/model was to get a visual overview of the measured parameters, the resources present in the area of interest and the potential impact from discharges in space and time, all available on one screen (Figure 5). Various environmental data has different spatial resolution (Figure 1) and in most cases they also measure at different temporal resolution from seconds to hours. Visualising the different sensors and their various spatial resolutions in the model increases the total overview tremendously. The portal also has a time-slider, enabling the user to adjust the temporal resolution of the model. The model enables the users to establish an understanding of the geographical area of interest. In combination with this distant overview, the model also enables a close-up (“digital zoom”) of details of the geographical area; the presence and condition of the, in this case, coral reef structures and how the discharges of drill cuttings and water-based drilling fluids would disperse (given as a prognosis in the planning process or as verification with actual measurements during or after the operation) in the area over time with, at any time, the given current speed and direction.

A model that visually presents important and optimised information to the users with regards to what impacts to expect and how an environmental monitoring programme in the particular area should be designed to monitor the predicted impacts was developed through interdisciplinary collaboration between biologists, information technology personnel, cyberneticians and social scientists. This information is important with respect to selection of sensor platform(s) and sensors to use and the corresponding areal cover needed since the type(s) of sensor platform(s) used should be dependent of topography, resources and the expected extent of the possible impact from the discharges. Furthermore, the types of sensors used should be adjusted to the type of resources present, while the type(s) of discharges should decide what kind of endpoints that should be monitored. By getting all essential parameters visualised simultaneously at one screen, the model enable us to approach the available information from a very different perspective than if the same information were given separately, one after the other.
Figure 5: 3D model of the Morvin oil field, presenting the predicted coral risk (coloured lines around the identified coral structures). The risk is based on the coral reef condition (Poor-excellent) and the modelled sedimentation, based on measured hydrographical data. Figure based on Ulfsnes et al. (2014).

4. Discussion

Based on the human cognitive capacities to detect and classify objects and movements (Biederman, 1987; Shiffrar and Thomas, 2013; Smith and Kosslyn, 2014) and the camera’s low degree of data transformation (Ihde, 1979; Ihde, 1991) this paper has launched images as a comprehensive tool with the potential of enhancing environmental knowledge. Furthermore, the essential contribution of interdisciplinary collaboration to enhance innovation and, in our case, to extract the inherent knowledge available in images and models has been demonstrated through Carlile (2004) integrative framework for managing knowledge across boundaries. Enhanced knowledge can be related to the additional information provided by the images or models as such or it relates to the potentially improved cross disciplinary understanding due to the images or model’s communicative properties in itself. The latter is further discussed under “Future applications for use of images in decision making processes”.
Since different scientific disciplines interpret data in their own tradition (Carlile, 2004), cross disciplinary collaboration need to find collaborative tools, or boundary object(s), that have an individual case-by-case adjusted meaning that can be understood by each of the actors involved (Star and Griesemer, 1989). According to (Ihde, 1979), images of horizontal instrumental variation (Figure 2 a) are to a little extent transformed compared to if we were using our own eyes. This knowledge can be used to facilitate interpretation and understanding of additional measurements that are more transformed and abstract for people in general. For instance, if a transparent version of the heat map (Figure 2 c) is projected on top of the original photo(s), this would ease the general understanding and interpretation of the data tremendously since the data (plot on top of the photo) is perceived more like a photo (Figure 6). Furthermore, taking this approach further, we argue that photos might be used to communicate and explain more abstract and complex data, such as multisensory data and multivariate data analysis (images in upper right of Figure 7 b). Even though not a photo, the model from case 2 does appear as a photo and the graphic presented in this case (Figure 5) will have the same effect on humans; it eases our ability to interpret all essential information and in addition it makes the spatial extent manageable.

The human challenge in the spatial domain occurs when the object of interest is of such a size that the human vision and perception can’t get the overview without having to move around or closer to the object of interest to obtain a sufficient level of details. Additional aspect to the geographical extension, areas that in practise are inaccessible for humans such as access to deep waters, areas with a high risk of explosion for instance during fire on an oil rig are all examples where use of modelling is highly valid in situation awareness. Presenting results by use of new approaches can in itself enables completely new ways of utilizing data and opens up for further engaging and understanding the source information. For instance, Adams (2013) describes use of digital media, such as 3D models and models combined with photos in archaeology as an approach that opens up for new way of engaging and understanding the source material. As for Adams (2013) sketch of an archaeological site, we will through the 3D model get access to a much higher spatial resolution than a human eye can observe by combining the close-up details from the camera and reducing the spatial extent to something that can be handled by the human’s vision on a screen (observing an area of tens to thousands of meters by only moving the eyes). Another advantage that might be highly valid for the interpretation of knowledge of the object(s)
or phenomenon of interest is that both models and photos can be used to manipulate the real world by removing unwanted and disturbing elements or features such as biofilm (e.g. bacterial mats) and kelp or to retract the waters inherent optical properties (concentrations of phytoplankton, coloured dissolved organic carbon and total suspended matter), having a great effect on the visibility in the water (Johnsen et al., 2013).

As described above, images should have the potential to be understood, independent of professional background and experiences. However, even though images reduce profession specific demands, they are not self-exploratory. Every image has an interpretive tension (Burri and Dumit, 2008) and issues such as knowledge of the specific object of interest, perception and interpretation skills, beliefs, goals and expectations will always alter both the accuracy and speed in selecting meaningful and desired information (Smith and Kosslyn, 2014). To be able to interpret and utilise the full potential provided by images they need to be prepared and/or transformed. Development of algorithms for automatic or semi-automatic image analysis are, in most cases, dependent of humans performing manual labelling of the specific species of interest from a certain number of photos, needed as a training set of the automated detection. According to Smith and Kosslyn (2014) attention to only more than one source, for instance looking at more than one species at the time, the selected information will become imperfect since the attention then has to be divided between the various sources (different species) present. Due to this, the human vision is selective, which bias the level of attention towards selected objects that might be more processed than others (Carrasco et al., 2004; Chun et al., 2011). One way to deal with reduced attention and selective vision is to group organisms of similar shape/features and dedicate the attention to one group at the time, finalise the detection of the first one, before initiation the labelling of the next (Schoening et al., 2016). The unsupervised approach for grouping events based on features and change detection can help in this process by guiding our attention to groups of already clustered organisms. Another approach applied to keep attention is to use information sharing (several screens) for “on the fly” video annotations. In these cases dedicated personnel annotate dedicated features simultaneously, for instance in the MAREANO programme biologists and geologists uses the same real-time annotation tool to annotate fauna and benthic environment from video, respectively (Buhl-Mortensen et al., 2015; Buhl-Mortensen, pers. com.). Also the fame rate of the videos or time-lapse photos, will influence the human perception (Shiffrar and Thomas, 2013; Smith and Kosslyn, 2014). Stimuli, in our case
images, presented too quickly (< 0.5 s) seems to preclude the attention of the second (Raymond, 2003). This mechanism (“attentional blink”) does, however, not seem to appear to different features of the same object (Raymond, 2003). This furthermore underlines the importance of focusing on one group of organisms at the time. Additional issues to consider when performing manual labelling is elucidated by (Schoening et al., 2016).

4.1. Future application for use of images in decision making processes

This paper has focused on the human cognitive capacity to understand photos and graphical presentations (such as presented in Figure 4) and how interdisciplinary collaboration on processing and interpreting of these can enhance the environmental knowledge by overcoming our limitations in the temporal and spatial domain. Due to the images potential of acting as a boundary object, we will also claim that images have the potential of playing an important role in improving operational decisions in organisations. As Carlile (2004), Leedom et al. (2007) claims that data can be communicated only if the actors have established a sufficient unified understanding. In the sensmaking/constructivist tradition knowledge is based on each individual’s unique experience, expertise and interest (Leedom et al., 2007). Both Carlile (2004) and (Brown et al., 2015) underline the importance of having a shared mission and a constructing dialogue between the actors involved and that these actors must be experts within their own field of expertise, in addition to be open minded and interested in other disciplines. In addition, Brown et al. (2015) pinpoint institutional support and bridging research, policy and industry as absolute preconditions for facilitation of interdisciplinary collaboration in daily work.

Using this approach on the two cases it would provide more accurate information on natural variations of the species dynamic (Case 1), which in its turn can enable a risk based management regime that are more capable of dividing natural variations from impact from industrial activities and point discharges when applying the methodology in such areas. This knowledge make decision makers better prepared to take proper decisions in an operational setting, for instance related to drilling in a coral area. A 3D model (case 2) will be highly valid both as part of the planning process upfront a survey or an operation (Ulfsnes et al., 2014) and to perform an optimised environmental monitoring by ensuring the right spatial and temporal resolution of the measurements. From a risk based approach, this emphasises the mutual dependencies between
modelling and environmental monitoring (Beyer et al., 2012; Godø et al., 2014b; Nilssen and Johnsen, 2008; Nilssen et al., 2015a; Nilssen et al., 2015b). Models are used to identify the most important risks. The environmental monitoring programmes should reflect the identified risks and effectiveness of the applied mitigation measures. In addition, to improve extrapolations (Almklov et al., 2014) and accuracy in the modelling (Rye et al., 2012), the environmental monitoring should also measure parameters essential to improve the models, such as current speed and direction, turbidity and sedimentation. Such an approach would contribute considerable to ensure sound decisions. It will, however, require understanding and recognition from the actors involved both on the individual and organisational level.

5. Conclusions and future perspectives

Increased use of images and models in environmental mapping and monitoring has a considerable potential to enhance the knowledge about this environment. Interdisciplinary collaboration is essential to extract the inherent information in time and space provided by these images and models. The fact that images in general are understood by humans independent of background and experiences and that they are so plastic that they mission can be adjusted from case-to-case, indicates that they should be suitable boundary objects in interdisciplinary collaboration in environmental monitoring. In a future perspective, these properties should also make images a valid communicative and collaborative tool to ensure better decisions.

However, introducing images into environmental monitoring has also lead to unexpected challenges that still have to be solved. One such an area is the ontology for species identification, including taxonomy and routines and standards for proper categorisation and metadata-tagging of images. Traditional species identification requires physically access to the organisms as the taxonomy usually is based on morphological details not found in the images. Furthermore, sufficient levels of details for the categories need to be established. An ontology that is too detailed can lead to a too complicated system where we easily can get lost, while a too aggregated system might provide a system that are too general to obtain knowledge of sufficient accuracy. Together with the development of automatic or semi-automatic images analysis elucidated in this paper, these aspects are essential to solve before the inherent knowledge provided by images can be fully implemented and utilised.
6. Abbreviations and definitions

BIIGLE: Bielefeld Image Graphical Labeler and Explorer is a Web 2.0 based platform containing easily uploaded images that can be accessed by collaborating scientists.

Boundary object: objects which are both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites. They are weakly structured in common use, and become strongly structured in individual-site use. They have different meanings in different social worlds but their structure is common enough to more than one world to make them recognizable, a means of tradition.

GIS: Geographic Information System

Heat map: a graphical representation of data where the individual values contained in a matrix are represented as colors.

Horizontal instrumental variation: Measurements within this category are to a little extent transformed compared to the human vision.

Interdisciplinary: collaboration between different disciplines to solve a particular task or mission.

Instrumental measurements of high contrast: measurements with a high degree of magnification.

Instrumental measurements of low contrast: measurements with a high degree of reduction.

LoVe: Lofoten-Vesterålen

RGB: Red, green and blue (the colours used in ordinary photo cameras).

Vertical instrumental variation: Measurements within this category are highly transformed compared to the human vision and the immediate recognition has therefore disappeared. These measurements have to be read in a particular scientific tradition.
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Appendix

Figure 6: Example on how to “drive” complex data towards a presentation closer to the human perception by projecting a transparent version of the heat map (Figure 2 c) on to the original photo (Figure 2 a).
Figure 7a: Schematic description of the selected approach for polyp activity annotations: At the syntactic level the web-based image annotation and labelling system BIIGLE was used in the interdisciplinary collaboration between computer scientists and biologists. Based on previous experiences a proposed set of polyp categories were provided by the computer scientists (in BIIGLE). The biologists wanted to increase the number of categories to get more accurate measurements of the actual polyp activity. At the semantic level the diverging understanding and wishes were identified and jointly agreed definitions of categories were established (exemplified with polyps classified within the different categories; fully expanded (F E), fully/partly expanded (F/P E), partly expanded (P E), partly expanded/retracted (P E/R) and retracted (R)). At the pragmatic level a so called Gold standard is established based on human manual annotations. The Gold standard uses only those polyps that were labelled as the same category by at least two of the three experts. The Gold standard was used as the training set for the machine leaning and development of algorithms for polyp activity. Feedback loop: algorithms are established, a new structure (number of categories of polyp activity) and a gold standard for polyp activity are established (the algorithms are under development, so images of the automatic polyp categorisation are at present not available).
Figure 7 b: In the syntactic level detection of biological activities in a cold water coral reef and in the coral rubble underneath the reef over time are performed from photos. In the semantic level species of interests are identified and an attempt to automatic and/or semi-automatic detection is done. Different approaches are needed for each species (from upper left to lower left: level of polyps activity for the reef building cold water coral *L. pertusa*, detection of *L. pertusa* colour, unsupervised change detection over a certain time interval and shrimp abundance, respectively). When algorithms are developed, other sensors measurements, such as temperature, and current speed and direction, are used to try to explain the identified behaviour patterns, here exemplified in the Pragmatic level by a principal component analysis (PCA) score plot.
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1987 Hans Christian Pedersen Dr. philos Zoology Reproduction in Atlantic Salmon (Salmo salar): Aspects of spawning, incubation, early life history and population structure
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1990 Asbjørn Moen Dr. philos Botany The dynamics of habitat use in the salmonid genera Coregonus and Salvelinus: Ontogenic niche shifts and polymorphism
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The impact of environmental conditions of density dependent performance in the boreal forest bryophytes *Dicranum majus*, *Hylocomium splendens*, *Plagiochila asplenigides*, *Ptilium crista-castrensis* and *Rhytidiadelphus lokes*.

Aspects of population genetics, behaviour and performance of wild and farmed Atlantic salmon (*Salmo salar*) revealed by molecular genetic techniques.

The early regeneration process in protoplasts from *Brassica napus* hypocotyls cultivated under various g-forces.

Mate choice, competition for mates, and conflicts of interest in the Lekking Great Snipe.

Modulation of glutamatergic neurotransmission related to cognitive dysfunctions and Alzheimer’s disease.

Social evolution in monogamous families: Young Atlantic salmon (*Salmo salar L.*) and Brown trout (*Salmo trutta L.*) inhabiting the deep pool habitat, with special reference to their habitat use, habitat preferences and competitive interactions.

Host specificity as parameter in estimates of arthropod species richness.


The Cuckoo (*Cuculus canorus*) and its host: adaptations and counteradaptations in a coevolutionary arms race.

Methods for the microbial econtrol of live food used for the rearing of marine fish larvae.

Sexual segregation in the African elephant (*Loxodonta africana*).

Seawater tolerance, migratory behaviour and growth of Charr, (*Salvelinus alpinus*), with emphasis on the high Arctic Diezet charr on Spitsbergen, Svalbard.

Biochemical impacts of Cd, Cu and Zn on brown trout (*Salmo trutta*) in two mining-contaminated rivers in Central Norway.

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Production and nutritional adaptation of the brine shrimp *Artemia* sp. as live food organism for larvae of marine cold water fish species.

Lichen response to environmental changes in the managed boreal forest systems.

Male dimorphism and reproductive biology in corkwing wrasse (*Symphodus melops* L.).

Coevolutionary adaptations in avian brood parasites and their hosts.

Spatio-temporal dynamics in Svalbard reindeer (*Rangifer tarandus platyrhynchus*).
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<td>Olfactory coding and olfactory learning of plant odours in heliothine moths. An anatomical, physiological and behavioural study of three related species (<em>Heliothis virescens</em>, <em>Helicoverpa armigera</em> and <em>Helicoverpa assulta</em>)</td>
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2011 John Odden ph.d Biology  The ecology of a conflict: Eurasian lynx depredation on domestic sheep
2011 Simen Pedersen ph.d Biology  Effects of native and introduced cervids on small mammals and birds
2011 Mohsen Falahati-Anbaran ph.d Biology  Evolutionary consequences of seed banks and seed dispersal in Arabidopsis
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2012 Aleksander Handå ph.d Biology  Cultivation of mussels (Mytilus edulis). Feed requirements, storage and integration with salmon (Salmo salar) farming
2012 Morten Kraabøl ph.d Biology  Reproductive and migratory challenges inflicted on migrant brown trout (Salmo trutta L.) in a heavily modified river
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2012 Robert Dominikus Fyumagwa Dr. Philos Biology  Anthropogenic and natural influence on disease prevalence at the human–livestock-wildlife interface in the Serengeti ecosystem, Tanzania
2012 Jenny Bytingsvik ph.d Biology  Organohalogenated contaminants (OHCs) in polar bear mother-cub pairs from Svalbard, Norway. Maternal transfer, exposure assessment and thyroid hormone disruptive effects in polar bear pups
2012 Christer Moe Rolandsen ph.d Biology  The ecological significance of space use and movement patterns of moose in a variable environment
2012 Lise Cats Myhre ph.d Biology  Effects of the social and physical environment on mating behaviour in a marine fish
2012 Tonje Aronsen ph.d Biology  Demographic, environmental and evolutionary aspects of sexual selection
2013 Jørgen Rosvold ph.d Biology  Ungulates in a dynamic and increasingly human dominated landscape – A millennia-scale perspective
2013 Pankaj Barah ph.d Biology  Integrated Systems Approaches to Study Plant Stress Responses
2013 Marit Linnerud ph.d Biology  Patterns in spatial and temporal variation in population abundances of vertebrates
2013 Xinxin Wang ph.d Biology  Integrated multi-trophic aquaculture driven by nutrient wastes released from Atlantic salmon (Salmo salar) farming
2013 Ingrid Ertshus Mathisen ph.d Biology  Structure, dynamics, and regeneration capacity at the sub-arctic forest-tundra ecotone of northern Norway and Kola Peninsula, NW Russia
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<td>Light in the dark – the role of irradiance in the high Arctic marine ecosystem during polar night</td>
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