Farming in a High Energy Environment: Potentials and Constraints of Sustainable Offshore Aquaculture in the German Bight (North Sea)

Chancen und Limitierungen extensiver Offshore-Aquakultur in der Deutschen Bucht

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Dedicated to my wife

Gesche

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Summary

The aim of this study was to identify scientific criteria and to acquire performance data for the development of mariculture in the context of sustainable multifunctional use of offshore space and natural resources.

In connection with current plans for a massive expansion of wind farms in offshore areas of the North Sea, the idea emerged to combine these with the installation of extensive mariculture for bivalves and macroalgae. Since offshore wind farms provide safety from shipping and infrastructure for attachment and service support, the opportunity for a multiple-use concept presented itself. However, prior to such a multifunctional development, it is necessary to determine the appropriate biological, technological and management requirements as well as the performance characteristics that would allow the employment of favourable and cost-effective methodologies. To this end, special focus was placed on the combination of extensive offshore shellfish and seaweed farming at exposed sites within the proposed offshore wind farms.

This thesis deals in detail with

1. the effects of abiotic and biotic factors on the growth potential of indigenous macroalgae and bivalves in extensive mariculture systems exposed to the stressful conditions of offshore habitats: (a) effects of physical forces on the cultivated species, (b) various parameters characterising the growth performance of species, (c) testing these parameters while using a variety of substrates and technical setups, (d) survival and health conditions, (e) recruitment, (f) parasite infestation of mussels in relation to inshore and offshore exposure, and (g) site-specific responses of the species to the various harsh offshore environments,
2. the interaction between physical offshore processes and man-made structures in areas of the German North Sea Territory where mariculture has potential,
3. the conditions for possible combination of mariculture systems with offshore wind farms in terms of the legal framework and possible management strategies, and
4. the socio-economic and legal consequences and interactions for offshore mussel farming with the existing conventional inshore bottom culture activities.

The research locations were specifically selected sites in the offshore region of the German Bight, mainly in the outer estuary of the River Weser, the offshore waters off the Island of Helgoland, several offshore areas where wind farms are planned, and habitats along the northern part of the Island of Sylt.

In this yet relatively young research field the performance of different offshore culture systems with attached macroalgae (*Laminaria saccharina*) and blue mussels (*Mytilus edulis*) was assessed at monthly sampling intervals. These procedures were carried out using research vessels, boats and scuba surveys, while determining morphometric parameters (e.g. length, width, thickness) as well as weight for growth analysis of mussels and seaweeds. Furthermore, the condition index, the meat content and the degree of parasite infestation of blue mussels were determined. The abundance of mussel larvae in the water column and the resulting settlement success of post-larvae on various spat collectors were investigated. Seaweed studies included attachment strength, breaking and drag forces on kelp sporophytes in order to describe the resistance of cultivated Laminarians to high-energy environments. Additional assessment criteria were biochemical parameters (e.g. chlorophyll-, nutrient-, POC- and TON-concentrations and their ratios) to describe the food availability for mussels and the nutrient composition for algal growth as well as oceanographic parameters (currents, waves, swell, salinity, temperature, light attenuation) to describe the wave climate and current velocities of the study sites in the offshore environment. Technical studies comprised two system designs (longline, ring structure) of various set ups (submerged or floating mode) in different locations (offshore or inshore) to find an appropriate culture design to sustain growth and survival of cultivated species.

Further, a specially designed offshore spat collector was used for settlement investigations of mussel post larvae. Some fundamental studies were carried out in order to pave the way for the realisation of open ocean aquaculture in offshore wind farms (e.g. multifunctional use of offshore habitats in terms of avoidance of stakeholder conflicts, the legal framework for such activities in coastal areas and in the *Exclusive Economic Zone* (EEZ), the multi-use concept in terms of integrated coastal zone management).

Laminaria saccharina showed sufficient length increments in offshore habitats growing on a submerged ring system. It could be demonstrated by drag and breaking-/dislodgement force experiments that algae were capable of resisting the high-energy environment of the North Sea. The concentration of mussel larvae in the water column decreased offshore and resulted in a low settlement success while at the same time infestation load decreased and was lacking at offshore suspended collectors. The three system designs showed different results. While the offshore ring proved to be superior for seaweed cultivation under the harsh conditions, the longline showed some major drawbacks in terms of materials used, design and installation modes (submerged or floating). The spat collector largely withstood the harsh hydrodynamic conditions of the North Sea. The hitherto fragmented legal framework for the offshore waters was found to be one of the key constraints for the successful implementation of multifunctional use schemes. However, participation of all involved stakeholders may provide a window of opportunity to turn the existing lack of offshore regulations into a positive momentum, as scope exists to move with the development of new offshore co-management concepts beyond existing management approaches.

Whether such offshore installations would provide sufficient economic returns could not be answered yet, as experience on the maintenance of offshore wind farms is lacking so far.

However, the discovery that *Laminaria saccharina* resists offshore forces and shows sufficient length increments and mussels growing in offshore habitats are not affected by parasites may provide a key incentive for positive commercial use.

It thus can be shown that there is a high potential for farming the "deep blue" in the German EEZ, provided that some of the constraints, of which the lack of legal framework and technical aspects seems to be most severe, are resolved in the near future.

Zusammenfassung

Ziel dieser Doktorarbeit war die Anfertigung eines wissenschaftlichen und technischen Fundaments für eine marine Aquakultur in der Deutschen Bucht unter dem Aspekt nachhaltiger und multifunktionaler Nutzung von Offshore-Gebieten und deren natürlicher Ressourcen.

Die bisher hauptsächlich an Land und in Küstennähe gelegenen Nutzflächen für Windenergieanlagen sollen in den nächsten Jahren auf Offshore-Gebiete in der deutschen Ausschließlichen Wirtschaftzone (AWZ) ausgedehnt werden. Da die geplanten Anlagen in den Windparks Verankerungsmöglichkeiten bieten werden, könnte hier die Möglichkeit für eine multifunktionale Nutzung durch Kombination mit Aquakultursystemen gegeben sein. Um dieses Konzept auf Machbarkeit und wirtschaftliches Potential hin zu prüfen wurden die aus biologischer und technischer Sicht nötigen Vorraussetzungen sowie das bei der Durchführung erforderliche Management untersucht.

Als Aquakulturkomponente für die potentielle multifunktionale Nutzung der Offshore-Windparks wurde die extensive Muschel- sowie Kelpzucht auf ihre Eignung geprüft und folgende Schwerpunkte untersucht:

(1) Einfluss der biotischen und abiotischen Faktoren auf das Wachstum von heimischen Algen und Muscheln an exponierten Standorten: (a) Wirkung hydrodynamischer Effekte auf die Kulturorganismen, (b) Wachstumsparameter, (c) verschiedene Kulturtechniken, (d) Unversehrtheit, (e) Brutfall, (f) Parasitierungsgrad und (g) Resonanz auf harsche Kulturbedingungen an verschiedenen Standorten.
(2) Resistenz von Offshore-Techniken in Gebieten der deutschen Nordsee, die das Potential für marine Aquakultur aufweisen.
(3) Gesetzgebung im Sinne einer multifunktionalen Nutzung sowie Aufstellung einer Managementstrategie.
(4) Sozio-ökonomische und rechtliche Konsequenzen von Offshore-Muschelzucht mit traditioneller Besatzmuschelfischerei sowie deren Interaktionen.

Die Untersuchungsgebiete erstreckten sich auf mehrere Offshore-Bereiche der Deutschen Bucht, insbesondere auf das Weserästuar, auf Bereiche um Helgoland, auf Gebiete in der deutschen AWZ, in denen Windparks geplant sind, sowie auf Areale im Rückseitenwatt der Insel Sylt.

Die praktische Durchführung umfasste monatliche Probennahmen an verschiedenen Kultursystemen, an denen Miesmuscheln (*Mytilus edulis*) oder Zuckertang (*Laminaria saccharina*) wuchsen. Die Proben wurden bei Ausfahrten mit Forschungsschiffen und durch den Einsatz von Tauchern genommen. An den Proben wurden folgende Parameter untersucht: Morphologie (Länge, Breite, Dicke) und Gewicht von Muscheln und Algen, Konditionsindices, Fleischgehalt und Parasitierungsgrad von Miesmuscheln, die Abundanz von Miesmuschellarven in der Wassersäule und der Ansiedlungserfolg der Post-Larven an unterschiedlichen Kollektoren, die Haftungskraft von Haptopheren, die Bruchlast von Kauloiden und die Widerstandskraft des gesamten Thallus von *L. saccharina* gegenüber physikalischen Kräften. Zusätzlich wurden biochemische Parameter (Nährstoff-, Chlorophyll-, POC- und TON-Konzentrationen sowie POC/TON Verhältnisse in der Wassersäule) bestimmt, um die Nahrungsverfügbarkeit und -qualität für Muscheln und die Nährstoffzusammensetzung für das Algenwachstum zu ermitteln, und ozeanographische Parameter (Strömungen, Wellen, Salinität, Temperatur, Licht) gemessen. Die technischen Untersuchungen konzentrierten sich hauptsächlich auf zwei Systeme (Langleine und Offshore-Ring), die in zwei Zuständen (schwimmend oder untergetaucht) an unterschiedlichen Orten (küstennah und küstenfern) ausgebracht wurden, um ein geeignetes Design zu finden, welches die Kultur von Algen und Muscheln erlaubt. Ferner kam ein Offshore-Brutsammler zum Einsatz, der Aussagen über den Ansiedlungserfolg von Muschellarven zuließ. Zusätzlich wurden Studien zum Integrierten Küstenzonen Management

durchgeführt, um mögliche Folgen der momentan geltenden Rechtssprechung abschätzen zu können.

Laminaria saccharina zeigte unterschiedlichen Längenzuwachs an untergetauchten Systemen im Offshore-Bereich. Kraftuntersuchungen an Haftkrallen, Kauloiden und Thalli ergaben, dass diese Alge den in exponierten Habitaten der Nordsee herrschenden Kräften gut widersteht. Die Konzentration von Miesmuschellarven verringerte sich bei zunehmender Entfernung von der Küste und sorgte daher für einen geringen Ansiedlungserfolg im Offshore-Bereich. Bei den Parasitierungsuntersuchungen zeigte sich andererseits, dass Muscheln an Brutsammlern im Offshore-Bereich nicht von Makroparasiten befallen waren. Der Erfolg der drei Offshore-Kultursysteme gestaltete sich unterschiedlich. Der Brutsammler und der Offshore-Ring konnten den Offshore-Kräften standhalten. Die Langleine hingegen wies einige Nachteile auf, die sich insbesondere auf die Materialeigenschaften, das Design und das Verfahren selbst bezogen.

Die bisherige Gesetzgebung ist im Bereich der deutschen AWZ unvollständig und lückenhaft und stellt ein Schlüsselproblem für die Umsetzung einer multifunktionalen Nutzung dar. Bei grundsätzlicher Beteiligung aller möglichen Nutzer der AWZ bietet sich jedoch genügend Spielraum, um dieses Defizit in der Rechtssprechung zu entkräften und ein Offshore-Co-Management aufzubauen.

Eine kommerzielle Machbarkeitsanalyse wurde in dieser Studie nur am Rande durchgeführt. Ob Offshore-Marikulturaktivitäten gewinnbringend sein können, kann hier nicht beantwortet werden, da zunächst der Bau der Offshore-Windparks abgewartet werden muss. Die Ergebnisse aus den biologisch-ozeanographischen Untersuchungen in dieser Arbeit ergaben jedoch, dass hinsichtlich des Längenwachstums von *L. saccharina* und deren Resistenz gegenüber starken Kräften sowie durch das Fehlen von Makroparasiten in offshore-gezüchteten Miesmuscheln für beide Kandidaten durchaus wirtschaftliche Potentiale bestehen.

Abschließend ist zu sagen, dass die Offshore-Aquakultur in der deutschen AWZ grundsätzlich möglich erscheint und dass die Probleme, angeführt durch die momentanen rechtlichen Rahmenbedingungen und die technische Realisierung, in naher Zukunft gelöst werden könnten.

Introduction and Overall Objectives

"Mariculture" and "offshore aquaculture" are two terms used in this thesis that indicate (a) the dominating chemical (saline) matrix of the environment in which it takes place and (b) the harsh physical (hydrodynamic) conditions to which this activity is exposed at locations beyond shallow and protected coastal waters. "Open Ocean Aquaculture" (OOA) is another term increasingly used in the literature. This term is interchangeable with "offshore aquaculture".

Scope of the Thesis

Only few scientific studies dealing with the prospects of offshore aquaculture were available prior to the beginning of the present study, and little was known about the biological and technical requirements and the general feasibility of Open Ocean Aquaculture. Very few long-term experiments under harsh hydrodynamic conditions exist but data on system and species performance are urgently needed to derive methodologies for the assessment of its environmental and economic viability. Therefore, this doctoral thesis focuses (a) on the cultivation techniques and the subsequent performance characteristics of indigenous bivalve and seaweed species exposed to extensive offshore aquaculture farming conditions, (b) investigates the effects of the prevailing hydrodynamics at specific offshore sites within the national boundaries of the German North Sea, (c) assesses the technical requirements needed for farming structures in high energy environments and their possible combination with offshore wind farms. Additionally, this study analyses (d) plans for a multi-use concept of offshore areas for various stakeholders and examines (e) the prevailing case laws to support such activities.

Systems used for this study were longline and ring structures as well as specifically designed offshore spat collectors. All of these systems were designed to operate in submerged and floating modes and were deployed at those locations in the German Territorial Sea and the Exclusive Economic Zone (EEZ) which were potential areas for offshore wind farms. An assessment of the mariculture potential of two indigenous species in offshore sites was undertaken; namely the bivalve *Mytilus edulis* and the seaweed *Laminaria saccharina*. For both candidate species growth rates, biomass yield, mortality and loss, as well as resistance to high energy environments were followed over several growth seasons. Additionally, the spatial abundance of blue mussel larvae, settlement success of post-larvae on exposed spat collectors and parasite infestation of mussels in relation to in- and offshore exposure were determined. Hydrodynamic parameters such as current velocities and direction, wave and swell heights, frequencies and directions were measured in order to calculate forces imposed on the cultivated organisms. Biochemical parameters (e.g. nutrient-, chlorophyll-, particulate organic carbon- [POC] and total organic nitrogen [TON] concentrations) were measured and POC/TON ratios were calculated at given sites to describe both the food availability for filter feeders and nutrient contents for macroalgal cultures. The technical trials focussed primarily on the performance of different off-bottom culture systems (including materials) and their alternative design modifications to improve technical and biological performance. These tests were always linked to offshore wind farm infrastructure at exposed sites in order to prepare for the combination of the two very different industries. This is even more important in order to promote the potential of new evolving management schemes in the EEZ were little regulation has evolved so far. A set of legal key elements that safeguard and enhance this development were identified which are considered to permit different integrated management schemes, thereby satisfying the legal demands in the existing jurisdictions in the coastal states (called "Länder"), as well as the coastal and offshore areas (state and federal laws). Obviously, without these a sustainable, multifunctional development of an offshore industry at any location cannot be guaranteed. These co-evolved adaptation criteria are in fact often overlooked by biologists, industry and legislators but are the key to development success. Therefore, stakeholders and practical measures for management were defined on the basis of bio-technological results, which could potentially support synergies between offshore resource uses such as wind farming and mariculture.

The approach to the above concept was realized by (1) a theoretical feasibility study, (2) the subsequent selection of two test areas to conduct the experimental research presented in this thesis, and (3) the deployment of mooring systems for environmental monitoring of key parameters needed to evaluate mariculture potential in offshore areas.

1. The initial theoretical feasibility study provided the fundamental outline for the various field trials in terms of design and regulative framework with the scope to assess some critical socio-economic implications on a theoretical basis.
2. The first test area was located in the vicinity at the offshore lighthouse "Roter Sand". The second test area was located in the tidal backwaters of the island of Sylt.
3. Furthermore, 18 mooring systems were deployed in several locations within the German Bight most of them adjacent to planned offshore wind farms. At these locations the basic biological, chemical and oceanographic conditions were monitored.

Thus the present work focused on four major (specific) topics:

1. to acquire specific information on the cultivation potential of the marine aquaculture candidates when raised under harsh environmental conditions with a focus on biological performance criteria and bio-chemical requirements,
2. to develop and test various culture system designs which resist strong currents and high waves and support the cultivation of the target species,
3. to assess the current legal framework in providing the necessary jurisdiction with appropriate criteria to support offshore aquaculture activities in the EEZ under a multi-use concept (such as wind farms), and
4. to establish a synergy scenario of different stakeholders (e.g. offshore aquaculture, inshore conventional mussel farming, wind farms and other marine resource users) in the context of an integrated coastal zone management framework.

To achieve the objectives, a multi-disciplinary and inter-disciplinary approach is needed in which several parts of the presented studies can be considered as stand-alone scientific projects and publications. However, the greater scientific challenge is in the conceptual integration of the various elements of the aggregate knowledge base into a systems approach. The following subchapter entitled "The Research Fields Involved" provides a more detailed description of the specific research elements required for the integrated approach while identifying the respective working hypothesis. The major topics covered in the publications and patents, which are referred to by their roman numerals, are:

- Marine Aquaculture	Publications I-X
- The Offshore Environment	Publications I-X
- Mussel and Seaweed Cultivation	Publications I-III, VI-X, Patent I
- Techniques Tested for Open Ocean Aquaculture	Publications I, VI-VII, Patent I-II
- Aspects of Integrated Offshore Management	Publications I, IV-V

The thesis is based on a total of 10 scientific publications and 2 patents (see list on pages 7-8). These publications and patents contain the key elements as outlined above while at the same time several of them link and integrate the specific findings.

List of Publications and Patents Submitted for the Thesis

(All papers and patents are reproduced with the kind permission of the copyright holder and are listed in the appendixes I-XII).

PUBLICATION I

FEASIBILITY STUDY

I. **Buck BH (2002)** Open Ocean Aquaculture und Offshore Windparks: Eine Machbarkeitsstudie über die multifunktionale Nutzung von Offshore-Windparks und Offshore-Marikultur im Raum Nordsee. (Open Ocean Aquaculture and Offshore Wind Farms: Feasibility study on the multifunctional use of offshore wind farms and open ocean aquaculture in the North Sea). Alfred Wegener Institute for Polar and Marine Research Bremerhaven. Reports on Polar and Marine Research 412. 252 pp (see appendix No 1).

PUBLICATION II - III

REVIEW AND OVERVIEW ARTICLES

II. **Walter U, Buck BH, Rosenthal H (2002)** Marikultur im Nordseeraum: Status Quo, Probleme und Tendenzen. (Mariculture in the North Sea Area: Status Quo, Problems and Perspectives. In: Lozán JL, Rachor E, Reise K, Sündermann J, v. Westernhagen H (eds.). Warnsignale aus Nordsee und Wattenmeer - Eine aktuelle Umweltbilanz. GEO, Hamburg. 122-131 (see appendix No 2).

III. **Buck BH, Walter U, Rosenthal H, Neudecker T (2006)** The Development of Mollusc farming in Germany: Past, Present and Future. World Aquaculture 37(2): 6-11, 66-69 (see appendix No 3).

PUBLICATION IV - V

ANALYTICAL, CONCEPTUAL AND LEGAL FRAMEWORK – ARTICLES

IV. **Buck BH, Krause G, Rosenthal H, Smetacek V (2003)** Aquaculture and Environmental Regulations: The German Situation within the North Sea. In: Kirchner A (ed.). International Marine Environmental Law: Institutions, Implementation and Innovation. International Environmental Law and Policies Series of Kluwer Law International, The Hague. 64: 211-229 (see appendix No 4).

V. **Buck BH, Krause G, Rosenthal H (2004)** Extensive open ocean aquaculture development within wind farms in Germany: the prospect of offshore co-management and legal constraints. Ocean & Coastal Management 47 (3-4): 95-122 (see appendix No 5).

PUBLICATION VI AND VII

METHODOLOGY – ARTICLES

VI. **Buck BH, Buchholz CM (2004)** The offshore-ring: A new system design for the open ocean aquaculture of macroalgae. Journal of Applied Phycology 16: 355-368 (see appendix No 6).

VII. **Buck BH (in press)** Experimental trials on the feasibility of offshore seed production of the mussels *Mytilus edulis* in the German Bight: Installation, technical requirements and environmental conditions. Helgoland Marine Research (see appendix No 7).

PUBLICATION VIII, IX AND X

RESULTS – ARTICLES

VIII. **Buck BH, Buchholz CM (2005)** Response of offshore cultivated *Laminaria saccharina* to hydrodynamic forcing in the North Sea. Aquaculture 250: 674-691 (see appendix No 8).

IX. **Buck BH, Thieltges D, Walter U, Nehls G, Rosenthal H (2005)** Inshore-offshore comparison of parasite infestation in *Mytilus edulis*: Implications for open ocean aquaculture. Journal of Applied Ichthyology 21: 107-113 (see appendix No 9).

X. **Walter U, Buck BH, Liebezeit G (accepted)** Larval occurrence and settlement in the German Bight – a trial to estimate potentials for *Mytilus edulis* culture in offshore areas. Aquaculture International (see appendix No 10).

PATENT I AND II

SYSTEM DESIGN AND VIDEO-ANALYSING

I. **Buck BH, Buchholz CM (2004)** Trägervorrichtung zur Kultur von Makroorganismen in marinen Gewässern. (Holding construction for the cultivation of macro-organisms in marine waters). Patent No: DE 10 2004 010 652 (see appendix No 11).

II. **Buck BH, Wunsch M (2005)** Inspektionseinrichtung für Unterwasserstrukturen mit einer Positioniereinrichtung (Surveying unit with positioning device for underwater constructions). Patent No: DE 10 2005 020 070 (see appendix No 12).

The Research Fields Involved

The assessment of the potentials and constraints to sustainable aquaculture development in any marine habitat requires input from various scientific disciplines in order to direct this development towards a successful aquaculture undertaking (e.g. Lovatelli 1988, FAO 1989, Scarratt 1993, Boyd 2003). This holds in particular for open ocean aquaculture, where little practical experience is available to date, although recent research in this area is evolving rapidly (e.g. Condron & Powell 1997, Young & Corbin 1997, Turner 2001, Pérez et al. 2003, Bridger & Costa-Pearce 2003). Thus, pioneering work in biological and engineering disciplines is still required to close some of the critical knowledge gaps. The conceptual approach of this thesis is based on the theoretical feasibility study (**Publication I**) carried out prior to the practical research. Contributions to the biological and technical aspects of offshore mariculture in the North Sea formed the main objective for the biological investigations. Following this a brief overview of the main research fields covered in this thesis is given. The main deduced research questions generated from this framework of understanding are outlined.

Marine Aquaculture

Since the 1970s aquaculture[1] production has grown quite rapidly and is presently one of the fastest growing aquatic food production sectors in the world (FAO 2002). Global aquaculture now accounts for almost 41% of total edible fishery production totalling yearly in over 36 million tonnes of aquatic organisms (Tacon, 1998; FAO 2004a). Projections by the Food and Agriculture Organisation of the United Nations (FAO) of world fishery and aquaculture production in the year 2010 range between 107 and 144 million tonnes of which about 39 million tonnes or even much more will originate from aquaculture (FAO 2004b). This development has been enhanced by a wide-ranging decline in fisheries yields accompanied by an increase in public demand for aquatic products. With an annual share of more than 15% of total animal protein supplies, the production of capture fisheries and aquaculture plays a significant factor for the global food security (FAO 1999).

A wide range of aquatic products is raised in various systems onshore as well as in the ocean. According to the FAO (1999), approximately 300 different products, ranging from fish to shellfish, crustaceans and algae are produced in aquaculture systems today. Most of these traditional-founded aquaculture enterprises are concentrated along favourable (mostly well-protected) inshore water areas (Burbridge et al. 2001). Additionally, the installation of such aquaculture systems in developing countries benefits from the often weak enforcement of integrated coastal management schemes, which regulate equal access to the coastal resources (Davis & Bailey 1996, Adger & Luttrell 2000). Thus, the rise of aquaculture production has specifically taken place in developing countries, especially in Asia, which hold 80% of the global production share (Rana 1997, Lee & Turk, 1998). The importance of marine aquaculture products is increasing in Latin America and Africa (Baker & Jia 2000) and these days in North America and Australia (FAO 2004a).

Over the past two decades outputs have also substantially increased within the EU countries (FAO 1999). However, in contrast to production progress in developing countries, the aquaculture production in Europe has a short history and accordingly, regulatory frameworks in countries bordering the North Sea are diverse and still emerging (**Publication I-V**). Especially in Germany favourable coastal sites for the development of modern aquaculture are extremely limited. Production level in this food sector is therefore small (**Publication I-III**, Rosenthal & Hilge 2000). The intensive use of coastal habitats gives rise to spatial conflicts and cause increasing water pollution, thereby leaving little room for expansion of coastal aquaculture. This has stimulated the efforts to move offshore,

[1] The FAO (Food and Agriculture Organisation of the United Nations) defines aquaculture as the farming of aquatic organisms including fish, molluscs, crustaceans, and aquatic plants. Farming implies some form of intervention in the rearing process to enhance production as well as ownership of the stock being cultivated.

where little spatial regulations have been established so far and clean water can be expected (Dougall 1998).

Due to the technological capacity of the US and their extended marine areas, the movement of aquaculture activities into offshore[2] areas arose (e.g. Dalton 2004) and has caused other western countries to follow. To this point, some efforts have been carried out to successfully install offshore aquaculture constructions as pilot systems even in the open Pacific but none have so far reached a continuous commercial operation. In particular, projects carried out in the US were of prime importance for the successful installation of various offshore systems (e.g. Loverich 1997, Loverich & Gace 1997, Braginton-Smith & Messier 1998, Loverich 1998, Loverich & Forster 2000). These efforts led to the idea to include various disused oil platforms in the Gulf of Mexico in a multi-use concept (Miget 1994, Wilson & Stanley 1998). The National Sea Grant College Program funded such research projects to explore offshore regions for mariculture purposes. The Open Ocean Aquaculture Program at the University of New Hampshire is one of a few attempts (Ward et al. 2001) as well as the Hawaiian Offshore Aquaculture Research Project (HOARP) (Ostrowski & Helsley 2003).

In order to render these new potentials of offshore aquaculture production in the German Bight, the following issues need to be addressed:

- How can the development of open ocean aquaculture as well as aquaculture activities within Germany's territorial waters be encouraged? (*Publications contributing to this objective: I, II, III*)
- Is there a potential to use existing structures for the cultivation of aquaculture organisms in offshore environments? (*Publications contribution to this objective: I, III, V, VI, VII, X*)
- Is there a possibility to combine open ocean aquaculture with offshore wind farms? (*Publications contributing to this objective: I, III, V*)

The Offshore Environment

Like elsewhere, the utilisation of the marine waters in the German Bight is manifold and quite competitive, such as shipping (trade or private), recreational activities, extraction or disposal of gravel, marine missions, fisheries, mariculture, offshore wind farms, cable and pipelines, establishment of nature reserves and other marine and coastal protected areas (**Publication I, IV-V**, BSH 2004a). In contrast, the number of competing users within offshore regions is relatively low, thus favouring the offshore environment for further commercial development (e.g. offshore wind farms, open ocean aquaculture) (**Publication I, IV-V**).

Contrary to coastal inshore areas where beaches and their adjacent nearshore zones act as buffers to absorb wave energy, offshore regions can be described as high energy environments, fully exposed to waves, weather and currents. Numerous studies have shown that in offshore areas, waves can reach remarkable heights (e.g. Führböter 1979, Führböter & Dette 1983, Becker et al. 1992). High wind speeds occur regularly in offshore areas giving rise to the idea for renewable energy utilisation in offshore wind farms. Currently in Germany a major political incentive[3] exists to install offshore wind

[2] According to McElwee (1998) aquaculture, which is exposed to all biotic and abiotic conditions in unprotected open ocean environments is defined as offshore aquaculture. Muir (in Basurco 2001) defines offshore aquaculture as all locations beyond the coastline. In this thesis the term „offshore" is defined as all locations 6 nautical miles beyond the coastline.

[3] Wind energy continues to be the world's most dynamically growing energy source. The first initiative towards an economy based on renewable energy resources in Germany was set by the governmental decision to gradually reduce the use of nuclear energy. It is common belief, that the use of renewable energies contributes towards a sustainable development, contrasting with the gradually diminishing fossil-nuclear energy reserves. This national policy also reduces simultaneously the output of CO_2 to the atmosphere (Kyoto protocol), while fostering the efforts to produce more wind-generated energy in Germany. So far, this development has been successful to such an extent that almost 15% of the energy needs are covered by this technology. Germany invested heavily in windmills along the northern coast. According to the BWE (2004), Germany had 15,797 wind turbines with a rated power of 15,327 MW, which is 53.4% of Europe's and 39.1% of the worldwide power generation (6,370 MW in the US, 6,202 MW in Spain, 3,110 MW in Denmark and 2,110 MW in India).

farms (BMU 2002, Tiedemann 2003). The major reasons are the policy to reduce the dependence on conventional fossil energy resources as well as the need to reduce the environmental harmful CO_2 loads.

In the North Sea, strong tidal currents exist (Mittelstaedt et al. 1983) and in the higher latitudes ice movements during winter are frequent phenomena (Strübing 1999). Water temperatures depend on the seasons (BSH 2003) and salinity, however, varies only little (except for some estuarine areas) (BLMP 2002). In comparison to inshore areas, the water quality is regarded as very good (Dougall 1998, Takayanagi 1998, BSH 2003).

Especially the latter is considered a key incentive to move offshore with aquaculture operations and to use pylons or the jacket groundings of the offshore wind turbines as possible attachments to secure moorings of the mariculture constructions in this harsh environment (**Publication I, V**). Over the last decades, substantial insight has been gained on the forces active in the offshore environment. However, these data are only partly useful for the selection of offshore mariculture sites, because they have been gathered primarily for other user needs and therefore lack specificity to address the biological potential of these sites. Thus, little is known about the hydrodynamic properties (e.g. drag coefficients = C_D) generated by currents and waves to which all organisms are exposed. Knowledge on the tolerance limits are required which can be used to determine some major force effects on the organisms' habitus (Denny 1988, Vogel 1994).

Additionally, the intensity and direction of the currents responsible for the dispersal of mussel spat need to be assessed in order to estimate how far out mussels potentially settle and grow successfully.

This allows addressing the potentials and constraints of the selected candidates to commercial viable offshore aquaculture. Further, resistant cultivation techniques have to be tested in various modes (floating, submerged, different mooring designs) adapted to the offshore environment.

From this understanding, the following tasks were specifically addressed in this thesis:

- Which type of data are necessary to select favourable offshore sites? (*Publications contributing to this objective: VI, VII, VIII, X*)
- How do cultivated organisms respond to the varying physical offshore dynamics and is there a straightforward methodology to assess the resistance of cultivated organisms to survive in offshore habitats? (*Publications contributing to this objective: VI, VII, VIII, X*)
- How are differently constructed culture systems affected by high energy environments and can a suitable design be identified that withstands high energy offshore forces? (*Publications contributing to this objective: VI, VII*)

Seaweed and Mussel Cultivation

In the North Sea, only candidates which are indigenous can be considered so as to avoid the disruption of local flora and fauna in the highly sensitive areas in the Wadden Sea. This limits economic opportunities to the aquaculture enterprises, as only a few indigenous candidates are regarded as high-value species (**Publication I**, BLE 2001, 2002, 2003). However, since offshore mariculture systems cannot be visited on a regular daily basis, extensive culture species with modest service needs offer themselves as favourable candidates. In this study, the main focus was placed on the cultivation of the indigenous seaweed *Laminaria saccharina* and the bivalve *Mytilus edulis*. Mussels and seaweeds are cultured mainly in extensive systems throughout the world whereas the latter is traditionally-founded almost exclusively cultured in Asian countries.

World aquatic plant production was 10.1 million tonnes (40% of total aquaculture, FAO 2004a), of which 80% originated from China followed by Korea and Japan. In Europe, seaweed cultivation plays a minor role (5,000 tonnes in the year 2000, trend declining), (FAO 2004a). So far no commercial seaweed production exists in Germany, however, since 2002, roughly one tonne of *Laminaria saccharina* is farmed annually by an extensive fixed off-bottom longline technique in the Baltic Sea (Piker pers. comm., CRM 2001). *Laminaria saccharina* is a brown seaweed providing numerous valuable products: e.g. phycocolloids used as emulsifiers and stabilizers in the food and cosmetic industries (De Roeck-Holtzhauer 1991, McHugh 2003). Further, these brown seaweeds are used for waste water treatment and nutrient recycling of farm effluents in integrated aquaculture systems (Subandar et al. 1993). They have also been employed to absorb heavy metals from industrial sewage (Sandau et al. 1996, Stirk & van Staden 2000).

Laminaria saccharina can be "seeded" on ropes (see Chapter: "Techniques Tested for Open Ocean Aquaculture"), which are fixed to various suspended or floating culture designs. Unfortunately, there is a great concern that the pre-cultivation of Laminarians in tanks onshore results in a sensitive thallus, which can not withstand the forces experienced in offshore environments. Therefore, it is necessary to understand the behaviour of these plants being cultured under harsh weather conditions. Furthermore, site selection criteria need to consider the effects of nutrient concentrations and sedimentation loads within the water column on the cultivated seaweed.

This leads to the following questions:

- What is the growth potential of cultivated *Laminaria saccharina* in offshore locations in terms of biomass gain, specimen loss in storms and grow-out time? (*Publication contributing to this objective: VI*)
- Do cultivated organisms resist the forces generated in offshore environments and do they survive in offshore habitats? (*Publications contributing to this objective: VI, VIII*)
- What are the specific hydrodynamic properties expressed e.g. by drag coefficients (C_D) that are necessary to calculate drag experienced by the Laminarians? (*Publication contributing to this objective: VIII*)

The annual production of bivalves including mussels, clams, scallops, oysters, carpet shells and cockles reached 10 million tonnes, which is equivalent to the aquatic plant production (FAO 2002). In Europe, the blue mussel (*Mytilus edulis*) is the main culture species reaching up to 500,000 tonnes annually (major producers: Spain approx. 250,000 t, the Netherlands approx. 100,000 t, and France approx. 55-60,000 t; FAO 2004a). In Germany, there are two regions used for blue mussel cultivation, both bordering the North Sea: Lower Saxony (up to 16,000 t·year^{-1}) and Schleswig-Holstein (up to 42,000 t·year^{-1}) (Hagena 2002). The only other candidate, cultured in the German Bight, is the Pacific cupped oyster (*Crassostrea gigas*) with an annual production of about 85 t.

Prior to this thesis, only extensive on-bottom cultivation of blue mussels existed in Germany. These mussels originate from intertidal and subtidal inshore areas. They are generally highly infested with various parasites (e.g. Lauckner 1983, Dethlefsen 1992, **Publication IX**). Parasites, such as trematodes, copepods and polychaetes potentially harm the mussel (e.g. reduced survival under environmental stress, see Calvo-Ugarteburu & McQuaid 1998, Wegeberg & Jensen 1999; reduced growth and condition, see Taskinen 1998, Wegeberg & Jensen 2003; reduced production of byssus threads, see Lauckner 1983; generated sterilisation, see Seed 1976, Coustau et al. 1990; reduced condition, see Theisen 1987, Camacho et al. 1997; negative effects on oocytes, see Theisen 1987, Tiews 1988; reduced meat content, see Dethlefsen 1974, 1975; reduced shell strength, see Kent 1981). However, there may be a natural offshore distribution limit of these parasites, which in turn could be a positive incentive for offshore cultivation of mussels.

Due to the methodology (see Chapter "Techniques Tested for Open Ocean Aquaculture") used in the Wadden Sea (North Sea) the inshore and offshore aquaculturist increasingly depends on the recruitment of *Mytilus edulis* and the settlement success of mussel post larvae. Therefore, it is of

prime importance to understand the distribution of mussel larvae in the water body and to investigate the settlement success of mussels on a given substrate.
Key questions to address here are identified as follows:

- Can the growth potential of blue mussels be compared between inshore and offshore habitats in terms of food availability? (*Publications contributing to this objective: VII, X*)
- Is there a major difference in the parasite load of traditionally cultured mussels from inshore habitats compared to mussels cultivated in open ocean aquaculture and does parasite load affect growth performance? (*Publications contributing to this objective: IX*)
- How does the abundance of mussel larvae in offshore locations affect the settlement success on various seed collectors? (*Publications contributing to this objective: VII, X*)

Techniques Tested for Open Ocean Aquaculture

Worldwide several techniques exist to cultivate seaweeds and bivalves. The procedures mainly depend on the species, their life cycle phase of cultivation and the location for grow-out (e.g. Doty et al. 1987, Lovatelli 1988, Baluyut 1989, Kain (Jones) 1991, Hickman 1992, Scarratt 1993, Gosling 2003). When considering two species only, the macroalga *Laminaria saccharina* and the blue mussel *Mytilus edulis*, cultivation methodologies vary in co-culture as well as in single culture. Since an overall interest to move aquaculture activities to more offshore locations exists, different suggestions for technical structures have been made throughout the world (see proceedings of four OOA-Conferences: Polk 1996, Hesley 1997, Stickney 1998, Bridger & Costa-Pierce 2003).

Major difficulties in the development of suitable techniques for open ocean aquaculture are the harsh environmental conditions which place an enormous stress on materials. Depending on the impacting hydrodynamic properties, different technical setups can be distinguished. One of the interesting possible linkages of aquaculture is the combination with offshore wind farms as these would provide stable technical fixing structures for the cultivation systems (**Publication I, V**). So far the costly infrastructure for offshore aquaculture systems is one of the major drawbacks in the development.

According to Tseng (1989) the cultivation procedure of *Laminaria saccharina* can be divided into two separate steps: In step (1), the seedling phase, spores are artificially released from mature sporophytes and seeded on a given substrate (ropes wrapped around plastic frames), where germination of gametophytes, the sexual maturation of male and female gametophytes and at last the development of zygotes into juvenile sporophytes takes place. In step (2), the grow-out phase, culture ropes with juvenile sporophytes are transferred to the open sea. In the grow-out phase *Laminaria saccharina* sporophytes grow on ropes for one season to a frond length of approximately 2 m.

When natural reproduction of mussels occurs, gametes are released into the water column where fertilisation takes place (Strathmann 1987). The larvae undergo all trochophore and veliger stages when settling on a given substrate starting metamorphosis. According to Pulfrich (1995) and Walter & Liebezeit (2001) this process normally takes place at spring time (larval peak in May) in the German Bight. The cultivation of blue mussels can be divided into two steps: in step (1) the naturally occurring spat collection is achieved by deploying artificial substrates (Walter & Liebezeit 2003). Usually, spat collectors are made out of unravelled polypropylene lines or sisal ropes, to offer the mussel's post larvae substrate for settlement (Hickman 1992). After several months (step 2), collectors are retrieved and mussels thinned out and reseeded on ropes to provide space to improve growth and allow fattening (Scarratt 1993, Gosling 2003).

To operate culture phase (2) of both species, *Laminaria saccharina* and *Mytilus edulis*, an appropriate system design, such as suspended longlines or floating ring-structures, has to be deployed and securely moored in order to resist the stress forces of incoming waves and tidal currents as well as swell. In addition, it was necessary to assess what kind of technical structure supports best the growth of the organisms (e.g. prevention from loss or mortality) while also assessing whether such systems provide reasonable production returns. Finally, potential combinations with offshore wind turbines had to be assessed. Therefore, the following tasks were addressed in this thesis:

- Can a system design that resists the regular as well as extreme environmental high energy forces under North Sea conditions be constructed for seaweed and mussel cultivation alike? (*Publications contributing to this objective: VI, VII*)
- How can bio-technological and scale-up design criteria be incorporated into a multiple-use offshore activity that combines also with wind farm locations? (*Publications contributing to this objective: I, III, V, VI, VII*)

Aspects of Integrated Offshore Management

The overall highly competitive use of the German North Sea area highlights the need for sufficient regulations to optimise co-management of the resources (**Publication IV-V**).

Since a new stakeholder appears on the list of users, the emerging branch of offshore wind farms (Gierloff-Emden 2002, Dahlke 2002, Tiedemann 2003), new opportunities co-evolve to invest in accompanying activities. So far, 23 project applications for wind farms in the German Bight have been filed with a total number of wind turbines per farm ranging between 80 and 500 (BSH 2004a, 2004b). The interest to link such farms with aquaculture production is increasing. On November the 9th (2001) the Federal Maritime and Hydrographic Agency (BSH) granted the first approval for the installation of a pilot offshore wind farm. The Prokon Nord Company received the permit to install 12 wind turbines in the German EEZ of the North Sea with the option to expand the wind farm up to a total of 208 wind turbines by the year 2010. On December the 18th (2002) another company, Offshore-Bürger-Windpark Butendiek GmbH & Co. KG (OSB), obtained the authorisation to install 80 wind turbines until 2006. From March until October (2004) five further wind farm companies received their permits to install offshore wind turbines in the EEZ[4].

The advantage for Germany's offshore aquaculture development lies in the potential combination of these uses. While windmills use the wind above the surface to produce energy, their fixed pylons, commonly concrete fundaments or metal jackets, offer a basis to connect systems used in aquaculture. The combination of these two industries has to cope with some forces generated by the high energy environment and options for co-designing the infrastructure can be negotiated. Additionally, the multi-use concept of these two industries can assist to eliminate user conflicts.

The incentive for offshore farming is therefore twofold: (1) The wind farm companies show conspicuous interest in using the offshore areas in a multifunctional manner to avoid user conflicts with fishermen (Richert 2004, Feddersen 2004), who may lose parts of their traditional fishing grounds. In addition, (2) interests come from the Organisation of Shellfish Producers in Emmelsbüll-Horsbüll (Ewaldsen 2003), who see an alternative to offshore fishing and inshore seed collection in the establishment and operation of a mussel farm, at first at a small scale.

The management of ecosystems can be improved by learning from the development and outcome of a variety of possible management systems, their dynamics, implications and future perspectives (Berkes & Folke 1998). Especially in the tropics, the increasing numbers of aquaculture systems have changed the face of the coasts, which in turn has influenced the societies trying to gain their livelihood by the opportunities which the coastal system holds (Rönnbäck 2001). In Germany, aquaculture is yet

[4] (1) Energiekontor AG: 80 wind turbines, (2) Projektgesellschaft PNE2 Offshore mbH: 77 wind turbines, (3) Amrumbank West GmbH: 80 wind turbines, (4) WINKRA Offshore Nordsee Planungs- und Betriebsgesellschaft: 80 wind turbines, (5) Sandbank 24 GmbH & Co. KG: 80 wind turbines.

a very minor player with little consideration in coastal management schemes. However, similarities between offshore environments throughout the world exist with respect to the missing/limited legal regulations of activities within these areas (e.g. Cicin-Sain et al. 2001). Generally, only a few interest groups are actively introducing their own value perceptions and economic interests, which are not necessarily based on the local conditions, thus shaping the offshore environment to their interests. Due to their high degree of political representation, only little control of the outcomes of such activities has taken place so far.

However the increasing demand of human utilization of offshore areas, e.g. multifunctional use of offshore wind farms and open ocean aquaculture, requires new innovative management schemes. For the development of management recommendations that include offshore mariculture, knowledge on the productivity of different types of candidates is a prerequisite.

Out of this framework of integrated offshore management the following tasks were addressed specifically:

- How is the current legal structure of marine aquaculture with special reference to open ocean systems in the EEZ? *(Publications contributing to this objective: IV, V)*
- Is there a possibility to establish an integrated management approach in the offshore area? *(Publications contributing to this objective: IV, V)*

Logistic Approach and Timing for the Multi-task Research Work

Offshore aquaculture still needs to find its place in most national legislation worldwide (**Publication I, IV**, Polk 1996, Hesley 1997, Stickney 1998, Cicin-Sain et al. 2001, Bridger & Costa-Pierce 2003). Thus, prior to the start of any type of aquaculture installation, the legislative issues require attention as they are the key to the question where aquaculture can take place and what biological, technological and environmental criteria will be set and must be met. The lack of such a framework in offshore aquaculture may provide a window of opportunity to develop integrated offshore management schemes in which multifunctional use of ocean space is anchored while accommodating the biological and technological criteria that the available knowledge-base allows to employ.

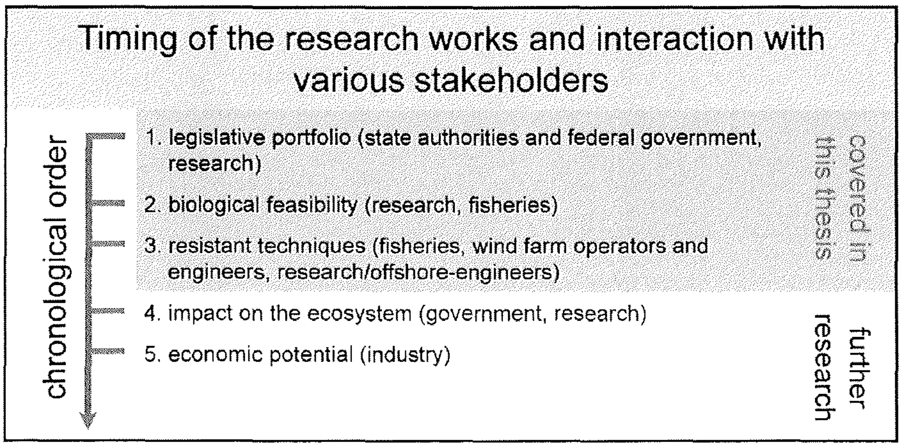

Figure 1: Chronological order of research sequence and main actors.

Following the assessment of potentials and constraints pre-set by the legislative framework, biological questions can be tackled. Only if the biological feasibility can be satisfactory assessed, and the required bio-technological adjustments be identified, it will be possible to determine under which economic and socio-economic conditions an offshore mariculture system may render positive returns to the owner and can operate sustainably. This involves mainly the cooperation between researchers and fisheries. Once the biological requirements are identified the main focus of the research deals with the development of robust techniques and cultivation structures that withstand the harsh environmental offshore conditions. The development and biotechnological performance tests can only be addressed in close cooperation with wind farm operators, engineers, local fishermen, mussel farmers, and fisheries scientists. If these three issues (legal framework needs, biological performance, technological requirements) are successfully answered, the impact of an offshore aquaculture activity on the environment must be assessed. Here, predominantly the government authorities and the experienced aquaculture-oriented scientists are in need of close cooperation to precisely identify the criteria and management regulations to attain an environmentally friendly and sustainable operation. Although economic considerations always have to be considered at each step of the development (and needs to be included into biological and technological study design) the economic viability of such multifunctional offshore aquaculture development can only be accurately assessed towards the end of the project. This requires the integration of knowledge from all involved in the development with bio-economics being only one key component. From this understanding, a logistic scheme for

the timing of the research work under the identified priority topics was developed, including the integration of various actors. The following scheme outlines the sequence of study elements enacted under the overall objectives of the thesis (Figure 1).
In this thesis much work was necessary to establish the essential base-line data for the various biological and technical aspects of offshore aquaculture as well as on the legislative issues.

The impact on the ecosystem was not subject of this thesis, as only two longlines and two ring systems were employed for a longer time period in open waters. The effects of large-scale development with expended units have not been assessed. It can be expected, however, that current regime, wave climate and carrying capacity will be altered and therefore these topics needs to be investigated when the industry expands.

Similarly, the assessment of the economic viability is beyond the scope of this thesis. However, discussions with key actors of the mussel production sector indicated a high interest with a growing incentive for such mariculture systems.

The findings of the multidisciplinary research work at last formed the basic foundation for the assessment of offshore aquaculture potential in a multifunctional resource use concept.

Results & Discussion

Because of the various scientific publications representing this comprehensive study and due to the complementary research objectives the results are compiled and interpreted in accordance with the specific objectives described above. An attempt is made to integrate these findings into a larger conceptual and more holistic approach.

1. Fundamental Investigations: The Feasibility Study

The theoretical feasibility study (**Publication I**) aimed to ascertain the context under which the biological, technical and economic feasibility of an offshore marine aquaculture structure have to be evaluated when considering the cultivation of marine organisms in the North Sea. The planned offshore wind farms offered the basic incentive and possibility for assessing the sites selected for the installation of more than 2000 wind turbines as offshore aquaculture sites, requiring co-management in the German part of the North Sea before the end of this decade (Gierloff-Emden 2002, Tiedemann 2003, BSH 2004b, BWE 2004). This feasibility study concentrated, therefore, on open ocean aquaculture at those sites, while conventional onshore „pond-based aquaculture“ or nearshore marine aquaculture were not covered in this study.

The terms *„Offshore Aquaculture and Open Ocean Aquaculture“* are to date largely unknown or seldom used in the German public, but have today become common „catch-phrases“ in the USA and Asia (Polk 1996, Hesley 1997, Stickney 1998). Due to limited conditions required for the development of modern coastal aquaculture and due to the widespread belief that aquaculture in the high energy environment of the German Bight is not feasible, Germany has experienced some reluctance to invest in the national development of this food production sector (Rosenthal & Hilge 2000, BLE 2001, BLE 2002, BLE 2003). The reasons for this stagnancy are manifold. Germany is highly populated but not a typical coastal country due to its short coastline and the fact that only a small fraction of the population lives in the coastal zone. Nevertheless, user conflicts among the stakeholders within the limited coastal regions do exist (Rosenthal 1997, Krause et al. 2003). Problems with regulations and assignment of areas in the North Sea and its near-shore waters to specific users surfaced and intensified these conflicts. In addition, complex local hydrodynamic conditions such as large wave heights and strong water currents have hindered the development of aquaculture along the North Sea (Buck & Walter 2002, Wirtz et al. 2002, Buck 2003). Germany's coastal waters also suffer from pollution due to river run-off, dense shipping traffic, urban drainage and nutrient release from intensive agricultural use of coastal areas (e.g. Albrecht & Schmolke 2002, Brenk 2002, Brockmann et al. 2002, Weigel 2002). A further factor inhibiting the potential economic marketing of aquaculture in Germany is the general public believe that aquaculture is a strictly environmentally harmful business venture. This belief is often promoted by environmental groups whenever a case of bad management in neighbouring countries occurs (ICES 2000, ICES 2001, ICES 2002).

Thus, support for research on this subject has also been reluctant in the past. The demand for studying all aspects in support of open ocean aquaculture activities in the region is immense if we are to find bio-technological solutions sufficiently fast to link with the development of offshore wind farms. A vast array of costly studies is needed to develop the bio-technologies from the experimental stage through pilot-scale to fully commercial scale operations. However, a major prerequisite in this development is the consideration of the potential requirements of a regulatory framework. Therefore, investigations of the theoretical feasibility study focussed on the four topics which are (1) candidate species and their physical and biological requirements, (2) technical requirements and safety considerations, (3) environmental aspects, and (4) the importance of the regulatory and socio-economic conditions and their "key drivers".

1. **Candidate species:** Macroalgae which extract nutrients directly out of the water column and mussels which filter plankton, were chosen as indigenous candidates for this study. These organisms can be cultivated extensively, largely without serious impacts on the environment except nutrient extraction and plankton grazing. The products that can be gained from macroalgae are subject to manifold commercial demands, most of these currently occur in Asian countries and the USA, with a noticeable increases in Europe (TDI 2003, FAO 2004a). Among mussels especially the blue mussel *Mytilus edulis* shows a high marketing potential on the German market (e.g. 26.500 t in 2001, BLE 2001; 22.000 t in 2002, BLE 2002; 24.000 t in 2003, BLE 2003) as well as on EU markets. The establishment of fish cages in offshore regions would only be possible on an intensive basis to guarantee profitability. A lobster culture would require excess expenditure on human labour while these costs are much less in competitive countries with more favourable protected sites and vast coastal resources. Next to high costs, the latter two sectors bear more technical difficulties in offshore systems compared to the effectively operating inshore systems. The results of the feasibility study suggest various indigenous candidates from which the blue mussel *Mytilus edulis* and the brown alga *Laminaria saccharina* were selected as suitable species for further investigations for offshore aquaculture in German territorial waters. These species have the highest potential for being cultivated under the hydrodynamic and environmental conditions prevailing in the North Sea. Their use can be expected to be environmentally sound as little interference with the environment is anticipated. Only the uptake of a small portion of the overall nutrient budget affects the ecosystem due to the filtration capacity of the mussels which alters the plankton biomass dynamics. Even the effect of pseudofaeces production can be assumed to be low as it will be rapidly diluted within the water column. Compared to other parts of the world, this industry will still be relatively small, despite the fact that it holds large economic potential on the German market.
2. **Technical requirements:** Several types of cultivation methods can be used under the North Sea conditions. Predominantly longline constructions are employed for the cultivation of algae and mussels, by which submersible ropes provide the attachment habitat on which the species can settle and grow. Other techniques, such as ring systems, which can be deployed in floating or submerged mode are suitable as well as the construction SOSSEC (Submersible Offshore Shellfish and Seaweed Cage; Buck & Smetacek, unpubl.). The advantage of submersible culture constructions is that the impact of harsh weather conditions and strong wave actions with extreme stress forces on the materials and interconnected structural elements – which affect the lifetime of the units - can be minimised. Thus, a technical linking of these units with the main pylon of the wind turbine dispenses the need for sophisticated and extremely expensive mooring and service units of the aquaculture system, which would also strongly impact the local benthic ecosystem (e.g. long and moving mooring chains). Due to the solid construction of the windmills, such systems would be very safely connected and interlinked.
3. **Environmental aspects:** The degree of water column mixing can be presumed to be high, as water masses are continuously moved and exchanged through strong tidal currents (Mittelstaedt et al. 1983). This high exchange also guarantees a continuous supply of clean, nutrient and plankton rich water with good O_2-conditions (BSH 2003). The influence of salinity and temperature in the areas of planned wind farms will not vary extensively and will be similar at all locations while remaining at all times in the tolerance to optimum range of the culture candidate species (Almade-Villela et al. 1982, Widdows & Donkin 1992, BSH 2003). The concentrations of pollutants (e.g. heavy metals, pesticides and near-surface agents) can be considered unperilous.
4. **Regulatory and socio-economic aspects:** An ecologically and economically sustainable success of offshore aquaculture can only be expected when the principle concept of an Integrated Coastal Zone Management (ICZM) approach is accepted. It is mandatory here that the various bio-energetics and cost-benefits for all stakeholders are considered simultaneously. That requires the integration of the different scientific fields, the various user group needs as well as the flexibility of the responsible authorities to reflect their needs for free operation and safe control in the appropriate

regulations. The involvement of the latter two groups is commonly described as the step from multi-disciplinarity to trans-disciplinarity (Becker et al.1999, Glaser et al. in press), requiring more than just science criteria. Further, all users have to be addressed right from the beginning of a new project in order to find an overarching consensus of all parties thereto.

In summary, there is ample need for practical research pertaining to aquaculture development in the North Sea in order to overcome the current lack of knowledge in Germany in this scientific and commercial sector on which biotechnology and the regulatory guidelines and enforcement measures are based (e.g. principles of BEP[5] and BAT[6] following the Code of Conduct for Responsible Fisheries[7]).

The feasibility study (**Publication I**) was used as a baseline for all further investigations represented in the **Publications II-X** with one shortcoming: the lack of a comprehensive cost-benefit analysis. This was considered beyond the scope of the study, although various data suitable for such an analysis were collected in **Publication I**. A selection of studies based on theoretical assignments (**Publication II-V**) and practical investigations (**Publication VI-X**) were carried out to address the four major topics mentioned above.

Theoretical and legal inquiries focussed on (1) the existing legal framework relevant to offshore aquaculture and the lack thereof, while (2) management strategies in terms of a multi-use concepts for offshore wind farming and open ocean aquaculture were assessed looking at a number of possible scenarios. This was undertaken not without considering the history and status quo of aquaculture development in Germany (1 & 2). Practical research concentrated on (3) biological investigations using the candidate species in performance tests to answer the questions whether these species (here: *Laminaria saccharina*) could resist high energy environments, while at the same time guaranteeing good growth parameters (*L. saccharina*, *Mytilus edulis*) and providing healthy products (*M. edulis*). Technical studies (4) were carried out by testing various system designs at inshore and offshore locations to investigate their location stability and endurance during wave and current forcing and their simultaneous potential to support candidate growth.

2. Field Observations and Analysis: Kelp and Mussel Cultivation

2.1 Methods and Strategies Employed

Being the first study on bio-technology for offshore aquaculture in areas of the German North Sea, it was necessary to carefully select the species and to focus on just two candidates for which the likelihood to assess their specific cultivation needs and behaviour properly can be completed successfully. Several technical aspects were studied on the basis of careful pre-selection of optional solutions tested elsewhere which had a chance for step by step adaptation to the North Sea conditions (**Publication I**). Modifications and new methodological inventions were successfully implemented during the trial cultivations and the biological feasibility analysis (**Publication VI, VII**). The species and the performance characteristics tested were:

a) the **cultivation performance** of *Laminaria saccharina*, which is directly linked to the wave and current impacts during the various stages of growth as well as the cultivation behaviour and performance of *Mytilus edulis*. Special attention was given to seed production based on the

[5] BEP = Best Environmental Practice
[6] BAT = Best Available Technique
[7] Code of Conduct for Responsible Fisheries = FAO (1995)

intensity of larval drift into offshore regions, their settlement on specifically designed artificial substrates and their quality performances in terms of parasite infestation rates compared to inshore conventional farming systems.

b) the major **bio-technical requirements** as well as the necessary adaptations and inventions were assessed for the various system components, focussing on designs that support the cultivation success of the two candidates.

2.1. (a) Cultivation Performance Observations

Studies on *Laminaria saccharina*

The influence of hydrodynamics on the cultivated candidates in the offshore environment was assessed by a two year monitoring programme, during which several cultivation systems were tested directly in an offshore area at the "Roter Sand" location of the outer Weser Estuary. The results were analysed with respect to the species performance of *Laminaria saccharina* in offshore habitats and were presented in two publications: **Publication VI** relates to the length change (LC) of Laminarian plants when attached to various system designs, while exposed to different modes and placed at different locations within the German Bight. **Publication VIII** studied the resistance of Laminarian plants to high waves and drag when also exposed to strong current velocities.

Several studies have noted that young sporophytes of *Laminaria* spp. show a rapid phase of seasonal growth during the first half of the year (e.g. Parke 1948, Kain 1963, Mann 1973) with a transition period thereafter towards slower growth during the second half of the year (e.g. Kain 1979, Lüning & Buchholz 1996). Onwards, Laminarian plants still show growth which is progressively declining from month to month (Lüning 1979, Creed et al. 1998). Thus, to assess the potential for commercially successful offshore aquaculture operations, the key interest focuses on adequate biomass gain over time. Emphasis in this study was placed on the magnitude of length increment per unit time as a criterion for growth. Most growth data for *L. saccharina* found in the literature are calculated with the phylloid's growth rate. However, as the algae were cultivated in dense bundles on the cultivation structures, the difficulty to relocate marked phylloids at the next survey did not allow the use of the commonly employed method of punched holes (Kain 1987) for assessing growth rate in Laminarian blades. On the contrary, length changes were recorded by which -on a monthly basis- a given set of randomly selected plants were measured and an average length calculated.

Results in **Publication VI** clearly show that length changes can differ according to exposure sites, system designs, installation mode and season. The length changes of young sporophytes were high after transfer from the laboratory (seeding unit) to the sea which coincides with findings of the other studies mentioned above. Length increment was best at the sheltered and nutrient rich Helgoland Harbour right after transfer of young sporophytes into the sea. Length increase to a final frond length of up to 2 m was, however, similar among nearshore and offshore conditions over the first season (at Helgoland Roads, Roter Sand, Sylt). These results mirror similar frond growth ratios described by various scientists (Parke 1948, Mann 1973, Kain 1979; Lüning & Buchholz 1996, Creed et al. 1998). The similar final lengths of offshore grown plants to those originating from inshore nutrient rich habitats may be explained by the fact that the surrounding water is continuously changing permanently thereby replenishing its nutrient supply, removing waste products and preventing the settling of silt (Kain & Norton 1990). The rapid interface exchange at the plant's surface may guarantee a good concentration and diffusion gradient for nutrient uptake (Wheeler 1980, Jones 1993), thereby compensating for potentially lower nitrogen and phosphate concentrations in the water column.

One draw-back for a more extended interpretation of the results in **Publication VI** lies in the fact that there are no data available from "real" offshore habitats as reference values. Further, due to extremely harsh weather conditions resulting in the loss of parts of the specific culture test construction, only few data were available on biomass yield, making the representativeness of the results somewhat questionable. Therefore, one finding pertaining to the utilisation of offshore habitats is that there are potentials to produce *L. saccharina* at least in similar yields as one can expect from nearshore and protected sites. Nonetheless, the major interest from a farmer's perspective is not the way of how to calculate the growth rate *per se* but the expected biomass yield after a season that is relevant for a commercial aquaculture enterprise. Due to the harsh environmental conditions which strongly impacted the employed technical cultivation structures that year the harvest success was limited and the question of true biomass gain could not be answered satisfactorily.

However, as a spin-off result the idea emerged to analyse the forces experienced by the attached algae in more detail (**Publication VIII**) and to assess, if and in what manner these forces affect the growth behaviour of *L. saccharina*. The results led to new insights with consequences for future biotechnological development.

The degree of exposure may influence the shape of the algae plants and their resistance to environmental forcing considerably. Findings from Koehl & Alberte (1988) and Johnson & Koehl (1994) demonstrated that algal plants grown in exposed sites show morphological differences to those originating from sheltered conditions. While the latter have phylloids with thick and undulate margins, those cultivated at offshore sites are thin and streamlined.

Only a few studies investigated macroalgal production as a function of current velocity. Gerard & Mann (1979) found highest production rates from sheltered *L. saccharina* due to higher nitrogen concentrations nearshore, however, Sjøtun et al. (1998) described a positive correlation between the annual growth and wave exposure. Despite the disadvantage of elongated plants to have an assumed smaller frond surface, the supply of nutrients increases with the intensity of water motion (Wheeler 1980), while at the same time photosynthetic rate (Koehl & Alberte 1988) as well as growth rate (Leigh et al. 1987) increases too. In this case it can be assumed that the currents support a strong nutrient uptake while the mainly horizontal orientation of the blades allows the exposure to high irradiance to support photosynthesis (Jones 1959).

As *L. saccharina* is a sessile organism which is attached to the culture line, the level of risk to lose the cultivated algae due to environmental forces (e.g. wave energy, current velocity) in offshore systems is of prime interest for mariculture enterprises (**Publication VIII**). Forces to break the Laminarian stipe or to dislodge the holdfast from the culture line were thus investigated as well as the drag experienced by the algae through waves and currents. Drag increased with size, current velocity, wave height, and with morphometric characteristics being more undulated instead of elongated. This demonstrates that the forces on the stipe result from hydrodynamic drag on the blades and that the drag is proportional to the blade area (Peterson et al. 1982).

As high energy environments with strong currents cause a more streamlined morphology in contrast to the protected environments (Gerard 1987), their narrow and flat blades flapped with lower amplitude and collapsed together into a narrower bundle in increasing water flow and thus creating a lower drag coefficient than those Laminarians with wider and undulated blades. The analysis in **Publication VIII** showed that plants from sheltered sites are easier taken apart than those from offshore sites and that most stipes from protected plants break before being dislodged. Further, it was shown that the dislodgement is a function of the forces experienced during growth. Following Koehl (1977) cell structures, such as the arrangement of the cellulose fibrils and visco-elastic gel matrix in the cell walls of the cortical tissue, support extensibility and therefore prevent the stipes from breaking. It can be assumed that stipes and holdfasts that experience strong currents since they are attached to ropes survive higher forces than those settling on substrates in protected environments. Plants transferred to sea in an early growth stage may adapt to the forces occurring in offshore sites (Buchholz & Buck, unpubl. data). The findings suggest that the mechanical forces necessary to break the stipe or to dislodge the holdfast must be quite high. For instance, at the shallow location "Roter Sand" wave and current velocity are normally insufficient to generate such forces. Thus, to render successful cultivation harvest of *L. saccharina* a combination of being strong (e.g. stipe and holdfast) and being extensible and flexible (bending) is most desirable.

The outcome of **Publications VI and VIII** is that there is no disadvantage to plants growing in offshore environments. On the contrary, cultures in sheltered conditions experience a higher drag at a given current velocity and wave height which results in an increase of the possibility of being dislodged and, due to a higher possibility of fouling, may loose more biomass than their counterparts in offshore areas. Consequently, the monitoring of the cultivation behaviour of *L. saccharina* provided expedient results on the nature of the influence of the offshore dynamics on their cultivation potential, including their quality characteristics. The influence of the offshore dynamics on the growth behaviour was assessed and discussed in **Publication VI** in an aquaculture context as well as their interlinkages to morphological responses of the single plant (**Publication VIII**). The question whether offshore farming provides a different final product composition and less seasonal variability of the concentrations of components of interests remains to be researched.

Studies *on Mytilus edulis*

The dynamic nature of the seasonal abundance of mussel larvae in the water column of the German Wadden Sea has shown that a significant larval peak can be distinguished in May (e.g. Pulfrich 1995, de Vooys 1999) that can be related to the natural spat fall from mussel beds within the tidal backwaters of the Lower Saxonian and Schleswig-Holstein islands. Walter and Liebezeit (2001) found out that even in years with a bad recruitment ratio on natural mussel beds, suspended culture techniques could overcome the shortage of seed mussels when settlement success in natural beds is low. Collecting vast amounts of mussel spat on artificial substrates in the open water column provides a sufficient supply for successful commercial cultivation. This is crucial for blue mussel aquaculture as the spat collection is the first vital step in the cultivation procedure (Hickman 1992) and therefore called "the pre-cultivation of mussels".

Using an annual monitoring network of 18 offshore test locations and one longline system it was assessed whether mussel larvae can drift offshore from mussel banks in sufficient number to settle on spat collectors in areas where wind farms are planned (**Publication VII, X**). Larval occurrence and spat collection was determined, next to chlorophyll content and POC/TON ratio as an indicator for food availability and quality.

Consequently, the monitoring provided first results on the numbers of mussel larvae in offshore areas of the German Bight (**Publication X**). It was found that an inhomogeneous distribution among all test stations existed, being highest in May at the Schleswig-Holstein (SH) coast ranging from 3,000-25,000 individuals·m^{-3} of water and lowest at the Lower Saxonian (LS) coast 25-1,030 ind.·m^{-3} (**Publication VII, X**). The resulting settlement success on artificial substrates was relatively low and varied at these coasts from 4-29 ind.·m^{-1} of rope (SH) and 55-700 ind.·m^{-1} of rope (LS), respectively (**Publication VII, X**). These findings contrasted with the typical larval concentrations found among the tidal backwaters ranging from 9,000 to 190,000 ind.·m^{-3} (e.g. Heiber 1988, Pulfrich 1995, Boysen-Ennen 1997, de Vooys 1999, Nehls et al. 2001, Walter & Liebezeit 2001). Interestingly, the concentration of larvae was low seawards of Lower Saxony whereas off the Schleswig-Holstein coast high densities of larvae were determined (**Publication X**). Due to the anti-clockwise tidal current in the North Sea (Becker et al. 1992) and due to the dividing influence of the Elbe River inflow the Schleswig-Holstein larvae can be assumed to be of local origin (e.g. tidal backwaters of the islands) whereas those found off the Lower Saxonian coast presumably originate not only locally but also from the Netherlands. This is despite the close spawning areas in the Wadden Sea and the sufficient plankton availability.

The low offshore abundance found during the monitoring programme may be the consequence of seasonal currents and wind forces, which result in a high dilution effect. Therefore, drifting mussel larvae to offshore sites result in declining densities in the water column (Young et al. 1998; Metaxas 2001). Further, most of the larvae drifted not sufficiently far enough to the wind farm sites where spat collectors and their moorings were situated. This is in concordance with the findings of Pineda (2000) who related the spatial drift of mussel larvae to a decreasing concentration of individuals per cubic meter of water going seawards. However, this horizontal drift to offshore sites is commonly described to result in the death of the larvae (McQuaid & Phillips 2000, Roegner 2000, Chicharo & Chicharo 2000) and is therefore considered as a loss to recruitment. The offshore chemical data of the monitoring programme suggest that food quality and availability was at no time limited, but showed a decrease towards the open sea. Thus, it can be assumed that the longer exposure to stressful offshore environmental conditions, such as predators (Young & Chia 1987, Rumrill 1991), adverse water turbulences and currents (Belgrano et al. 1995, Morgan 1995, Richards et al. 1995), but primarily the limited availability of hard substrates for settlement (Bayne 1965, 1983) leads to a reduced abundance of spat at offshore sites. At last, the monthly samplings of mussel larvae were too infrequent to allow a reliable estimate of larval abundance over a prolonged period but reflect nothing more than snapshot situations at the day of sampling. This has been demonstrated impressively by Brandt (2004), who described a single mass expulsion of mussel larvae, which has a short residence time at a given site. Monthly sampling clearly identifies the overall peak of the spawning season but not the dynamic daily shedding of gametes and subsequent dispersal of larvae which can lead to successful mass settling over greater distances.

Only one report was found in the literature investigating the capture of natural spat offshore the Santa Barbara coastline attached to an oil structure (Conte 1990), which unfortunately did not produce quantitative data on settlement success. Investigations on the pylons of the research platform "FINO[8]" 25 nautical miles off the Lower Saxonian coast showed a settlement of approximately 4,100 individuals$\cdot$m^{-2} (Joschko unpubl. data), however, the reasons for the overall low settlement success at our offshore sites must be left without comparison. Hence, it can be assumed that the observed low larvae concentrations in the water column were not sufficient enough to supply spat collectors with post-larvae. Nearshore spat settlement, about 2 nautical miles off the coast, was described to result in spat numbers of the range between 422 and 1281 ind.$\cdot$0.5 m^{-1} (Alfaro & Jeffs 2003), which can be attributed to the adjacent mussel farms one nautical mile away. Concerning the results of this study, it can be suggested that despite the low settlement success at some offshore spat collectors a combination of both cultivation steps could be employed: The laborious thinning and reseeding at the end of phase 1 should be dismissed as settlement data coincide with spat numbers used for reseeding prior to the grow-out phase (phase 2) in offshore cultures (Langan 2001). Therefore, an extensive way of mussel cultivation at some offshore sites may still prove feasible.

Macroparasites infesting *Mytilus edulis* influence the performance of mussels in various ways. The species involved are in particular trematodes, parasitic copepods and polychaetes, which all can have negative effects on fitness (Kent 1979, Theisen 1987, Camacho et al. 1997, Ambariyanto & Seed 1991), reproduction (Seed 1976, Theisen 1987, Tiews 1988, Coustau et al. 1990), and the immune defence against all kinds of environmental stressors (Sannia & James 1978, Kent 1981, Goater 1993, Wegeberg & Jensen 1999, Desclaux et al. 2004). While these mussel parasites are known to have no effects on human health (Zander pers. comm.) the reduced growth (Calvo-Ugarteburu & McQuaid 1998, Taskinen 1998, Wegeberg & Jensen 2003), the loss of mussels from culture lines due to a lesser byssus threat production (Lauckner 1983) as well as a lower meat content (Dethlefsen 1974, 1975) do have influences on the commercial effectiveness of culture operation and therefore, on the potential for the use of the species at the proposed sites. It was therefore of interest to investigate whether offshore sites are different in terms of the transmission path of life cycle stages of parasites via e.g. birds and intermediate hosts (e.g. snail) to the offshore mussel, or whether the life cycle is impaired or fully interrupted.

[8] FINO = Research platform in the North Sea and the Baltic Sea (Forschungsplattform in Nord- und Ostsee) for e.g. environmental impact assessments, investigations on underwater vibration and bird migration. The Germanischer Lloyd WindEnergie GmbH (GL-Wind) has been entrusted with coordinating the construction, erection, commissioning and operation of the research platform in the North Sea. The measurement platform is located in the immediate vicinity of the potential site of an offshore wind farm.

Studies on the parasite load of blue mussels (**Publication IX**) originating from inshore and offshore habitats have conspicuously shown that mussels settled on artificial substrates at offshore sites are free from macroparasites. While mussels from the intertidal are heavily infested by trematodes, parasitic copepods and polychaetes, those sampled at subtidal and suspended inshore habitats do have an infestation at a quite lesser extent. This reveals a homogeneous distribution of parasite larvae within inshore waters and results in a parasite gradient being highest at the intertidal, declining towards suspended substrates inshore. The high infestation at intertidal sites may be explained by the abundance of first intermediate hosts, thereby always guaranteeing the completion of the life cycle of these parasites (e.g. Villalba et al. 1997, Fuentes et al. 1998, Svärdh 1999, Fuentes et al. 2002).

The first intermediate hosts of the identified trematodes are snails, such as *Littorina* spp. or *Hydrobia* spp. (Montaudouin et al. 2000). Basically, these species are restricted to inshore areas which may explain the absence of trematodes in offshore mussels. Furthermore, a low density of copepod and polychaete larvae inshore and a dispersion effect with substantial "thinning out", the drifting further offshore is also accompanied by a well mixed water column and most likely explains the lack of encounters. Consequently, this results in the absence of these parasites in offshore suspended mussels. The platform ODAS II (20 nautical miles offshore) was an apparent exception and exhibited some offshore mussels carrying the parasitic copepod *Mytilicola intestinalis*. This outpost installation is a 20 year old research platform has already altered into an artificial reef which accommodates a high biological diversity of both flora and fauna (Buck, pers. observation). The observation of parasites at this site seem to signal that even after a very long exposure time in offshore situations, only parasitic copepods made it to an offshore installation. However, in the case of mussel farming suspended cultures do only spend a relatively short time in the water (up to two years) thus lacking the necessary time span to create a highly diverse "artificial reef".

2.1. (b) Observations on the Bio-Technical Requirements

The investigational strategy chosen for the development of scientific criteria to improve the culture technique was to employ initially already existing system designs and to analyse their physical and bio-technical performance under the harsh environmental conditions in offshore areas of the German Bight. Four different principle designs were employed: longline, grid, ladder and ring constructions (**Publication VI, VII**). These were used for on-growing. A specifically designed offshore spat collector for post-larval settlement of mussels was also used (**Publication X**). Besides ease of everyday handling, special attention was given to a number of biological criteria to evaluate the performance of the systems, e.g. how these designs supported or hindered good biomass growth of the candidates. A major challenge in this approach was to find the best technical modification for each of the systems that would resist the harsh offshore conditions best, while also providing good cultivation results and easy handling during service for maintenance and for harvesting. **Publications VI, VII and X** describe the test results of several pre-cultivation steps that were required for both candidate species which preceded the firm recommendations for the successful installation of the culture systems offshore.

Laminaria saccharina pre-cultivation

The cultivation of *Laminaria* utilised so-called "force-cultivation" (Critchley & Ohno 1997) techniques which commenced with the pre-cultivation in land-based facilities (**Publication VI**). This procedure to produce juvenile sporophytes is well-known and straightforward but labour- and cost-intensive (McHugh 2003) as the development of zygotes and the on-growing on ropes require indoor tank facilities. The pre-culture strategy employed ropes spread over the bottom of tanks while exposed to high irradiance to support photosynthesis, thus utilising the tank in a two-dimensional way only thereby resulting in high operational costs with relatively low output per unit investment.

Despite the creation of a low current in the tanks during the seeding of spores onto the culture line, *Laminaria* covered only the upper light exposed parts of the culture line. When lifted from the plastic frames (*curtains*), the result was that seeding was interspaced with sections without any settlement. This phenomenon suggests that either the turn-over strategy of the *curtains* was not adequate or that the rope on the back parts of the frames received insufficient or too infrequent light exposure to support sporophyte growth (**Publication VI**). This observation led to the development of a new seeding method, which uses a three-dimensional set-up. Two rotating drums, powered by an electric motor, were spooled with *Laminaria* ropes and submerged in the tank (Buck & Lüning unpubl. data). The rotation mode caused a cost-efficient and favourable exploitation of space and high frequency exposure to light. It permitted to harvest from the entire culture mat and all parts of the ropes could be seeded by continuous movement of the spore collectors. Thus the percentage of *Laminaria*-covered culture line was raised considerably, improving the output for both, the seeding density and the subsequent on-growing offshore.

L. saccharina sporophytes grew quite densely on the culture ropes showing different size classes. The largest size class competed successfully for light while at the same time overshadowing the smaller sporophytes. This development can be attributed to an early occurring intraspecific competition which was reported by Creed et al. (1998) for *L. digitata*.

However, considering the need for a commercially successful aquaculture operation the traditional procedure is cost-intensive where especially seeding on the culture lines requires further well-designed investigations to improve efficiency. For instance, the seeding strategy could be modified by (1) diluting the spore suspension and thereby leaving sufficient space for the individual *Laminaria* specimens or (2) by adjusting the structure of the culture ropes with adequate space when spooling on the drums to assure sufficient light exposure of all parts for photosynthesis. However, it has to be taken into account that slightly expanded space causes a negative feedback in supporting settlement and particularly overgrowth by other fouling organisms (Ivin 1996) and therefore needs to be tested over a wide range of space configurations.

The offshore system designs

The results of the technical studies allowed to identify two systems which were best suited for offshore operations from a biological point of view. However, more technical engineering research is yet required to find the most cost-effective mode of construction and choice of materials (e.g. corrosion, longevity to mechanical stress forces), which allows easy handling (e.g. construction, deployment, retrieval, service, repairs) at average and relatively harsh weather conditions.

The major focus of the technical investigation was placed on the development and maintenance of an offshore longline system that provided useful results, which are documented in **Publication VII**. The tests on ladder and grid constructions conducted by other scientists prior to this study (Lüning & Buchholz 1996) were adapted from modifications of the longline which previously faced the same operational difficulties in offshore environments. These are described in more detail below. Additionally, a ring system was employed and modified several times, providing the most satisfactory results in terms of the above mentioned bio-technical requirements over time (**Publication VI, Patent II**).

Performance of the longline design

The longline system design is probably the method that has been mostly used world-wide, especially for *Mytilus* cultivation (Polk 1996, Hesley 1997, Stickney 1998, Bridger & Costa-Pierce 2003). Similar to mussel rafts, the longline has been frequently modified over the course of time. In contrast to rafts operating in a floating mode on the water surface (Hickman 1992), making themselves unsuitable for high energy offshore environments, longlines can be deployed in a submerged mode at various depths to avoid some of these forces at near surface levels (Danioux et al. 1997). Such a flexible system was chosen for the German Bight and moored at the offshore lighthouse "Roter Sand" for long-term monitoring and testing (**Publication VII**).

Initially the first submerged longline system had some major technical difficulties. These difficulties related to the secure installation of the entire system, the choice of the appropriate length of the ropes, the calculation and the performance of the required buoyancy, the resistance of materials used and the safe retrieval of the system at harvest.

The continuous growth of the mussels and other fouling organisms resulted in substantial weight gain per rope and this caused risks of loss. Technical solutions had to be sought for as to the appropriate length of the ropes and their attached floats to support the system with the essential buoyancy. This required careful control and adjustment of buoyancy by adding floats. As surveys to the farm were only possible once a month, incomplete work and servicing at the longline was the result, which resulted in damage to parts of the lines. Collectors that started to gradually sink with increasing weight sometimes touched the sea bottom with their lower end, causing increasing loss of mussels while continuously scraping the floor with each wave movement. Moreover, low buoyancy and heavy weight caused tension stress on connector lines between longlines and therefore sagging between buoys occurred. Slack parts drooped also to the bottom or against collectors which got entangled with each other or with neighbouring lines, again resulting in loss of cultivated biomass. Additionally, one major limitation during the culture trials of mussels on the longline was the lack of expensive service equipment commonly used for the mechanisation of large-scale mussel cultures. Without proper devices it was necessary to pull the mussels off the rope manually as no commercial gear for re-seeding, sampling, and harvesting was available. Because such equipment is expensive and only justified for large-scale operations, a lot of cultivated biomass was lost through improvised handling during the experiments. Furthermore, the research vessel *Uthörn*, which was adequate for the deployment and the retrieval of concrete blocks, was neither suitable for the installation of parts of the constructions nor suited to tow the entire system. These drawbacks resulted in some technical and operational shortcomings of the study, mainly causing incomplete sampling and high loss of cultured biomass during the first year of the research trials.

The use of small inflatable boats for the inspection of the lines and for some sampling procedures was adequate as they could be easily manoeuvred between the lines and buoys. However, the employment of a ship crane to lift collectors was rather complicated and physically impossible as only little wave swell already hindered the retrieval of the line. For inspection, servicing, observation and measurement of underwater objects a submersible camera with a holding unit was developed (**Patent II**). The holding unit of the camera was a telescope bar with a small carriage, which was docked on the longline and could be moved along the ropes by using it as a track. This visual inspection of the entire longline and the collector harness limited laborious and costly scuba dives to a minimum. A modified version of the telescope bar and the carriage allowed additionally the sampling of water and mussel spat.

Thus, the experiences of the first year of practical offshore system operation revealed that it is of vital importance to combine the knowledge and skills of several professionals for the design, deployment and maintenance and operation of the offshore culture construction (e.g. biologists mechanical engineers, marine management, technical skills).

The second year (repeat of the trials) incorporated the experience gained during the first year of the project as much as possible. The breakthrough invention of the second longline trial was the incorporation of a steel hawser line, which provided sufficient shock absorption capacity and thereby greatly enhanced the resistance of the entire structure against the offshore forcing. The highly experienced and professional crew of the buoy layer vessel *Bruno Illing* of the local Water and Shipping Agency deployed and installed the entire longline skilfully so that the installation was correctly placed to the proposed design which made all the difference in performance. The segmentation mode of the horizontal line proved to be a big step forward in the second system design, as it allowed a fractional exchange or modification of sections of the system without interfering with others. This methodological improvement was particularly useful with respect to the scientific study design as well as to the realistic performance in a commercial production system. The longline could easily be equipped with the floats and maintained best its structure as theoretically designed. Instead of hand-spliced eyes, aluminium ferrules were inadvertently swaged on to the ends of some of the wire ropes, however, soluble aluminium in saltwater caused the loss of some parts of the longline and should not be used in future operations. Further, the perpendicular wire ropes which were spliced below the strands of the steel hawser longline did not resist the permanent bending generated by waves and currents and hence resulted in the loss of floats and collectors. This indicated difference in resistance to longitudinal and twisting forces and requires further research on material strength and engineering. A replacement of the short perpendicular steel rope by a metal plate (fixed to the longline by stainless wire rope clips) solved the problem and prevented the system from loss of collectors and floats.

Performance of the ring design

In contrast to the longline system, the design of the offshore ring system remained stable in harsh environments and supported growth of Laminarians while at the same time resulting in less fouling at the offshore site (**Publication VI, Patent I**). Key advantages in the performance of the rings were (besides ease of handling) that:

1. the rings could be towed into the harbour or lifted at sea by a power block to sample or harvest the algae, a feature requiring always calm conditions with longlines,
2. the size of the rings allowed quick servicing of the entire unit while lines will have to be handled individually,
3. the entire ring system was so far a self-made prototype which is not costly but will be even cheaper once mass produced,
4. the possibility to operate the ring in a floating and submerged mode allowed the cultivation of various sporophyte sizes while permitting escape to deeper waters during extreme storms or high UV-irradiation, and
5. the final modification made so far to the ring technique prevents the culture line from being scrubbed by other lines, thereby adding to operational safety and expanding the life time of the setup.

Several tests and modifications of the details of the ring design resulted in an extremely stable and manageable structure that was found suitable to protect the utility by a patent (see **Patent I**).

Performance of the spat collector design

The deployed spat collectors suited best for the investigation on settlement success of *Mytilus* post-larvae. The connected tufts of unravelled polypropylene ropes withstood the strong forces while at the same time allowed spat settlement. All spat collectors retrieved onboard of the research vessel *Uthörn* were densely covered with juvenile mussels and the concomitantly ongrowing of other fouling organisms. The tufts allowed the calculation of individuals per meter of rope.

However, as described above, some major problems arose to catch the marker buoy of the moored spat collector during harsh weather conditions and to retrieve the system on board without any damage or loss of mussels. Further, some spat collectors were lost due to the use of aluminium ferrules in seawater.

2.2. Effects of the Offshore Environment on the System Design and their Feedback on the Cultivation Behaviour

Culture site permits are in general controlled by the government authorities, however, it is of particular importance that selected sites offer optimum (or at least suitable) conditions to support the development of candidate species. Those "optimum" conditions refer mainly to biotic parameters, such as food and nutrient availability. Areas rich in plankton provoke a faster rate of mussel growth (Widdows et al. 1979, Berg & Newell 1986) and sufficient nutrient concentrations support good length increase of *Laminaria saccharina* (Conolly & Drew 1985). Abiotic parameters, such as current velocities as well as wave and swell action, provide enough water exchange. But a site should not be over-exposed to too high waves or storms that could seriously affect the day-to-day work on culture species and systems must be designed to cope with these extremes while being unattended. Storms lead to very strong water movement that can cause plants or mussels to cluster and break apart or even cause physical damage to the culture construction. Temperature and salinity should be stable and within the ecological potential of the candidate (Almade-Villela et al. 1982, Widdows & Donkin 1992, Gosling 2003, Doty et al. 1987). Icing conditions may not be seen as an offshore problem as long as the structures are submerged. However, icing may pose technical problems above or at sea surface (e.g. spray, windchill), particularly during extreme winters. The water depth is another factor, which has to be taken into account. The sedimentation load in the Wadden Sea is presumed to be high (Ehlers 1988, Brown et al. 1989), thus shallow locations (< 10 m) could result in a decreased filtration activity of mussels or cause shadowing effects among *Laminaria* bunches. On the other hand, deeper waters (> 50 m) require a more stable and robust construction and complicate the deployment of the system. A depth of 12-30 m seems to be the optimum range due to the fact that also submerged systems including the culture harness can be installed properly. At the location „Roter Sand" in the outer Weser estuary a permanent water quality control has to be done in order to prevent the outbreak of diseases potentially derived from the industrial and domestic effluents along the estuarine coast.

The techniques used in this study to culture *L. saccharina* offshore clearly identified the newly developed and consistently modified and improved ring-system as a suitable technology to withstand the forces generated by waves and currents. The results also show that the deployed system should be operated in a submerged mode to avoid the most critical surface layer where turbulent stress forces dominate. Further, the system must not be deployed too deep in order to stay within the effective light regimes for photosynthesis.

To conclude the experience with both system designs, it needs to be discussed whether it is advisable to critically and strictly select evaluation criteria according to the evaluation objective:

a) biological parameters, such as settlement success on collector ropes as well as mussel and seaweed growth,
b) the technical resistance/endurance of the entire system to external forcing (e.g. the wave and current action) in offshore areas.

While biological criteria have been discussed previously, here the technical design criteria for the entire system are primarily considered. The development of a cost-effective and cheap culture construction adapted to a given site should be addressed for future studies as this is beyond the present objectives of the study.

The above described issues can be resolved by accompanying research once a pilot-scale or commercial operation is in place. This would permit permanent monitoring and gradual improvement of good operation and management practices while at the same time using appropriate equipment. At this point the opportunity arises to develop BATs and BEPs which are urgently needed for regulatory and enforcement measures.

When deploying a longline system in the open sea a combination of both systems (polypropylene lines and steel hawser lines) can be suggested to operate a stable, wave resistant and durable system design. A material advantage was the polypropylene line which allowed bending and easy splicing at reduced costs while functioning reliably (biologically as well as technically). The use of several small floats supported proper buoyancy and could be easily adjusted and the segmentation mode of the longline promoted the maintenance of the entire construction.

A hose-like longline system can be used as an alternative (Lien & Fredheim 2003). Floats are replaced by PEH tubes, the so-called long-tube, which results in a more secure system with respect to sinking. Instead of single collectors a continuous collector can be used, which is hung like an alternating arrangement of intertwined ropes pegged to the horizontal longline. In addition, long-tubes and continuous collectors can be serviced and sampled by small boats, however, deployment and retrieval of the construction requires larger vessels and an experienced crew.

The ring system proved to be stable and a modification is not necessary. To expand the harvest yield more rings need to be deployed. It is therefore of great concern to set-up coupled rings and to test modified harvesting techniques. A floating construction could be deployed in inshore water sites in shallow water depth.

3. The Legal Portfolio in Relation to Offshore-Aquaculture

In order to establish offshore aquaculture within a multi-use concept in the German EEZ of the North Sea, the current legal structure for offshore management should be assessed with special reference to aquaculture and offshore wind farms. This task was undertaken and is documented in **Publication IV** and **Publication V**.

Like elsewhere, during the past decade, the offshore development in the German EEZ has mainly been driven in a *de-facto* response and open resource assess context. This situation, described by the seminal work of Hardin (1968) as "the tragedy of the commons", still lacks sufficient regulation (**Publication IV**). The German EEZ has faced a serious increase of highly competitive uses, especially by the shipping sector, cables and pipelines, extraction or disposal of gravel, marine missions and fisheries, among others (BSH 2004a). Most of these activities are driven by international operating and financially powerful stakeholders, who have a strong political "client" representation at juridical administration but are only little connected into the overall national management schemes (**Publication V**).

Despite the development of the UNCLOS (United Nations Conventions on the Law of the Sea) agreement (1982) sufficient commonly accepted international regulations for the EEZ are still in *statu nascendi*. On the regional level, several regulations (e.g. *EU Water Framework Directive*) exist which marginally are of relevance to aquaculture, especially within the coastal zone. However, in contrast to capture fisheries, specific European regulations relevant to aquaculture are still less established, except for land-based systems and for the transfer of cultured species for common commercial practice. Other regulations, such as the *Trilateral Wadden Sea Plan*, explicitly aim to limit the current inshore aquaculture areas along the North Sea coasts, but do not include any regulations to safeguard mariculture or to regulate offshore operations. National laws of Germany can be divided into those augmented by the Federal States ("Länder") for the coastal inshore areas (up to the 12 nautical mile zone) and those directed by the Federal Government ("Bund") for the EEZ. For the latter area, legal issues concerning the private use of Federal waters have not been sufficiently addressed. Presently, only one regulation, the "*Seeanlagenverordnung*" (Marine Facilities Ordinance) (SeeAnlV 2002), is designed explicitly to marine offshore area utilisation and thus regulates the approval procedure for site-specific constructions and operations (e.g. wind turbines and oil platforms). With this strictly isolative consideration of each offshore installation by the marine facilities ordinance (SeeAnlV 2002) conflicts with other agents and their interests are provoked. No regional integrative planning procedure is followed and thus other stakeholders may easily be overlooked or confronted with regulations that put their operation at risk rather than protect it.

The analysis reveals that the current management system in the EEZ can be characterised as a linear decision-making process, whereby each of the protagonists contribute in an independent fashion to the final decision, its implementation and its consequences. This policy of granting permits on a case-by-case basis, usually without examining cumulative impacts, increases the potential for conflicts between different user groups (Glaser & Oliveira 2004). The lack of long-term and total system planning is noteworthy and similar to current regulatory regime situations in other countries where management is structured sectorially with little horizontal cross-linking, e.g. for offshore activities such as aquaculture in the USA (Cicin-Sain et al. 2001). Contrasting the findings of Cicin-Sain et al. (2001) and Fletcher & Weston (2002) for the US EEZ, some overall planning of the management, development and conservation of the EEZ in Germany has taken place through the establishment of the geographic information system CONTIS by the BSH (BSH 2004a). This database provides a suitable tool in revealing where spatial conflicts with other uses do or may occur. However, the lacking legislative framework in the EEZ causes a high degree of uncertainty among the stakeholders about how to solve these conflicts.

Nonetheless, the current EEZ-concept holds potential for alternative management structures, i.e. multifunctional offshore management, as little regulation has been developed so far. For instance, one window of opportunity for the establishment of multifunctional use root in the permits obtained by the wind farm companies through the marine facilities ordinance (Dittbrenner pers. comm.). The collateral clause 13 (§ 7, SeeAnlV 2002) describes the need and designation of safety zones around wind farms in order to guarantee safety for shipping and wind turbines. However, if such safety zones, which prohibit any additional use in wind farm areas, are not explicitly necessary, other uses should not be excluded. Thus, alternative provisions for safety measures might be optionally developed, including – besides technical safety – the risk management to transfer exotic species and diseases not only via transfer of seed and spat for growth but also via shipping (e.g. ballast water regulations).

The above example clearly indicates that regulatory measures must also take the bio-technological requirements of offshore aquaculture into consideration, in particular when guidelines for operational safety and environmental quality control are at stake. If these requirements are not well known, bureaucracy may make regulations with best intentions but resulting in counterproductive restrictions that endanger rather than encourage innovative and integrative developments. The bio-technological research of this thesis offers some guidance with what a successful operating offshore farming industry requires, but lacks sufficiently comprehensive data that would allow deriving at Codes of Conduct (FAO 1995) with strict guidelines for BMPs[9].

However, the existing regulations which deal in some way or another with aquaculture have to be tied together in order to provide a basis for straightforward integrative regulations for all stakeholders at all levels. The major issues that have not yet been adequately addressed in the public policy arena relate to the need to ensure security of tenure for the project while fulfilling public trust obligations, i.e. raising the "precautionary principle" (Bodansky 1991). This includes conveying property rights in public waters that are traditionally free and open to all. Thus, Bengston et al. (2001) note that there is a requirement that all activities should be subject to a prior compulsory review of the potentials of multifunctional use, their potential environmental impact and their legislative guidance (control) to allow co-existence. This is especially timely with regard to the limited spatial resources in the German EEZ.

The required integrative legislative portfolio needs to be embedded into the existing international, regional and national jurisdiction and the term aquaculture must gain a consistent definition in all regulations.

The scope to create alliances and synergies between different stakeholder groups, here between offshore wind farmers and open ocean aquaculture operators, exists. However, to date the major reason for the slow progress to establish new innovative and integrative offshore management schemes is the difficulty of addressing different sets of rights and duties in offshore areas in an appropriate legislative context that does not interfere with the bio-technological requirements but allow the system to evolve in a competitive manner with similar systems in other regions.

[9] BMP = Best Management Practice

Conclusions

This study comprises several steps from reviews of the current state of the art, the acquisition of field data, employment of different cultivation techniques in a hardly researched science field, before a first assessment on the potentials and the constraints of open ocean aquaculture could finally take place.

The work provides an opportunity to generate findings about the perspectives and problems of offshore cultivation in the North Sea. Along this way, several conclusions are noteworthy:

The studies on macroalgae have shown that both biological parameters and technical aspects are suitable for the cultivation of *Laminaria saccharina* in offshore environments. Algal frond length increments and the resistance to strong forces have been proven to declare *L. saccharina* an eligible candidate for offshore cultivation. The ring technique in the submerged mode was the adequate design to support this Laminarian culture.

From the results of the offshore monitoring programme it was concluded that mussel farming in the offshore environment off the Lower Saxonian and Schleswig-Holstein coast is effective on a small scale and can be seen as an extensive way (1) to produce seed mussels to supplement the inshore on-bottom culture at times when a low spat fall occurs and/or (2) to produce market-size mussels without the laborious steps of thinning and reseeding and thereby saving costs. Further, due to the absence of parasites in offshore cultivated mussels farmers recognise the challenge to become internationally competitive.

These factors provide a major incentive to expand the development of mussel farming capacity into the offshore area of the German Bight. This would limit the spatial constrained production from the two existing main growing regions within the Wadden Sea of Lower Saxony and Schleswig-Holstein. The movement to offshore cultivation hence lowers the risk of failing continuity of supply to global markets.

Some major findings in design, materials and maintenance on longline systems could be obtained. Especially the technical experiences generated from the two-year operation of the offshore farm "Roter Sand" founded the basis for new insights to resistant techniques for offshore aquaculture. As not all tested cultivation designs survived the high energy environment, it is evident that for a future successful application of offshore cultivation, more research on the technical constrains of system designs is necessary.

Several factors of the potential of offshore aquaculture however are subject to a substantial influence by the current management regime of the EEZ. Thus, especially the legal portfolio has to be viewed as an active component within this development. The analysis in this study revealed, that new innovative management schemes are necessary in order to provide for a sustainable development of the offshore regions. Hereby, the prospect of multifunctional use by co-management may render a positive potential to overcome the current limitations set by the lack of an appropriate legislative framework.

In the combination of these results it can be concluded that offshore farming has a considerable potential for development in Germany. Numerous areas exist that are likely to be suitable for offshore farming in Germany. However, there is a likelihood that considerable public concern will be raised over new areas being proposed for this purpose, thus, these points to the importance of the development of new participation and management strategies in order to mitigate conflicts at an early stage.

Further investigations over a prolonged period are necessary to pay tribute to the natural dynamics of biological systems and thus to enhance the shortcoming of the data collected originating from two seasons only. Additionally, in order to further optimise the cultivation systems of which this study has provided the fundamental functional criteria, a complete planning and operating multi-disciplinary team is necessary. The results of this thesis thus provide tools for a rational allocation of space and resources for the establishment of potentially commercial and sustainable offshore mariculture.

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Publications and Patents

Appendix I

Publication I

Open Ocean Aquaculture und Offshore Windparks: Eine Machbarkeitsstudie über die multifunktionale Nutzung von Offshore-Windparks und Offshore-Marikultur im Raum Nordsee

Buck BH (2002) Reports on Polar and Marine Research 412. 252 pp.

1 2 3 4 5 6 7 8 9 10 11 12

Abstract

The feasibility study deals, on theoretical basis, with the potential multifunctional use of planned offshore-wind farms with commercial marine aquaculture (open ocean aquaculture) in the North Sea area. Exclusively, literature data from existing international experiences are reviewed here, as well as the output of several discussions with experts. Firstly, the study reviews the current "state of the art" of open ocean aquaculture. The data was derived from existing projects within the international scientific community, which focused on candidate organisms, and dealt with offshore technology and maintenance aspects. Choice of location and infrastructure needed was also extracted from the findings of these projects. It became clear, that, in terms of commercial marine aquaculture, Germany, in comparison to many other maritime countries throughout the world, has to date little knowledge and background. Only one offshore aquaculture project nearby the Island of Helgoland was carried out. The current complicated and even counteractive national jurisdiction is identified being one of the main reasons for this lack of knowledge and experience. Next, the vast array of marine protected areas, national parks, as well as input of urban wastewater adds to the calamity. However, especially the hydrodynamics of the North Sea play a key role as hindrance of establishing commercial marine aquaculture in Germany. Secondly, the study carries out a selection of parameters, which need to be met during the decision-making of the location and construction of an offshore aquaculture farm. Next to geo-physical parameters, as wave parameters and local current profiles, other abiotic parameter, such as degree of contamination through urban wastewater are addressed. Additionally, certain biological factors, such as plankton load and the concentration of chlorophyll within the possible locations were derived from existing data sets. A synthesis from these above parameters allowed the identification of suited candidates for a commercially running offshore-aquaculture. It is suggested to employ the cultivation of mussel (*Mytilus edulis*) and pacific oyster (*Crassostrea gigas*), as such a culture could be run extensively in the offshore region and the work-labour being minimal. Similar accounts for seaweed, such as *Laminaria saccharina* and *Palmaria palmata*. Thirdly, the study looked upon the possible selling market of the offshore aquaculture and their candidates in comparison to the performance of existing conventional operated farms in coastal waters. Main focus was placed on existing experience within the European community. It was put out, that a strong market exists for the suggested brown algae and red algae, which is likely to expand in the near future.

Appendix II

Publication II

Marikultur im Nordseeraum: Status qua, Probleme und Tendenzen

Walter U, Buck BH, Rosenthal H (2002) In: Lozán JL, Rachor E, Reise K, Sündermann J, v. Westernhagen H (eds.). Warnsignale aus Nordsee und Wattenmeer - Eine aktuelle Umweltbilanz. GEO, Hamburg. 122-131

1 2 3 4 5 6 7 8 9 10 11 12

Abstract

This chapter focuses on the current situation of aquaculture development in the North Sea region in the light of world-wide decline of wild fish stocks and increasing consumer demand for seafood. With 1.4 Mill. metric tons of annual production the culture of fish, especially salmon and trout, is the most commonly intensively employed aquaculture sector within the North Sea region. This has resulted in several environmental problems, such as eutrophication of the adjacent water column of the aquaculture facility due to food pellets and faeces, as well as the spread of diseases and parasites. The major shellfish species, which is extensively cultured in many countries along the North Sea, is the blue mussel, followed by the Pacific oyster. Several shellfish culture techniques have emerged, which are described and discussed in respect to impacts on the environment as well as their future prospective. The chapter closes with a call for integrative action among the North Sea region states for the further promotion of ecologically and socio-economically sound aquaculture development by endorsing the idea of ICZM in order to sustain its economic potential as alternative livelihood for coastal communities.

2.3.6 Marikultur im Nordseeraum: Status quo, Probleme und Tendenzen

UWE WALTER, BELA H. BUCK und HARALD ROSENTHAL

Mariculture in the North Sea Region: Status Quo, Problems and Perspective: *This chapter focuses on the current situation of aquaculture development in the North Sea region in the light of world-wide decline of wild fish stocks and increasing consumer demand for seafood. With 1.4 Mill. metric tons of annual production the culture of fish, especially salmon and trout, is the most commonly intensively employed aquaculture sector within the North Sea region. This has resulted in several environmental problems, such as eutrophication of the adjacent water column of the aquaculture facility due to food pellets and faeces, as well as the spread of diseases and parasites. The major shellfish species, which is extensively cultured in many countries along the North Sea, is the blue mussel, followed by the Pacific oyster. Several shellfish culture techniques have emerged, which are described and discussed in respect to impacts on the environment as well as their future prospective. The chapter closes with a call for integrative action among the North Sea region states for the further promotion of ecologically and socio-economically sound aquaculture development by endorsing the idea of ICZM in order to sustain its economic potential as alternative livelihood for coastal communities.*

Marikultur in Europa

Die Fänge der Weltfischerei stagnieren (85 Mio. Jahrestonnen), der Bedarf an Fischereierzeugnissen jedoch wächst (FAO 2000). Eine deutliche Steigerung der Fischerei bzw. Ausbeutung der Fischressourcen ist unwahrscheinlich. Damit steigt die Bedeutung der Aquakultur.

Die Hälfte aller Fischereiressourcen ist bis an die Grenze ihrer Ertragsfähigkeit genutzt. Der Bedarf wächst durch (a) die steigende Weltbevölkerung und (b) den gehobenen Lebensstandard breiter Schichten, die sich hochwertige Produkte leisten wollen und können. Die weltweite Zunahme aquatischer Produkte basiert überwiegend auf der Ertragssteigerung der Aquakultur und erreichte 125 Mio. Jahrestonnen im Jahre 1999. Jährliche Zuwachsraten von fast 10% führten zu etwa 39 Mio. Jahrestonnen aus der Aquakultur (Wert 1998 etwa 52 Mrd. US $) (FAO 2000).

In Europa hat die Zucht von Karpfen und Forellen Tradition. Karpfen werden überwiegend in angelegten Teichen mit natürlicher Nahrungskette (oft mit Zufütterung) erzeugt. Auch Forellen produziert man in angelegten Teichen und außerdem in Fließkanälen, Langstromrinnen und Rundbecken, in denen pelletiertes Futter zur Mast verwendet wird. Wenngleich die Ertragszahlen aus der Süßwasserproduktion stagnieren, hat Europa bis heute doch ein breites Angebot an gezüchteten Arten zu bieten. Viele Arten werden jedoch vorrangig für Besatzzwecke produziert, um die Nachfrage aus der Sportfischerei zu bedienen. Einige Arten werden zur Bestandsstützung und -pflege produziert. Hierher gehören die Meerforelle (*Salmo trutta trutta*) und der Ostseeschnäpel (*Salmo oxirhynchus*).

Im Meer überwiegt die Haltung in Netzgehegen: Atlantischer Lachs (*Salmo salar*) in nordischen Ländern, Wolfsbarsch (*Dicentrarchus labrax*) und Meerbrassen (*Sparus aurata*) im südeuropäischen Raum. Ebenfalls etabliert, aber mit weitaus geringeren Mengen, ist die Aufzucht von Steinbutt (*Psetta maxima*) und Aal (*Anguilla anguilla*). Einige Arten sind noch neu in der modernen Aquakultur und werden in geringen, aber ständig zunehmenden Mengen produziert. Hierher gehören der Heilbutt (*Hypoglossus hypoglossus*) und der Steinbeißer (*Anarhichas lupus*).

Unter den Schalentieren hat die Miesmuschel (*Mytilus edulis*) große Bedeutung. Die europäische Aquakulturproduktion für Mollusken betrug 1997 etwa 1,7 Mio. t (Wert 3,8 Mrd. US$) oder 4,6% der Weltproduktion (VARADI et al. 2001).

In den letzten Jahrzehnten hat die Aquakultur an den europäischen Küsten erheblich zugenommen, allerdings nur zu einem geringen Teil im Nordseeraum. Die Anzahl der kultivierten Arten ist gestiegen. Mengenmäßig wird der Zuwachs in der Aquakultur von den traditionellen Arten bestimmt. Immer diverser werden die eingesetzten Verfahren in der Aquakultur, wobei bislang überwiegend die gleichen Systemprinzipien angewandt werden. Neben konventionellen Teichen (mit Naturboden), Fließkanälen und Rundbecken für die Fischzucht, werden für Schalentiere im Gezeitenbereich ufernahe Pfahl- oder Gestellkulturen sowie Einfriedungen eingesetzt. Über tieferem Wasser sind Floß- bzw. Langleinen übliche Systeme. Gelegentlich werden mehrere Arten in kombinierten Systemen erzeugt (Polykultur), eine Entwicklung, die zunehmend Beachtung findet.

Marikultur in den Nordseeanliegerstaaten

Nur einige Küstenregionen der Nordsee bieten gute Voraussetzungen für die Marikultur. Viele Küstenbereiche sind sehr exponiert und eignen sich nicht für herkömmliche Verfahren. Deshalb ist die Aquakulturproduktion an europäi-

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schen Küsten außerhalb des Nordseeraumes auch deutlich höher, wobei gerade der Mittelmeerraum eine dominierende Rolle in der Aquakultur einnimmt. Die Nordseeanliegerstaaten erwirtschafteten etwa 355.000 t im Jahre 1970 und 1,4 Mio. t im Jahre 2000 (Wert 3,2 Mrd. US $) (FAO 2002) (*Abb. 2.3.6-1*).

Heute erzielt die Aquakultur der Nordseeanlieger ein Wachstum von etwa 10% pro Jahr (Wertzuwachs etwa 14%), was etwas mehr als der europäische Durchschnitt ist. An diesem Zuwachs ist hauptsächlich die Lachsproduktion beteiligt, welche von 300 t im Jahre 1970 auf über 560.000 t im Jahr 2000 angestiegen ist. Nur ein Teil der Lachse wird tatsächlich an Nordseeküsten der Anlieger erzeugt, die Mengen sind jedoch statistisch nicht leicht von der Gesamtproduktion zu trennen. Die Forellenproduktion der Anliegerstaaten nahm in der gleichen Zeit im Brack- und Meerwasser von 400 auf 59.000 t zu. Die Produktionsmengen für Miesmuscheln schwanken um 85.000–154.000 Jahrestonnen, während die Austernproduktion in den drei Jahrzehnten von 100 auf 3.400 t zunahm. Weitere Kulturarten, wie z.B. Stein- und Heilbutt, Kabeljau und verschiedene Muscheln (Teppich-, Herz- und Pilgermuscheln) spielen zur Zeit eine untergeordnete Rolle.

Fischkultur

Lachse und Forellen: Norwegen ist unter den Nordseeanliegern das wichtigste Erzeugerland von Lachsen (77%) und Meerforellen (*Tab. 2.3.6-1*). Sie werden vornehmlich in Netzgehegen in weitgehend geschützten Buchten und Fjorden herangezogen. Schottland steht trotz begrenzter Küstenhabitate an zweiter Stelle. Auf den Orkney- und Shetland-Inseln wurde die Lachsproduktion zwischen 1991 und 1997 um das Fünffache auf 27.000 t gesteigert. Mit steigendem Angebot sanken die Preise. Aus einer exklusiven »Nischenware« wurde ein Massenprodukt. Der oft als »Hähnchen des Meeres« titulierte Lachs geriet zwischen 1985 und 1990 durch hohen Antibiotikaeinsatz bei den Konsumenten zeitweise in Misskredit, was auch den übrigen Aquakulturprodukten schadete. Durch Konsolidierung, strenge Umweltauflagen und steigenden Kostendruck fand eine Konzentration und Sanierung innerhalb dieses Wirtschaftszweiges statt, wobei der profitable Markt erhalten blieb. Heute werden beispielsweise 90% der schottischen Produktionen von nur 10 Firmen abgedeckt. Die Produktivität wuchs durch verbesserte Futtermittel, gute Krankheitskontrolle und artverträglichere Technologien schnell an.

Der Ertrag von Regenbogenforellen (*Oncorhynchus mykiss*) wuchs in Norwegen zwischen 1990 und 2000 um das 13-fache. In Dänemark stammt wegen der begrenzten Möglichkeiten an den Küsten nur ein kleinerer Teil der Forellenproduktion aus dem Meer (etwa 7.300 Jahrestonnen, fast ausschließlich Ostsee).

Andere Fischarten: Andere Fischarten sind in der Marikultur rund um die Nordsee noch unbedeutend. In Norwegen und Großbritannien werden verschiedene »Kulturkandidaten« in Pilotprojekten erprobt. Wandersaiblinge (*Salvelinus alpinus*) werden in eingefriedeten Seegebieten in geringen Mengen erzeugt. Die Forschung zur Setzlingsproduktion des Heilbutt (*Hippoglossus hippoglossus*) führte nach Jahren zum Erfolg und brachte in Norwegen einige 100 t jährlich. Eine Steigerung auf 5.000 t für das Jahr 2006 wird erwartet (Anon 2001). Die kommerzielle Aufzucht von Dorsch (*Gadus morhua*) ist noch immer ein ungelöstes Problem. Allerdings konnten gefangene Jungfische in Käfigen erfolgreich gemästet werden. Die Kultur des Steinbutts (*Psetta maxima*) kann in Europa als etabliert bezeichnet werden (über 5.000 t im Jahre 2000, ICES 2001). Spanien und Frankreich sind Haupterzeugerländer. Rund um die Nordsee werden bislang nur kleinere Mengen in Norwegen, Großbritannien und Dänemark gezüchtet. In Schleswig-Holstein wurden über viele Jahre von einem etablierten Elterntierbestand kommerziell Jungfische für den Besatz spanischer Anlagen erzeugt. Aufbauend auf den jahrzehntelangen Erfahrungen wird ab 2001 erstmals der Steinbutt auch an der deutschen Nordseeküste bis zur Marktgröße herangezogen.

Molluskenkultur

Miesmuschel (Mytilus edulis): Die Miesmuschel wird entlang der Nordseeanliegerstaaten als wichtigste Art extensiv kultiviert (*Tab. 2.3.6-2, Abb. 2.3.6-2*). Sie wird im Rheinmündungsgebiet (Oosterschelde) und im Wattenmeer entlang der niederländischen, deutschen und dänischen

Tab. 2.3.6-1: Produktionsmengen (t) der wichtigsten Fischarten aus Marikultureinrichtungen im Nordseeraum im Jahre 2000 (*2001) (Quelle: FAO 2002).

	Atlantischer Lachs	*Regenbogen-forelle*	*Saibling*	*Kabeljau*	*Steinbutt*	*Meerforelle*	*Heilbutt*	*Andere*
Norwegen	436.736	49.040	168	167				1.018
Großbritannien	128.959	784			107	42	1	
Schweden		1.579						
Dänemark		7.264						
Deutschland*					5			

Küste vornehmlich in Bodenkultur produziert. In Dänemark werden überwiegend Wildbänke befischt. Das Zentrum der britischen Muschelkultur an der Nordsee liegt im Wash, weitere kleinere Kulturgebiete ziehen sich entlang der britischen Ostküste bis hinauf zu den Orkney- und Shettland-Inseln.

In den flachen Ästuaren der britischen Nordseeküste wird die Bodenkulturmethode, in den tiefen und geschützten schottischen Meeresarmen (Lochs) dagegen die Langleinenkultur angewandt (EDWARDS 1997). Auch in Norwegen und Schweden werden in zunehmendem Maße Miesmuscheln kultiviert, wobei die Langleinenkulturmethode dominiert (HAAMER 1997, STRAND & VØLSTAD 1997).

Wichtigstes Erzeugerland im Nordseeraum sind die Niederlande. Im Mittel wurden dort zwischen 1990 und 2000 mehr als $^2/_3$ der Gesamtproduktion der Nordseeanlieger erzeugt. Deutschland trägt gegenwärtig knapp ein ¼ zur Gesamtproduktion bei.

Bodenkultur: Im Wattenmeer finden wir vorwiegend die Bodenkulturmethode, die in den letzten Jahrzehnten von einer zunehmenden Mechanisierung und stark einschränkenden Kontrolle durch die Regierungen gekennzeichnet ist. Speziell ausgerüstete Muschelkutter (bis zu 40 m Länge, Tiefgang unbeladen < 2 m) stellen das heutige technische Gerät dar. Junge, 10–40 mm große Muscheln werden von natürlichen inter- oder subtidalen Muschelbänken unter strikten Auflagen aufgefischt und auf zumeist ständig vom Wasser bedeckte Kulturflächen in geringerer Dichte ausgebracht. Dort verbleiben sie 600–700 Tage, bis sie Konsumgröße erreicht haben. Auch hier gibt es strenge Auflagen u.a. über Mindestgrößen und Befischungszeiträume. Von guten Kulturflächen können zwischen 55–100 t Muscheln pro Hektar geerntet werden (SEAMAN & RUTH 1997).

Langleinenkultur: Muschelproduzenten setzen seit den 1960er Jahren auch im Nordseeraum auf verbesserte Verfahren in der Langleinenkultur, wobei zwischen der Gewinnung von Saatmuscheln und der Mast zur Marktreife unterschieden wird (HAAMER 1997, STRAND & VØLSTAD 1997). Miesmuschellarven siedeln direkt an künstlichen Substraten unterschiedlicher Form, die an Langleinen befestigt sind. Diese als Kollektoren bezeichneten Brutsammler bestehen aus synthetischem Material. Schwimmkörper halten die Konstruktion an oder nahe der Wasseroberfläche, Grundgewichte aus Beton oder Anker in Position. Nach einer ersten Wachstumsphase an den Tauen wird der Muschelbewuchs abgenommen, ausgedünnt und für eine zweite Wachstumsphase an andere Taue befestigt oder in Netzstrümpfe überführt. In Abhängigkeit von der geographischen Lage des Betriebes erreichen die Muscheln nach ein bis zwei Jahren Konsumgröße (HICKMAN 1992). Von einer typischen schwedischen Langleinen-Einheit können so bis zu 400 t Muscheln pro Hektar geerntet werden (ACKEFORS & HAAMER 1987).

Auch in den traditionellen Ländern mit Bodenkultur gibt es Versuche, Langleinenkulturen einzusetzen, wie z.B. in der Oosterschelde und im niedersächsischen Wattenmeer (WALTER & LIEBEZEIT 2001). Hintergrund ist die Suche nach einer verlässlichen Methode für die Saatmuschelgewinnung an geeigneten Standorten. Natürlicher Brutfall von ausrei-

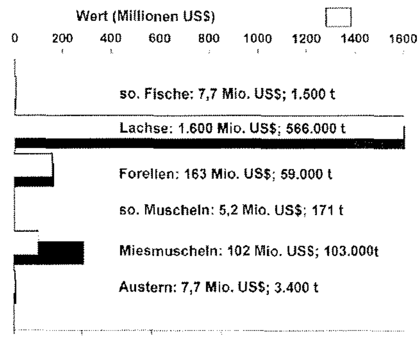

Abb. 2.3.6-1: Produktionsmengen und Erträge aus der Marikultur der Nordseeanliegerstaaten im Jahre 2000 (FAO 2002). Die Lachsproduktion enthält auch die norwegische und schottische Produktion außerhalb der nationalen Nordseeküste.

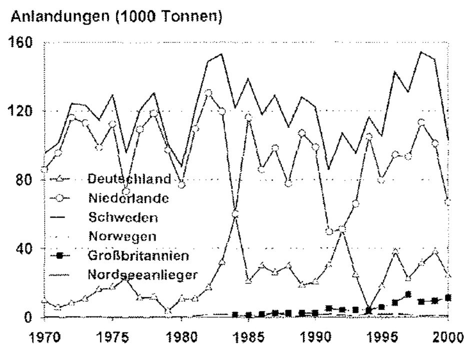

Abb. 2.3.6-2: Entwicklung der Miesmuschelproduktion der Nordseeanrainer während der letzten drei Jahrzehnte. (zusammengestellt aus verschiedenen Quellen).

chender Dimension ist auf den bisherigen Muschelbänken (die teilweise geschützt sind) zu unregelmäßig, um den Bedarf an Saatmuscheln zu decken.

Untersuchungen im niedersächsischen Wattenmeer zeigen, dass es auch in Jahren ohne nennenswerten Brutfall im intertidalen Raum zu einer starken Besiedlung von künstlichen Substraten kommt, wenn diese im Freiwasser exponiert sind. An Brutsammlern aus verschiedenen Seilmaterialien konnten im Jahr 2001 im Mittel 9 kg Brut pro laufender Meter gewonnen werden (WALTER & LIEBEZEIT 2001) (*Abb. 2.3.6-3*).

Austern: Weitere Kandidaten, die in allen Nordseeanrainerstaaten in extensiven Zuchtanlagen kultiviert werden, sind die Europäische Auster (*Ostrea edulis*) und die eingeführte Pazifische Auster (*Crassostrea gigas*).

Seit Anfang der 1990er Jahre wird in den Niederlande *O. edulis* wieder im kleinen Maßstab gezüchtet. Die Produktion liegt zwischen 150 und 400 Jahrestonnen, wobei die Brut aus der Oosterschelde bzw. aus Brutanlagen in Frankreich oder England stammt. England hatte, was die Produktionsmenge in Jahrestonnen angeht, ähnliche Anlandungen wie die Niederlande. In der zweiten Hälfte der 1990er Jahre kam es aber zu einem starken Rückgang.

Ökonomisch bedeutsamer ist heute die Pazifische Auster. Der massive Krankheitsausbruch bei der europäischen Auster durch *Bonamia ostreae* und *Marteilia refringens* brachte diese Form der Kultur in Frankreich zum Erliegen. Ein Ersatz wurde durch die Einführung der resistenten Pazifischen Auster am Anfang der 1960er Jahre gefunden. Auch die Nachbarländer waren betroffen und nutzen die Alternative. Die Niederlande sind heute mit einer Produktionsmenge von 2.500–3.500 Jahrestonnen im Bereich der Nordseeküste unter den Anliegerstaaten führend, gefolgt von England und Deutschland, wo eine Anlage im Sylter Wattenmeer betrieben wird (*Tab. 2.3.6-2*).

Alle Betriebe sind abhängig von der Versorgung mit Saataustern, die größtenteils in Frankreich, Irland und England in Brutanlagen gezüchtet werden. Jedoch unterscheiden sich die Kulturmethoden je nach Standort und Wachstumsstadium der Auster erheblich voneinander. Für Saataustern mit einer Länge bis zu 20 mm werden z.B. in den Niederlanden Seilkulturen und Laternennetze (Oosterschelde) und in Deutschland Netzsäcke (Sylt), sogenannte »Poches«, verwendet. Halbwachsaustern (>20 mm) können neben den erstgenannten Methoden auch an Langleinen oder in Austernkästen gezüchtet werden (England und Niederlande).

Bei den Laternennetzen handelt es sich um stockwerkartige, übereinander angebrachte Netzkästen. Diese werden einzeln an Auftriebskörpern oder parallel an Langleinen aufgehängt. Der Vorteil bei der Laternennetzkultur gegenüber der gezeitenexponierten Poche-Methode ist die ganztägige Verweildauer in der Wassersäule, die es den Austern erlaubt, ständig Nahrung zu filtrieren, und somit für ein rasches Wachstum sorgt. Weiterhin wirkt die ständige Bewegung des Systems einem Verklumpen der einzelnen Austern entgegen. Nachteilig ist die schwierigere Wartung der Laternennetze und das Entfernen von Aufwuchs. Dieser wird bei der Poche-Methode bei Niedrigwasser durch das regelmäßige Wenden der im Litoralbereich auf Eisentischen positionierten und leicht zugänglichen Austernsäcke vermieden. Wegen der günstigen Erreichbarkeit der Poches kann für die Arbeit schweres Gerät (Trecker) eingesetzt werden, um die Säcke zu heben und zu wenden oder bei Eisgang oder Ölunfällen in geschützte Bereiche zu bringen.

Bei der Langleinenmethode werden die Austern ebenfalls an vertikal aufgehängten Seilen angebracht und durch Netzsäcke am Ort gehalten. Diese Methode ist sehr aufwendig und kann nur in geschützteren Küstengebieten eingesetzt werden.

Andere Muschelarten: Andere Muschelarten haben in der Marikultur der Nordseeanliegerstaaten keine große Bedeutung. Geringe Mengen an Jakobs- oder Pilgermuscheln werden in Norwegen und Großbritannien produziert. Saatmuscheln dieser Arten stammen aus Wildfängen und er-

Abb. 2.3.6-3: Dicht bewachsener Muschelkollektor von Seilkulturen aus der Jade (WALTER & LIEBEZEIT 2000).

reichen in Netzstrümpfen oder Laternennetzen, an Langleinen oder Flößen hängend nach 2–4 Jahren Mindestgröße, um vermarktet zu werden. Weiterhin werden in Großbritannien kleinere Mengen der einheimischen Herzmuschel *Cerastoderma edule* und der tropischen Teppichmuschel *Tapes philippinarum* in Bodenkultur gezüchtet.

Makroalgen

Die Kultur von Algen für die Gewinnung von Algeninhaltsstoffen (Phykokolloide) nimmt weltweit gegenüber der Nutzung von Wildressourcen zu. Phykokolloide werden in vielen Bereichen des täglichen Lebens eingesetzt, so z.B. in Zahnpasta, Seife, Joghurt, Marmelade und Speiseeis. Weiterhin sind vielseitige Anwendungen in der Pharmazie, in der Papierindustrie, in der modernen Hydraulik, der Fotoindustrie (Emulgatoren) und vielen anderen Einsatzgebieten (z.B. Biosorptionsmittel zur Aufbereitung von Schwermetallen) bekannt. Auch in Nahrungsergänzungsmitteln sind Algenprodukte vermehrt wegen der speziellen Eigenschaften zu finden.

Es gibt zur Zeit keine kommerzielle Aquakultur von Makroalgen im Nordseeraum. In England und in Deutschland (u.a. Sylt, Bremerhaven) gibt es Forschungsprojekte, wo Zuchtmethoden für Makroalgen erprobt werden, die auf spezifische Produkte für den Kosmetik- und Nahrungsmittelmarkt sowie für die Abwasserreinigung in Polykulturen und als Biosorptionsmittel für Sondermüll zielen.

Umweltprobleme der Aquakultur

Die Expansion der Aquakultur in den vergangenen Jahrzehnten hat zu einer stärkeren Nutzung geschützter Standorte geführt. Solche geographisch günstigen Standorte wurden insbesondere für die Fischzucht bald knapp. Die anfangs gemachten Fehler sind teilweise auf unzureichende Kenntnisse, verstärkt durch Mangel an Umsicht und Vorsorge, zurückzuführen. Die moderne Intensivhaltung führte teilweise zu vergleichbaren Szenarien wie in der Landwirtschaft: Umstellung von Naturnahrung zu produzierten Futtermitteln, prophylaktischer Einsatz von Medikamenten und – im Falle von Krankheitsausbrüchen – ein erhöhter Einsatz von Therapeutika.

Unzureichende Fütterungsmethoden führten anfangs zu Futterverlusten, die den Meeresboden mit organischer Fracht belasteten. Zunehmende Betriebsgrößen führten zur Überlastung von zahlreichen Standorten mit begrenzter assimilativer Kapazität (z.B. übermäßige Ablagerung von Fäzes und Stoffwechselprodukten sowie lokale Anreicherung von Nährstoffen). Bei Krankheitsausbrüchen kann eine höhere Dichte von Parasiten und Krankheitserregern auch zu einem erhöhten Risiko für die Übertragung auf natürliche Bestände im anlagennahen Umgebungswasser führen. Schließlich ist das Entkommen von Kulturorganismen problematisch, wenn diese sich unter natürliche Artgenossen mischen und sich an der Fortpflanzung beteiligen. Dadurch kann die genetische Vielfalt gefährdet werden.

Schon frühzeitig haben einschlägige Organisationen auf die Problematik aufmerksam gemacht und verschiedene Auflagen vorgeschlagen. Dauerhaft kann die Aquakultur nur erfolgreich sein, wenn sie standortspezifische Belastungsgrenzen nicht überschreitet. Nachhaltigkeit kann nur erreicht werden, wenn auch sozio-ökonomische Kriterien im Einklang mit verantwortungsbewusstem Umweltmanagement gepaart werden.

Fischkultur und Umwelt

Vor allem die intensive, küstennahe Käfighaltung von Fischen (insb. Lachse) führte anfangs durch die übermäßige Zufuhr von Nährstoffen und Chemikalien zu lokal begrenzten negativen Umwelteffekten (PEARSON & BLACK 2001).

Nur ein kleiner Teil der Nährstoffmengen in der Nahrung wurde in Fischbiomasse umgewandelt. Zwischen 67–80% der zugeführten Stickstoffmengen gingen über den Stoffumsatz in die Umwelt verloren (HALL et al. 1992). Heutzutage ist jedoch das Verhältnis zugunsten der Fischbiomasse verbessert worden. Beim Phosphor werden nur etwa 10–20% der in der Nahrung enthaltenen Mengen ausgeschieden. Insgesamt werden etwa 70 kg Stickstoff und 10 kg Phosphor bei der Produktion von einer Tonne Zuchtlachs in das Wasser abgegeben (DOSDAT 2001).

Die löslichen Ausscheidungsprodukte werden in der Wassersäule verteilt und tragen im unmittelbaren Umfeld der Käfiganlagen zur kurzfristigen Erhöhung der Nährstoffkonzentration (vor allem in Form der Stickstoffverbindungen) bei. In der Regel können Mikroalgen das erhöhte Nährstoffangebot aufgrund der zu kurzen Verweilzeit nicht in erhöhtes Wachstum umsetzen.

Tab. 2.3.6-2: Produktionsmengen (t) der wichtigsten Molluskenarten aus Marikultureinrichtungen im Jahre 2000 (Quelle: FAO 2002).

	Miesmuschel	*Pazifische Auster*	*Europäische Auster*	*Kl. Pilgermuschel*	*Herzmuschel*	*Gr. Pilgermuschel*	*Teppichmuschel*	*Andere Austern*
Norwegen	791	<0,5						
Großbritannien	11.107	633	4	58	43	41	29	479
Schweden	443							
Deutschland	24.112	85						
Niederlande	66.800		200					2.000

Über die Ausscheidung von Feststoffen (Fäzes) sowie den Verlust von Futterpellets kommt es unterhalb der Käfige je nach Stärke der vorherrschenden Strömungen am Standort zu Anreicherungen der Feststofffracht am Meeresboden oder zu weiträumiger Dispersion. Aufgrund langjähriger Untersuchungen kann anhand von hydrodynamischen Modellen, die die Strömungen, die Futterrate und Besatzdichte sowie den temperaturabhängigen (jahreszeitlich schwankenden) Stoffumsatz berücksichtigen, die Akkumulation vorausberechnet werden (Hevia et al. 1996). Aufgrund derartiger Vorhersagen werden heute in den meisten Ländern durch Auflagen die Eintragsmengen so limitiert, dass ein Sauerstoffmangel weitgehend vermieden und ein Minimum an Benthosfauna existieren kann, die durch Bioturbation für einen Stoffumsatz sorgen. Die zunehmende Sauerstoffzehrung durch den mikrobiellen Abbau der organischen Substanz unterhalb von Netzkäfigen verschlechtert die Lebensbedingungen der im Sediment lebenden empfindlichen benthischen Organismen, sodass die Artenzahl abnimmt, die Individuenzahl der Opportunisten jedoch durchaus steigt (Gowen et al. 1990). Wird die Produktionsmenge nicht der assimilatorischen Kapazität angepaßt, kann es im Extremfall zu anoxischen Zonen kommen.

Während die Nährstoffbelastung und die Auswirkungen auf das Benthos durch geeignete Auflagen begrenzt werden können, müssen die Wechselbeziehungen zwischen den Kultur- und den wildlebenden Arten verhindert werden. Die großen Mengen regelmäßig mit Nahrung versorgter Fische locken Räuber an, die als potentielle Krankheitsüberträger fungieren.

Muschelkultur und Umwelt

Die Kultur von Muscheln ist weitgehend eine extensive Form der Aquakultur. Als Filtrierer sind Muscheln in der Lage ohne zusätzliches Futter auszukommen. Sie nutzen natürlich vorkommendes Phytoplankton und organische Partikel aus dem Wasser. Nutzbare Partikel werden aufgenommen und verdaut. Unerwünschte Partikel werden als schleimumhüllte Pseudofäzespartikel zusammen mit den Fäzes ausgeschieden. Diese Partikel sammeln sich als »Muschelschlick« in der Umgebung der Muscheln an.

Als Folge der filtrierenden Ernährungsweise transferieren Muscheln organische Substanz aus der Wassersäule in das Sediment (Olin 2002). Im Gegensatz zu Fischfarmen, die Nährstoffe eintragen, entziehen die Muschelkulturen organische Substanz aus dem Freiwasser und setzten diese in körpereigene Substanz um. Mit der Muschelernte wird diese Substanz dem aquatischen System entzogen. Muschelkulturen können genau dann Umweltprobleme sein, wenn natürliche Muschelsaatvorkommen überbeansprucht werden und Krankheitserreger, Parasiten bzw. andere fremde Arten durch die Aquakulturaktivitäten ausgebreitet werden (Kaiser 2001).

Muschelkulturen basieren weitgehend auf der Verwendung junger Muschelsaat, die von natürlichen Muschelbänken zum Abwachsen auf spezielle Kulturflächen verbracht werden. Das Auffischen von Muscheln mit Dredgen kann je nach der verwendeten Methode die Bodenfauna schädigen. In der Miesmuschelkultur werden relativ leichte Dredgen eingesetzt, die in den aus Pseudofäzes und Fäzes gebildeten »Muschelschlick« eindringen und die darauf siedelnden Muscheln abschöpfen. Die Ablagerungen werden dabei abgetragen und suspendiert. Problematisch wird die Entnahme, wenn in Jahren ohne ausreichenden Brutfall übermäßig abgefischt wird (Dankers & Zuidema 1995). Wie sich die Entnahme von Muschelsaat auf die marine Umwelt auswirkt, wird unterschiedlich beurteilt. Kaiser (2001) kommt zu der Einschätzung, dass die Effekte auf das Sediment im Subtidal nicht langanhaltend sind und sich lokal weitgehend auf das Gebiet der befischten Bank begrenzen. Außerdem erholen sich das Benthos und der Meeresboden nach einem solchen Eingriff sehr schnell. Für die Wirbellosengemeinschaft einer mit Saugdredgen abgeernteten Kultur der Teppichmuschel (*Tapes philippinarum*) wird ein Zeitraum von etwa einem Jahr angegeben (Spencer et al. 1998). Anders sehen dies Herlyn & Millat (2000). Sie führen starke Rückgänge in der Muschelbedeckung in den Bänken bzw. den Totalverlust intertidaler Muschelbänke auf frühere Saatmuschelbefischungen zurück.

Die Gewinnung von Muschelsaat aus der Wassersäule an Hängekulturen verursacht nahezu keine Beeinflussung natürlicher Muschelbestände. Einem Großteil der sich an diesen künstlichen Substraten ansetzenden Miesmuschellarven würde eine dauerhafte Ansiedlung auf einer natürlichen Muschelbank aufgrund der vielen Räuber und ungünstigen Strömungsverhältnissen ohnehin nicht gelingen.

Kulturmuscheln konkurrieren mit anderen Filtrierern um das verfügbare Phytoplankton. Dabei beeinflussen sie das Wachstum von Muscheln im Strömungsschatten (Wildish & Kristmanson 1984) oder verringern die Populationen anderer Wirbelloser, deren Larven sie einstrudeln. Beim Abwachsen auf Bodenkulturen oder unter Tischkulturen gemäß der französischen Poche-Methode reichern sich große Mengen »Muschelschlick« an. Wie insbesondere für Bereiche unterhalb von Netzkäfigen beschrieben, führt dieses organisch reiche Material zu Veränderungen im Meeresboden, vor allem zur Sauerstoffzehrung und damit zu veränderten Lebensbedingungen benthischer Organismen.

Aufgrund ihrer Ernährungsweise fungieren Muscheln als Biofilter. Sie tragen damit zur Verringerung des Gehaltes an organischen Partikeln und der Trübung bei. Bei der Ernte werden große Mengen Nährstoffe aus dem System entnommen, pro Tonne Miesmuscheln sind das 6,6 kg Stickstoff und 0,9 kg Phosphor (MEIXNER 1991).

Die Umsetzung von Muschelsaat aus anderen Muschelgebieten ist neben dem Ballastwasser der Schifffahrt als ein Weg erkannt, auf dem fremde Arten unabsichtlich eingeschleppt wurden (PILLAY 1992). So infizierten zeitgleich in den 1960er Jahren mit der Einführung der Pazifischen Auster (*Crassostrea gigas*) zwei einzellige Parasitenarten, *Marteilia refrigens* und *Bonamia ostreae*, die einheimischen Austernbestände (*Ostrea edulis*), was zu einer hohen Sterblichkeit führte. Unabsichtlich mit Austernsaat wurden weitere Arten eingeführt, so die Algen *Sargassum muticum* und *Undaria pinnatifida*, die Molluscen *Urosalpinx cinerea* und *Crepidula fornicata* sowie der Copepode *Mytilicola intestinalis* (PILLAY 1992).

Auf ähnliche Weise scheint auch die giftige Blüten erzeugende Alge *Fibrocapsa japonica* in die Küstengewässer der Niederlande und Deutschland gelangt zu sein.

Krankheiten und Parasiten

Zusäzlich können eingeführte Arten Quellen neuer Krankheitserreger und Parasiten für die Wildarten sein. Entflohene Fische aus Aquakulturbetrieben sind darüber hinaus ein Risiko für die einheimischen Arten, da sie mit den Wildformen konkurrieren und zu deren genetischen Veränderungen beitragen können. Es besteht die Befürchtung, dass entflohene Farmlachse sich mit den lokalen Formen kreuzen. Diese Mischlinge können Eigenschaften in die Wildpopulation einführen, die eine verringerte Fitness und Produktivität nach sich ziehen (BEVERIDGE 2001).

Wie unangepasste Wirtschaftsweise in der Aquakultur zu Umweltproblemen führen kann, lässt sich anhand der Ausbreitung von Parasiten und pathogenen Keimen aufzeigen. Der Einsatz von Fischbrut aus fremden Aufzuchtstationen, Staaten oder Seegebieten hat mehrfach zur Verbreitung von Fischparasiten geführt. Parasiten sind meist an ihre unmittelbaren Wirte angepasst, wodurch sie dort keine ernsthaften Schäden verursachen. In Kontakt mit anderen Wirtsarten, die nicht dieselben Anpassungen besitzen, können sie zu hohen Verlusten unter den fremden Kulturarten der Einsatzgebiete aber auch deren Wildpopulationen führen. Auf diese Weise wurde der Trematode *Gyrodactylus salaris* von der Ostsee auf norwegische Zuchtlachse übertragen. Ebenso ist ein Zusammenhang zwischen Lachskulturen und vergrößerten Populationen der parasitären Copepoden *Lepeophtheirus salmonis* und *Caligus elongatus* in der Umgebung der Kulturen wahrscheinlich. Die Infektionsrate bei wilden Seeforellen (*Salmo trutta trutta*) und Wandersaiblingen (*Salvelinus alpinus*) mit parasitären Copepoden war im Bereich mit vielen Lachsfarmen am höchsten (BJØRN et al. 2001). Zusätzlicher Stress bis hin zu einer gesteigerten Mortalität unter den infizierten Salmoniden sind die Folge des Befalls durch diese Parasiten.

Die Entwicklung der Aquakultur wurde auch von einer Zunahme der infektiösen Krankheiten unter Farmtieren begleitet. Verantwortlich dafür ist vor allem der Handel mit lebenden Tieren, als Vehikel zur Verbreitung von bakteriellen und virösen Erkrankungen. Dieses blieb nicht nur auf die Farmfische beschränkt, sondern griff auch auf Wildformen über. So wurde die bakterielle Furunkulose von eingeführten Zuchtlachsen von Schottland nach Norwegen exportiert, mit fatalen Folgen sowohl für Kultur- als auch Wildpopulationen. Intensive Aquakultur erhöht zudem die Wahrscheinlichkeit eines Ausbruchs von Krankheiten. Dichter Besatz und nicht optimale Wasserqualität durch die Anreicherung von Nährstofffrachten sind Stressfaktoren, die in Gefangenschaft zu einer Verringerung der Widerstandsfähigkeit führen (BLAZER & LAPATRA 2002).

Da in der Aquakultur höhere Organismendichten als in der Natur erzielt werden, ist eine Vielzahl von therapeutischen und anderen Chemikalien im Einsatz (eine Übersicht geben COSTELLO et al. 2001). Neben äußerlich wirkenden Substanzen gegen Ektoparasiten wurden in der Vergangenheit eine Vielzahl von Antibiotika in der Aquakultur eingesetzt. Dieses führte zu langfristigen Antibiotikaresistenzen von Bodenbakterien unter Fischfarmkäfigen. Seit den 1980er Jahren, als mehrere Hundert Milligramm Antibiotika pro Kilogramm erzeugtem Fisch eingesetzt wurden, nahm ihre Anwendung jedoch deutlich ab (MARONI 2000). Der Rückgang ist auf die Entwicklung von Impfstoffen gegen die ökonomisch wichtigsten Infektionskranheiten, bessere Auswahl der Farmstandorte, optimiertes Wirtschaften (Begrenzung der Besatzdichte, wechselnd brachliegende Standorte) und bessere Hygiene zurückzuführen (MARONI 2000).

Neben veterinärmedizinischen Substanzen werden auch desinfizierende und Antifoulingagenzien auf Kupferbasis in der heutigen Aquakultur eingesetzt. Trotz zunehmender Regelung des Einsatzes von Xenobiotika vor allem auf EU-Ebene besteht immer noch ein Mangel an Informationen über den Einsatz solcher Stoffe und ihren Einfluss auf die Umwelt (ALDERMAN et al. 1994).

Vermeidung von negativen Einflüssen durch die Aquakultur

Beste Umweltpraxis

Eine Orientierung, wie unerwünschte negative Einflüsse vermieden werden können, bietet der »Verhaltenskodex für verantwortliche Fischerei« der FAO (1995). Unter dem Artikel 9 »Entwicklung der Aquakultur« werden die Staaten aufgefordert, einen administrativen Rahmen zur Förderung und zur ökologisch nachhaltigen Entwicklung der Aquakultur zu entwickeln. Um dieses Ziel zu erreichen, werden eine Reihe von geeigneten Bewirtschaftungsregeln definiert, die die Auswirkungen der Aquakultur so gering wie möglich halten sollen.

Die wichtigste Vorsorge, um manche der angesprochenen Umweltprobleme zu vermeiden, besteht in der richtigen Auswahl des Standortes. Die Wasserqualität und die hydrologischen Bedingungen sollten so sein, dass Stress erzeugende Bedingungen vermieden werden. Die Produktion sollte sich im Gleichgewicht mit den Gegebenheiten der lokalen Umwelt und Ökologie halten. Besatzdichten, die Rücksicht auf die Bedürfnisse der Fische nehmen, führen zu gesunden Organismen mit einem besseren Immunsystem. Unter solchen Kulturbedingungen benötigen die Tiere kaum veterinärmedizinische Substanzen. Die Anpassung der Futtermenge und des -rhythmus an die physiologischen Bedürfnisse, orientiert am Appetit der Tiere, minimiert die Futtermengen. Zusätzlich verringert der Einsatz von leicht verdaulichem, energiereichem und mit dem richtigen Angebot an essentiellen Aminosäuren versehenem Futter die Fäzesmenge. Eine verbesserte Nahrungszusammensetzung mit einem auf 30–35% erhöhten Fettgehalt und einem auf 1% halbierten Phosphorgehalt hat zu einer Verringerung der Verluste geführt. So konnten die Nährstoffmengen, die pro erzeugter Tonne Fisch an die Umwelt abgegeben wurde, bis Mitte der 1990er Jahre um 58% (N) bzw. 85% (P) auf 55 bzw. 4,8 kg/t verringert werden (Enell 1995).

Unter Berücksichtigung dieser und anderer Regeln der »besten Umweltpraxis« lassen sich die Auswirkungen der Marikultur minimieren (Costello et al. 2001).

Polykultur

Ein anderer Ansatz, um Umwelteffekte von Nährstoffen aus der Fischkultur zu minimieren, sind Kombinationen mit anderen Zuchtorganismen (Algen oder Muscheln). So gedeihen Algen in der nahen Umgebung von Lachskäfigen sehr viel besser als in größerem räumlichen Abstand. Dabei profitieren sie vom höheren Angebot an gelösten Stickstoffverbindungen aus den Ausscheidungen der Fische. Aber auch das Wachstum von Muscheln wird durch ein erhöhtes Nahrungsangebot an partikulären Substanzen in der Umgebung von Netzkäfigen gefördert.

Potentiale für eine Aquakultur im Offshore-Bereich

Marikulturanlagen weit entfernt von der Küste – auch als »offshore«- oder »open ocean«-Aquakultur bezeichnet – gibt es weltweit nur an wenigen Standorten. Zunehmend werden jedoch auch großskalige Pilotvorhaben durchgeführt (Polk 1996). Auch viele kommerzielle Betreiber haben sich bereits mit ihren Käfiganlagen aus den sehr geschützten Standorten herausbegeben. In Norwegen, Irland und Schottland findet man zunehmend Käfigbatterien in mehr exponierten Gebieten, die allerdings noch nicht als »offshore« gelten können. Diese Entwicklung ist ein deutliches Indiz, dass es kaum noch Raum in unmittelbarer Ufernähe für eine weitere Expansion der Aquakultur gibt. Dieses liegt zum einen an der begrenzten Eignung von Inshore-Standorten aus der Sicht des Umweltschutzes, zum anderen an der derzeit starken Nutzung der Nordseeküste durch andere Interessenten mit zunehmenden Raumnutzungskonflikten. Offshore-Aquakultur hat viele umweltrelevante Vorteile, erfordert jedoch eine teure Infrastruktur. Es bietet sich daher an, zukünftig mehrere Nutzungsarten, die ähnliche Anforderungen an die Infrastruktur haben, zur Kooperation und zu integriertem Management zu bewegen. Besonders gut kann dies gelingen, wenn mehrere Ressourcennutzer ihre Aktivitäten gemeinsam planen. So ist es durchaus denkbar, die geplanten Offshore-Windparke mit dem Einsatz von Aquakultursystemen zu verbinden (Buck 2002). Bei der Fülle der beantragten Offshore-Windparke würden sich große Potentiale für eine kombinierte Windpark-Marikulturnutzung eröffnen. In den weit abgelegenen Windparkgebieten herrschen gute Wasserqualitäten und hohe Durchmischungsgrade in der Wassersäule vor, was gerade die extensive Kultur von Muscheln und Makroalgen fördern würde. Dabei ließen die Standbeine der Windanlagen eine sichere Verankerung von Zuchtsystemen zu. Gleichzeitig könnten Serviceplattformen für eine gemeinsame Nutzung kostengünstig für alle Betreiber entwickelt werden.

Gegenwärtig sind derartige Überlegungen nur punktuell experimentell angegangen worden. Es gilt, die Optionen durch wissenschaftliche Studien auszuloten und ihre Machbarkeit mit empirischen Daten, die an Pilotanlagen relevanter Größe erarbeitet wurden, zu verifizieren. Der Forschungsbedarf ist groß aber bereits weitgehend definiert. Zudem müssen Techniken erprobt und angepaßt werden, die vor allem den harschen Bedingungen in der Nordsee standhalten.

Wünschenswert wäre eine parallele Entwicklung der erforderlichen Aquakulturtechnik mit der Konzeption der Verankerung der Windkraftanlagen. In gegenwärtig laufenden Forschungsprojekten werden erste Versuche mit Miesmuscheln, Austern und Makroalgen an untergetauchten Langleinenkonstruktionen durchgeführt.

Kreislaufanlagen

In neuerer Zeit werden wieder Kreislaufsysteme, in denen das aus den Zuchtbecken ablaufende Brauchwasser aufbereitet und wiederverwendet wird, als zusätzliche Methode zur Erweiterung der Aquakultursysteme diskutiert. Man hofft, damit Umwelteffekte zu minimieren, da sich solche Systeme besser kontrollieren lassen. Solche Systeme setzen sich aus den eigentlichen Hälterungsbecken, den Pumpen, den Belüftungssystemen zum Sauerstoffeintrag und Kohlendioxidabfuhr, der Temperaturregelung, den mechanischen und biologischen Filtern sowie Systemkomponenten, die der Desinfektion (sowie zur pH- und Lichtkontrolle) dienen, zusammen. Solche landgestützten Anlagen bieten die Möglichkeit einer weitgehenden Kontrolle der Umweltbedingungen. So können Produktionsabläufe z.B. unabhängig von der Jahreszeit gesteuert werden, allerdings mit hohem Kostenaufwand. In welcher Form und für welche Arten solche Systeme gegenüber konventionellen Verfahren auch konkurrenzfähig gemacht werden können, ist ein Anliegen der derzeitigen begleitenden Forschung. Im Nordseeraum sind im Prinzip alle Szenarien des Einsatzes von Kreisläufen denkbar, (a) für die Quarantänehaltung, (b) für die Brut- und Besatzerzeugung (schon heute in vielen Teilen der Welt ein wirtschaftlicher Weg) und (c) zur Mast bzw. bis zur Vermarktungsgröße. Ein besonderer Vorteil ist, dass die Abwasser- und Feststofffracht quantitativ kontrolliert werden kann. Ebenso sind Kontakte zwischen den Zuchttieren und den Wildformen weitgehend unterbunden sowie die Gefahr der Krankheitsübertragung gering, vorausgesetzt, zulaufendes und ablaufendes Wasser werden entkeimt. Arbeiten zur Entwicklung der Kreislauftechnologie im Brack- und Meerwasser werden in Europa (auch in Nordseeanliegerstaaten) gegenwärtig vorangetrieben. In der Süßwasserproduktion erreicht diese Technologie - nach langen Jahren der Fehlschläge - in einigen Bereichen kommerzielle Realität (z.B. Wels- und Aalzucht in Holland). Im marinen Bereich gibt es gegenwärtig fünf solcher Anlagen, eine Pilotanlage befindet sich an der schleswig-holsteinischen Nordseeküste.

Zukunftsaussichten für die Aquakultur an der Nordseeküste

Produktion

In den letzten drei Jahrzehnten gehörte die Aquakultur weltweit zu den am schnellsten wachsenden Branchen der Nahrungsmittel produzierenden Industrie. Im Nordseeraum ist das zum Teil nicht zutreffend. Zum einen stammen die hohen Produktionsmengen, die in den Datenbanken (FEAP, FAO) für einige Länder angegeben werden, nicht ausschließlich aus dem Nordseeraum, sondern eher aus dem Nordatlantik oder der Ostsee (z.B. Norwegen und Dänemark), zum anderen erreicht die Landwirtschaft in den Nordseeanliegerstaaten ein höheres Wachstum als die Aquakultur. Bei einem Vergleich der Produktionsmengen aus der Landwirtschaft (Viehzucht und Anbau von Kulturpflanzen) und aus der Aquakultur kann sich letztere mit nur 1–2% gegenüber der Landwirtschaft beweisen. Doch für die Deckung der Nachfrage an marinen Ernährungsprodukten kann eine substantielle Steigerung der Nahrungsmittelproduktion aus dem Wasser nur durch eine Intensivierung der Aquakultur möglich sein. Die Aquakultur trägt dazu bei, mehr Fisch anbieten zu können, ohne den Druck auf die Wildbestände zu erhöhen.

Umweltimage

In aquatischen Lebensräumen führt die Zugabe von Nährstoffen mit dem Ziel einer Produktionssteigerung gleichermaßen wie an Land zu einer Degradation der betroffenen und benachbarten Ökosysteme. Beim Ausbau der Aquakultur muss deshalb besonders auf Nachhaltigkeit und Umweltverträglichkeit (marine Eutrophierung und Schadstoffbelastung, Biotopkonversion, Landverbrauch in Konkurrenz zu anderen Nutzungen, Grundwasserversalzung) geachtet werden. Die Aquakultur sollte auf umweltverträgliche, langlebige und angepaßte Formen eingestellt sein. Hilfreich wäre hierbei die Weiterentwicklung und Durchsetzung der internationalen Kriterien und Kennzeichnungssysteme. Die im FAO-Verhaltenskodex aufgestellten Grundsätze sowie die Richtlinien für deren Umsetzung liefern hierfür eine ausbaufähige Grundlage.

Die rasche und ungeregelte Ausweitung der Aquakulturproduktion hat in einigen wenigen Fällen zu Umweltschäden geführt und Konflikte angesichts begrenzter Ressourcen ausgelöst, was auch zu einer negativen Wahrnehmung der Aquakultur in der Öffentlichkeit führte. Deshalb besteht die Notwendigkeit, Strategien für Politik und Planung zu entwickeln, welche die sozialen, ökologischen und gesetzgeberischen Fragen im Zusammenhang mit einer nachhaltigen Entwicklung der Aquakultur in Betracht zieht. Es müssen Wege erörtert werden, um das Image der Aquakultur im öffentlichen Bewusstsein zu heben. Ihre Vorzüge und Risiken sollten in fairer Weise abgewogen und behandelt werden. Eine positive Wahrnehmung der Öffentlichkeit gegenüber der marinen Aquakultur ist wichtig, um ihr Potential zu nutzen, insbesondere in Regionen, wo die Aquakultur wenig Tradition hat und aufgrund schlechter Fallbeispiele in Misskredit geraten ist. Nach Meinung von FAO-Experten geht dieses negative Bild oft auf die teilweise verzerrt dargestellten Umweltauswirkungen zurück, die durch die Lachs- und Garnelenkultur hervorgerufen werden. Trotz des potentiell gutenMarktes für diese Aquakulturprodukte werden Garnelen im Nordseeraum überhaupt nicht gezüchtet und Lachse stammen eher aus Betrieben im Nordatlantik bzw. aus der Ostsee. Es dürfen daraus keine generellen Schlüsse gezogen werden, denn die Aquakultur schließt hier andere Arten wie z.B. Miesmuscheln ein. Muschelzucht wird in Nordeuropa seit einigen Jahrhunderten betrieben und hat keine nennenswerten Umweltschäden verursacht.

Kennzeichnung von Bioprodukten

Der Marktwert und die Akzeptanz eines Aquakulturproduktes wird von der Gewässergüte mitbestimmt. Um Schlagzeilen, wie »Chloramphenicol: Aldi ruft Shrimps zurück« (ANON 2002a) zu vermeiden, muss es das wichtigste Ansinnen von Aquakulturbetrieben sein, gesunde Umweltbedingungen für seine Kulturen zu erhalten, um einen fairen Marktwert für sein Produkt zu erzielen. Dieses Bewusstsein greift zunehmend um sich, wie das Beispiel der ersten vom »Naturland«-Verband zertifizierten Biolachse zeigt (ANON 2002b). Es müssen weitere Kriterien für ein Ökokennzeichen für Aquakulturprodukte entwickelt werden. Denkbare Ansätze dazu wären (a) die Lage des Standorts sowie den Sauberkeitsgrad des verwendeten Wassers zu kennzeichnen, (b) auf eine Genmanipulation oder Hormonbehandlung des erzeugten Produktes zu verzichten, (c) keine Verfütterung von Fischmehlprodukten an die zu produzierenden Fische aus nichtquotierten oder überfischten Beständen durchzuführen, (d) eine Beschränkung des Medikamenteneinsatzes bei gleichzeitiger strenger Kontrolle zu gewährleisten und (e) die Populationsdichte klar festzulegen. Neben den Kriterien für ein Ökokennzeichen könnten auch Kriterien für ein konventionelles Zeichen für Aquakulturprodukte entwickelt werden.

Besatzmaßnahmen

Neben dem Sektor der Ernährung kann die Aquakultur bei der Erhaltung einiger gefährdeter Arten helfen. Durch Besatzmaßnahmen konnten die Bestände der Meerforelle und des Ostseeschnäpels erhalten werden. Andere bedrohte Arten könnten zukünftig auch durch die Aquakultur erhalten werden. Auch bei der Wiedereinbürgerung von Arten (z.B. des Störs in Nord- und Ostsee) kann die Aquakultur diesen Arten Hilfestellung leisten. Damit öffnen sich ganz neue Möglichkeiten, denn mit dem Aspekt der Artenerhaltung bekommt die Aquakultur einen ganz neuen Sinn.

Sozio-Ökonomie

Die Aquakultur spielt eine wichtige Rolle im Hinblick auf die Verbesserung der sozio-ökonomischen Lage vieler Küstengemeinden, da sie alternative Beschäftigungsmöglichkeiten bietet. Doch auch wenn die Entwicklung im allgemeinen positiv beurteilt werden muss, sieht sich diese Produktionsform doch vor eine Reihe von Problemen gestellt. So wurde in jüngster Vergangenheit mit einem zunehmenden Investitionsbedarf »letztes Neuland« in Richtung offene See betreten. Mittlerweile gehört die Marikultur zu vielen Nutzungen, die Druck auf die Küstengebiete ausüben. Dabei gewinnt diese Form der aquatischen Produktion zunehmend an ökonomischer Bedeutung. In manchen Ländern werden alternative Erwerbsquellen in abgelegenen Gebieten, in denen die Möglichkeiten sonst nicht vielfältig sind, angeboten, was durch das Beispiel der Lachsfarmen in Schottland, Irland und Norwegen belegt wird. Dennoch wird die Aquakultur immer mehr als Bedrohung für andere Tätigkeiten gesehen. Vor allem der Tourismussektor bemängelt, dass die Aquakultur Flächen beansprucht, die zur Freizeitgestaltung genutzt werden könnten und dass sie mit ihren Abfallprodukten die Qualität der nahegelegenen Badewässer beeinträchtigt. Neben Regularien, die eine nachhaltige ökologische Entwicklung der Marikultur fördern, fehlt es an Entscheidungen, die den Rahmen aller Nutzungen in einem Meeresgebiet gleichberechtigt abstecken. Die Entwicklung eines integrierten Küstenmanagements (IKZM) könnte Konflikte vermeiden und damit auch der Marikultur eine Perspektive an unseren Küsten sichern. Mit modernen IKZM-Strategien könnte dafür gesorgt werden, dass alle Nutzer der Nordsee in ein Programm einbezogen werden und alle gemeinsam versuchen, Konsens bezüglich der Nutzung von Flächen in der Nordsee zu finden.

In der »Bangkok-Erklärung zur Aquakultur« wurde die Wichtigkeit der Zusammenarbeit zwischen Industrie- und Entwicklungsländern betont, z.B. durch Netzwerke von Expertengruppen, Technologietransfer und die Entwicklung einer entsprechenden Politik. Unterstrichen wurde auch die Notwendigkeit entsprechender politischer und wirtschaftlicher Rahmenbedingungen für diejenigen Menschen, die ihren Lebensunterhalt mit der Aquakultur und anderen Aktivitäten in Küstengebieten bestreiten.

Ökonomie

Die Aquakultur ist für den Nordseeraum eher eine Chance, als ein Risiko. Dabei stellt sich trotzdem die Frage nach der Rentabilität: Wie können mehr potentielle Aquakulturfarmen kommerziell nutzbar sein. Einige Nordseeanliegerstaaten importieren Fische aus Ländern, wo diese günstiger produziert werden. Warum soll man also für den Weltmarkt verstärkt Fischwaren produzieren, die preislich nicht mit den »Billiglohnländern« konkurrieren können? Die Antwort kann nur in der Zukunft liegen, wo neben wirtschaftlichen Interessen gerade die Frage der Nachhaltigkeit und der Ressourcenschonung an Bedeutung gewinnt ♦

Appendix III

Publication III

The Development of Mollusc farming in Germany: Past, Present and Future

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Summary

For centuries, shellfish, mainly *Mytilus edulis*, are cultured along the Wadden Sea coasts of Lower Saxony and Schleswig-Holstein. The Pacific oyster, *Crassostrea gigas*, is cultivated on a small scale in the backwaters of the Island Sylt (Schleswig-Holstein). Methods of growing range from intertidal and subtidal bottom culture with relaying of seed mussels in productive areas and dredge harvesting (mussels) to intertidal rack culture using mesh bag systems and lantern nets (oysters). However, the North Sea exhibits harsh conditions and limited sites suitable for aquaculture while resource use is also extremely multi-faceted and highly competitive. Due to these factors modern aquaculture development in Germany is rather restricted. Even so aquaculture development in Germany has the potential to be extended; this is only possible by expanding into new areas. It is envisaged that through the multifunctional resource uses, in particular in conjunction with offshore wind farms, open ocean aquaculture will see a variety of new forms of integrated production systems for established and unconventional species.

The development of mollusc farming in Germany: Past, present and future

B.H. Buck[1], U. Walter[2], H. Rosenthal[3] and T. Neudecker[4]

History of Aquaculture in Germany

Most European countries with access to the sea are engaged in coastal aquaculture in one way or another. Although Germany has been and still is involved extensively in aquaculture research and development, the country has a relatively short shoreline in relation to its inland area (Figure 1) and has, therefore, placed little emphasis on coastal aquaculture. Additionally, the environmental conditions along the North Sea coast are harsh and it is only recently that the issue of potential direct expansion of the industry in the marine environment has been revisited. In this sense, the country can be considered a newcomer to adopt modern aquaculture within its coastal waters. Traditional aquaculture practice in Germany includes carp and trout farming in earthen ponds, raceways and other modern facilities. Traditional farming was based mainly on ecological concepts as witnessed by the pioneering research work reflected in the early text books of the past century.

During recent decades, however, there has been a remarkable trend towards more intensive and more ecologically sound production methods for fish. This was reflected mainly by the increasing use of supplemental feed of high energy and decreasing nutrient contents. Intensification reached its highest level in the former East Germany (GDR) area. Because of the unification of Germany, the high production level in the former GDR could not be maintained in the new Federal States, called "Länder," because the conceptional approach was not designed to be competitive in a free market economy.

Production in the country still does not meet the demand for most fish culture products. These are imported to a great extent with the exception of carp where overproduction occurred in 1990/91 but imports continued from former east block countries because of the price structure. Today, a few new freshwater farms are being built according to the latest technical standards in terms of construction and handling as well as to effluent standards, employing polishing ponds and artificial wetlands while also using settling ponds. The technique and management practices on older farms are being improved continuously. To produce fish of high quality, the cleanest possible water for breeding and fattening is used. In several areas, partial recycling is employed because of water shortages and because of the need to minimize water extraction, inasmuch as farmers have to pay for ground water usage.

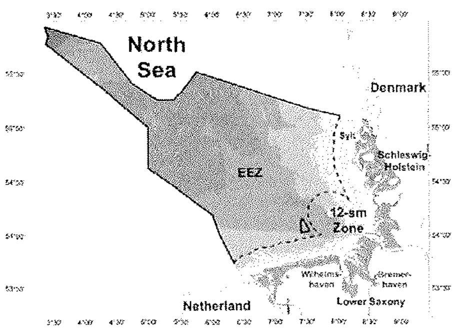

Fig. 1. Map of the German North Sea bordering the Netherlands with the State of Lower Saxony (southwest), the State of Schleswig-Holstein (northeast), bordered by Denmark (north).

Shellfish Farming in Germany

The fishery of the European oyster in the German Wadden Sea, mainly around the island of Sylt, was based on a long-standing tradition of local fishermen and that fishery continued until the stocks collapsed during the early part of the past century. There has never been a true aquaculture practice for native oysters (*Ostrea edulis*) along the German coasts because the natural beds along the coasts of Sylt and Amrum, as in most of the East-Frisian Wadden Sea, were already depleted around the 1880s. This led to a ban by the Prussian Government on the fishery between 1882 and 1891. The ban did not provide the expected results for recovery and, therefore, a restocking program was initiated between 1894 and 1896 with seed oysters imported from France. That activity can be considered from a historical point of view as the first attempt in Germany to become involved in a quasi-aquaculture management of the fishery. However, the seed oysters from France did not adapt well because of their thin shells, which were not adapted to harsh tidal wave action. Better results were obtained later with seed oysters obtained from the Netherlands in 1906, 1907 and 1914. Thereafter, attempts were made to improve the seed production on the natural banks along the German coast, in a repeat of early attempts in 1898 and 1899 to relay young oysters from further offshore sites to Wadden Sea banks. Today we know that the environmental and hydrodynamic conditions, in particular during winter, were not favorable for the expected success.

A more serious attempt to culture oysters began around the early 1920s when a holding and depuration plant was built on List (Sylt) to relocate the Husum plant and trading organization. It was there that the *Biologische Anstalt Helgoland* became heavily involved in research to culture the oyster while extensive Dutch seed oyster imports occurred: 1925 = 1 million individuals; 1926, 2.5 million. Despite those attempts, no commercial aquaculture developed, mainly because it was believed that the product would not be cost-effective compared to other European competitive producers.

Several attempts to establish *Ostrea edulis* on the Baltic Sea coast of Germany also resulted in failure. There were two attempts to introduce the American oyster, *Crassostrea virginica*, to the western Baltic Sea coast in 1879/1880 and 1884. About 1.2 million seed oysters and 5,000 larger individuals were placed near Apenrade and the Gjenner Bight, which later became Danish territory. Although the oysters grew well and appeared in the fishery three years later, no self-sustaining population was established and no further trials were conducted because the salinity was considered to be too low in some years to achieve natural reproduction.

Mussel farming along the German North Sea coast, in the States of Lower Saxony and Schleswig-Holstein, has a long-standing tradition and depends today largely on established extensive farming techniques based on the knowledge that good recruitment may not necessarily lead to good growth in the same location. However, this knowledge was not translated into a systematic farming approach during the early years of the past century.

Although fishing on natural mussel beds in the German Wadden Sea, along the Schleswig-Holstein coast in particular, has taken place for centuries, an extensive, combined fishery-culture system has developed only since the end of World War II.

Shellfish Farming Systems in Germany

Compared to fish culture, shellfish, such as oysters and mussels, need only a fairly primitive form of husbandry to attain worthwhile yields.

Exploited Species

Mussels. Blue mussel aquaculture in Germany is a highly specialized branch of the fishery sector. The typical working vessels are about 30-40 m long, up to 9 m wide and are able to carry 100 t of mussels in 1-2 holds. Vessel draft is well below 1 m unloaded, due to the shallow depth along the coast. A crew of three men fishes with 2-4 dredges, simultaneously. Equipped with modern navigation systems, hydraulic winches to pull the dredges on board, and strong injector pumps to flush out the seed mussels through hatches below the water line, the operation has become very effective. Sorting machines to separate live mussels from dead shell and mud are also technical improvements that help greatly to ease the work.

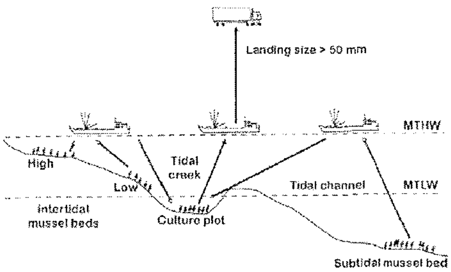

Fig. 2. Schematic representation of the various production strategies for mussel farming in the tidal and subtidal areas of the German Wadden Sea. Modified from Seaman and Ruth (1997).

Mussel aquaculture involves placing small mussels (0.5-4 cm long) in an area where growing conditions are optimum and where the culturist has exclusive rights to the harvest. Juvenile mussels are collected from dense, wild beds in the subtidal or the intertidal part of the Wadden Sea area (Figure 2). They are replanted at densities of 30-40 t/ha (5-20 mm shell length) to 100 t/ha (half-grown size: 20-40 mm shell length) on specific culture plots. This allows the mussels to increase their growth rate and double their size within a year. However, the downside of bottom culture is that the mussels are subject to predation from ducks, starfish or other undesirable species.

Today 80-culture plots of 20-100 hectares covering a total area of 4,100 hectares are granted by the authorities. A good plot will return 55-100 t/ha of mussels (Hurlburt and Hurlburt 1980, Seaman and Ruth 1997). The yield to seed ratio in Lower Saxony is at 1.2-1.3 (Gubernator 2000). Mussels are usually harvested when they reach a size well over 50 mm shell length (mostly 70 mm). To reach this size will require 12 to 24 months on the culture plots. Harvestability will depend on the market demands, on the condition of the mussels and on timing of gametogenesis and spawning.

Oysters. The natural European flat oyster (*Ostrea edulis*) resources in northern Germany played a significant role in the fishing industry until 1900, as outlined above. However, natural oyster beds were highly vulnerable to heavy and unregulated exploitation and the native oyster virtually disappeared from our waters. Since the beginning of the 1980s, efforts have been undertaken to establish a local oyster farm.

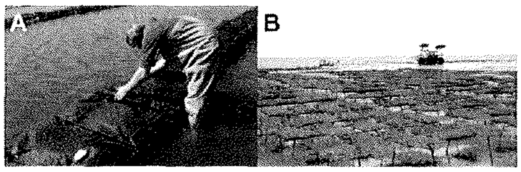

Fig. 3a/b. Mesh bag culture. (a) Oyster bags on racks, being serviced (turned). As one can easy see, the topside is quickly overgrown by filamentous algae during warm summer days. Frequent turning is important to allow good water exchange. (b) A rack field for oyster growout in operation. View is during low tide with buoyancy tractor in the background.

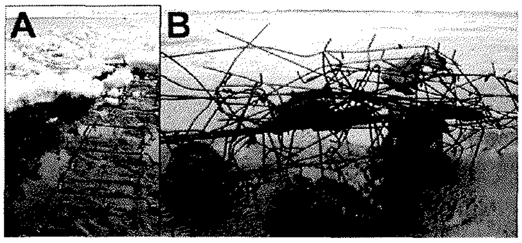

Fig. 4a/b. Damage to oyster racks. (a) An icy winter can severely damage the racks. Therefore, they must be recovered in the late fall and stored on land (farmers tend to postpone this to the last minute to utilize every day for growth: sometimes they are too late to respond when sudden storms occur. (b) After a strong winter, racks left in the tidal areas may be totally destroyed.

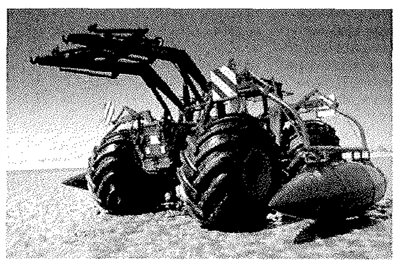
Fig. 5a/b. Service tractor. (a) Tractor with hydraulic arms and large, wide wheels to minimize pressure impact on the Wadden Sea bottom. (b) Tractor in action for transport and placement of bags.

For this purpose an exotic species, the pacific oyster *Crassostrea gigas*, was imported, which was known to be successful in France to overcome the disease problems encountered with the native oyster. Governmental assistance was obtained through research grants to explore the requirements of the species in accordance with the environmental conditions along the German coast. Test culture trials with *C. gigas* took place at several locations along the North Sea coastline, employing the strategy to move undersized oysters for overwintering to the milder conditions within tanks ashore (Neudecker 1984a, 1988).

One of the conditions set by regulatory authorities was that the seed oysters would have to come from a certified hatchery in Europe. Past experience with the introduction of seed oysters from America to France revealed the potential transmission of diseases and associated exotic fauna and flora. The oyster spat used for culture were, therefore, brought in from hatcheries in Great Britain and Ireland, which fulfilled the quarantine requirements. The transfer of seed oysters from those hatcheries continued for many years until today. Now only the growout phase to bring oysters to market size is practiced along the landward protected side of the Island Sylt. There, rack culture is employed on tidal flats, with most racks being exposed intertidally, while only some are operated subtidally (Figure 3a-b).

For experimental purposes, there were several different techniques examined with respect to growing oysters (Meixner 1973, Neudecker 1984b). One technique at the Flensburger Förde (Baltic Sea coast, low salinity) used lantern nets hanging from a fixed longline attached to a floating raft or buoy. In comparison to French oysters, the average meat weight of Baltic oysters was higher (Neudecker 1988). Other systems used were cages with trays, to which oysters were attached by cement, a labor-intensive process (Neudecker 1982). The great advantage of this culture method was that the positioning into deeper waters could be arranged easily, whether for production or for overwintering and conditioning in the spring before transfer to the North Sea growout areas. However, with other developments in the European market, the technique proved not to be competitive.

Other forms of already well-established culture systems included the use of plastic mesh bags filled with juvenile oysters, commonly called "poches". The bags are made from extruded polyethylene material, commonly provided by French companies. Appropriate mesh size for oyster rearing is determined by shell size to maximize water flow yet guarantee that the stock is retained in the enclosure. Both ends must be folded over and fastened by some means, such as plastic ties or PVC pipe, to create the bag. The flat bags are transferred to the intertidal zone where they are supported horizontally on iron racks fixed to the bottom at a predetermined depth (Figure 3a-b). This culture method also requires due attention, but much less than the previously described methods. Every 2-3 months, sometimes more frequently during the summer season, the bags are turned over to reduce clustering of the oyster shells, but more importantly, to reduce growth of filamentous algae and barnacles with subsequent increased fouling on the bags, which, in turn, leads to reduced water exchange and subsequent oxygen depletion with a reduced phytoplankton supply to the oysters (Figure 3a).

Although growth is good during summer along the Sylt Wadden Sea coast, it is still too slow to reach market size during the first year. Therefore, overwintering becomes important. One problem is severe ice coverage and heavy storms during some winters, damaging the culture racks and bags (Figure 4a-b). It is for that reason that all bags are stored in land-based tanks at a water temperature of 2-6°C during the winter season and all racks are removed and reinstalled in the spring.

Tractors, designed with balloon-like wheels, have been developed to carry the heavy bags and rods even with rising tides (Figure 5). The tractors are also used to reduce labor while assisting in turning the bags during the growout period. While the technique of using tractor-like vehicles is well established in several countries, the special needs for nature protection in the German Wadden Sea has led to specific conditions placed officially on the farmer. The size of the tires is determined by the maximum weight of the tractor, with loading not to exceed a certain pressure on the sediment of the Wadden Sea, so as to not disturb the benthic community.

At an age of two years the oysters are removed from the mesh bags and sorted by size. Oysters with a total length of 7 cm and larger have reached market size and are harvested. Smaller oysters are retained, reloaded into the bags and remain there for another growing season. The plastic mesh bag system is the only technique that has proved commercially viable and survived the trials of the last decades.

Others. In mollusc culture, mussels and oysters are the main candidates. Other species are presently not cultured but attempts in the early 1980s to develop a limited fishery with common edible cockles (*Cerastoderma edule*) and grooved carpet shells (*Venerupis decussatus*) were undertaken on a trial basis. They were accompanied by research and monitoring programs to establish whether fisheries could be operated in a sustainable manner. The endeavors failed for various reasons, including the fact that the exploitable volume per unit of time was too small to remain economically viable and the risk of permanent overfishing was too high.

Recently there were some test trials undertaken with abalone (*Haliotis tuberculata*). That was primarily on a research basis using recirculation systems, while, at the same time, several other candidates were tested in a polyculture context.

Production Statistics

Shellfish have the potential to contribute significantly to marine food production. Along the coast of the German Wadden Sea, extensive mussel farming through relying on leased beds has been practiced for many decades. For example, annual yields of about 50,000 t of meat have been

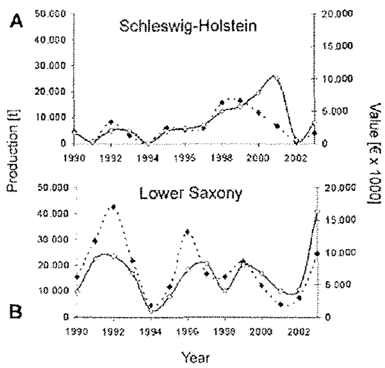

Fig. 6a/b. Shellfish aquaculture production and value in German coastal waters. (a) In Schleswig-Holstein and (b) In Lower Saxony. Data compiled from various sources.

quoted for on bottom culture of mussels around the German North Sea coast. Mesh bag culture of oysters at the island of Sylt achieve 100 t per year.

Before the 1980s, in Schleswig-Holstein and Lower Saxony, harvests on average seldom exceeded 6,000 t annually. Since the mid 1980s, a gradual increase in production has been noted, however, great fluctuations have occurred. While in 1997 harvests accounted for 5,750 t (Lower Saxony), the yield increased in 1998 to 15,600 t and to 16,600 t in 1999. The total production area presently does not exceed 1,300 ha and the entire operations are guided by a management plan of the State of Lower Saxony. In Schleswig-Holstein, the production increased from 4,583 t in 1994 to 32,874 t in 1996 (Fischerblatt 2003a, 2003b, FAO 2004).

Figure 6a,b demonstrates the development of landings of blue mussels from leased culture grounds. Statistics show low production levels in the 1950s, 1960s and 1970s with mean yields of 7,000, 8,600 and 12,100 t. In the 1980s, mean landings doubled to 25,500 t compared to the 1970s, with a further increase in the last decade to 27,800 t. Total production levels in Lower Saxony and Schleswig-Holstein within the last 50 years varied between 2,800 and 61,000 t/yr, leading to an average production level of around 16,300 t (26,000 t since the 1980s). Since 1990, the value of landings fluctuated between 1, 2 and 14.7 x 10^6 €. The mean value of landings of 9.5 x 10^6 € is shared between Lower Saxony (1/3) and Schleswig-Holstein (2/3) according to FAO 1999 and Hagena 2002).

In the past, especially in the 1990s, a large fluctuation in landings occurred not only in Lower Saxony but also in other areas along the Wadden Sea coast (Dijkema 1992). This development can be attributed to several years of very limited spatfall, with virtually no young mussels on wild natural plots. In times of low recruitment the fishery was thought to be responsible for a decline in natural mussel bank ar-

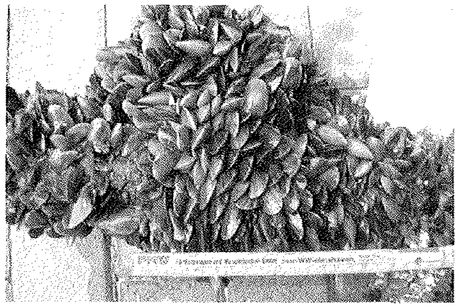

Fig. 7. Seed collector with a cluster of mussels (up to 5 cm after four months use).

eas. Therefore, NGO's put a lot of pressure on the shellfish fishery, which is carried out within the limits of Wadden Sea National parks. Since 1996 the situation improved due to one extremely good spatfall after the last hard winter of 1995-96. In the future, mussel and oyster farming along the German coast will face severe restrictions in licensed areas because of the many competing stakeholder interests within the German Wadden Sea areas.

Potential for Further Development

In response to bad recruitment for several years, research was started in 2000 to determine if suspended culture techniques could be used to produce seed mussels under the exposed conditions of the North Sea. Depending on the season, the maximum bivalve larval abundance peaked to 5-15 x 10^3 larvae/m^3 in the water column (Walter and Liebezeit 2001). Seed collection is carried out by deploying collectors down-current of wild mussel colonies (Figure 7). Recruitment on artificial substrates was very high even in years with no recruitment on natural plots. In 2000, a mean of 70,000/m^2 of collector of blue mussel spat were recorded (Walter and Liebezeit 2001).

There are severe limitations to an increase in production on conventional sublitoral and intertidal bottom culture systems along the German coast. These limitations relate mainly to the extensive conflicts between various coastal resource users, in particular the need for maintaining (extending) Marine Protected Areas (MPAs). The limiting regulatory framework is described below. Besides this, there are a number of environmental threats to mussel farmers because the North Sea coast of Germany accommodates one of the world's busiest shipping routes. Tanker accidents – and equally important continuous and frequent small oil spills – pose a permanent threat to the farmers who often experience extended closure of their operations after an oil spill. Even small events can render the entire production of a season useless. Further, shellfish are excellent filter feeders, known to accumulate environmental pollutants rapidly and effectively and this is utilized in environmental monitoring programs ("mussel watch"). Because major rivers drain into the German Bight of the North Sea, the threat of accidental contamination beyond tolerance limits for human consumption cannot be ignored, despite the efforts to reduce pollution derived from land-based and riverine sources. The recent 100 year flood in the Elbe River demonstrates the risks involved. It remains to be seen how much of the remobilized contaminants during the flood eventually will reach the coast and to what extent this may affect mussel farmers. The only option within German national marine waters seems to be the expansion to more exposed, offshore, farming.

Regulating Aquaculture in a Multiple Use Setting

The overall high use of the German North Sea coast is extremely multi-faceted and highly competitive; mainly from trade or private shipping, recreational activities, extraction and disposal of gravel, navy missions, fisheries, cable lines and the establishment of nature reserves and other marine and coastal protected areas. This diverse and multiple utilization demands a complex regulatory framework to optimize the sustainable and multiple resource use in the face of an uncertain future of the natural and socioeconomic systems (Buck et al. 2003).

The emerging branch of marine aquaculture faces a particular problem as a newcomer in an otherwise well-established setting of stakeholders in the coastal zone. Its needs as an industry have not been considered within existing management schemes. Due to harsh environmental conditions in the North Sea (high energy coasts), modern aquaculture development is certainly limited, in particular when considering conventional coastal culture systems. This is one of the many reasons why Germany has seen a rather level production in this sector over the past few decades (Rosenthal and Hilge 2000). There are some regulations which are common to all aquaculture activities in parts of the EU Directives framework and national regulations.

European Union Directives. Within the European Community there are several regulations that are relevant to aquaculture. The fisheries industry, including aquaculture, is dependent on environmental conditions, quality of the farmed waters and product handling, in terms of hygiene conditions for the safety of human health (Theodorou 2001). However, specific European legislation relevant to limiting the effect of aquaculture on biodiversity is less well established than for capture fisheries. The EU public health provisions are related to the chain of activities involved in the production, harvesting and marketing of marine products for human consumption. EU legislation includes Directives and Council Decisions related to the infrastructure, usually composed of the public agencies of the Member States, capable of assessing water quality (classification), monitoring culture and harvesting activities, and providing adequate surveillance of the chain of supply from the point of production to the point of consumption (Theodorou 2001). Among the applicable Community legislation, there are (1) Directive 79/923/EEC, which concerns the quality of shellfish waters in order to support shellfish life and growth of edible products and applies to coastal and brackish waters (CEC 1979; the parameters which are applicable to the designated waters are listed in the Annex) and (2) Council Directive 91/492/EEC and 97/79/EC, which lay down the health conditions and hygiene of live bivalve molluscs (CEC 1991, CEC 1997).

Federal Laws and Regulations of Concern for Shellfish Farming. Within the Federal political structure of Germany the Government enacts national orders, which are mostly completed through the jurisprudence of the Federal States. The Federal States, or "Länder", are in charge and are responsible for the laws, which deal with the use of water and

(Continued on page 66)

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(Continued from page 11)

with environmental protection. Within the Federal regulatory framework, the Sea Fisheries Law concerning the open sea states the term fisheries without covering aquaculture.

On a federal state level, all Länder bordering coastal waters, such as Bremen, Hamburg, Lower Saxony and Schleswig-Holstein have their own regulations concerning fisheries within the State Fisheries Laws (Bremen: Bremisches Fischereigesetz [BremFiG, 1991]; Hamburg: Hamburgisches Fischereigesetz [1986]; Lower Saxony: Niedersächsisches Fischereigesetz [Nds.FischG, 1978]; Schleswig-Holstein: Landesfischereigesetz [LFischG, 1996]). However, the State Fisheries Laws of Lower Saxony and Schleswig-Holstein are the only ones on German coasts that regulate the cultivation of marine organisms, such as oyster farming and the combined mussel and fish culture (§ 16 and 17 Nds.FischG, § 40 and 41 LFischG). Additionally, Lower Saxony and Schleswig-Holstein have Coastal Fisheries Regulations (Küstenfischereiordnung; Nds.KüFischO and KüFO) that regulate shellfish culture operations (§ 10 Nds.KüFischO and § 4 and 5 KüFO).

Along the German North Sea coastline an array of Natural Parks are designated as the National Wadden Sea Park of Lower Saxony, Hamburg and Schleswig-Holstein. Within these nature reserves National Park Laws are identified (National Park Law of Lower Saxony [2001], Law of the National Park of Hamburg [Gesetz über den Nationalpark Hamburgisches Wattenmeer, 1990], Nationalparkgesetz of Schleswig-Holstein [NPG, 1999]). The Laws in combination with the State Fisheries Laws regulate all aquaculture within the parks. While any kind of fishery, including aquaculture, is prohibited in the nature reserves of Hamburg, the NPG refers to the LFischG to specifically regulate the culture of blue mussels and oysters (§ 6 (2) and (3) NPG) within the area. The cultivation of shellfish is allowed in specific industrial areas within the park, but shellfish is restricted to blue mussel and oysters (Boysen 1991). Therefore, raising other species, such as cockles, clams or scallops is prohibited and, therefore, any development for shellfish aquaculture is extremely restricted.

The Nature Protection Law (Bundesnaturschutzgesetz [BNatSchG], 1998) applies to the growing and culture of mussels for scientific purposes (§ 20g (6), 3 BNatSchG) with the exception of endangered species (§ 26 (2), 1 BNatSchG).

Mussel farming is considered to be environmentally friendly with no clearly defined effluents, point source versus diffuse inputs, so that Federal Laws concerning water effluent quality criteria are not applicable. On the other hand, there are clear guidelines for water quality criteria applied to the safe operation of shellfish aquaculture (see EU Directive 79/923/EEC, 91/492/EEC and 97/79/EC).

The Mussel Management for Schleswig-Holstein. Fishing licenses, regulations on the culture area, minimum size of commercial mussels (5 cm), fishing season and maximum size for seed mussels (4 cm) are the main tools used to manage the mussel fishery. Shellfish sanitation has become more important in recent years. Algal toxins and bacteria have been analyzed regularly (Ruth 1993).

The legal basis for the mussel fishery in Lower Saxony is based on the State Fisheries Law (Nds.KüFischO, 1992) and the National Park Law (NPG 2001). Within the National Park Law of Lower Saxony shellfish cultivation is allowed and regulated in §9. Additionally, a management plan took effect in 1999. Two different governmental bodies are concerned with assessing the stock size and the distribution of seed mussels among the mussel companies in the next four years. Forty-eight of 187 locations of potential mussel beds were closed to fishing. The closures were accompanied by a research program that documents the development of those locations.

Case Study: The Mussel Management Plan for Schleswig-Holstein

The principal concept of the management plan for this German State is somewhat special in that it includes the environmental considerations for the largest German marine protected areas. Licensing for extensive mussel farming-fisheries are fully controlled and limited not only by area for seed harvesting and growout transfer, but also for the number of companies and boats involved, to the extent that companies eligible for a license must be located within two counties of the state. This also requires that all boats involved in this activity must be operated under German jurisdiction (home must be a German harbor). This guarantees that the entire activity is regionally bound and cannot be controlled from outside. The present regional licensing framework has set its conditions until the end of 2016. Such a timeframe allows for reasonable midterm planning and investment while rethinking and restructuring may be initiated well in advance of that date as needed (Ruth 2000, CWSS 2002)

Every skipper is advised to install an "electronic tachograph" (black box) on his working boat to provide all information necessary to control his work. The black box is run by the Fisheries Authority. The skipper of the vessel and the company do not have any access to the recorded data. Data are sent via satellite transmission to the main stations on land and then stored for later analysis by the authority. The data sets include the area of operation; the daytime and actual working hours; general information about the winch, such as type of winch used, depth and time of winch operation; and the production.

All the limitations mentioned below are based on the precautionary principle to protect the resource and to fulfill the obligations for the MPA within which part of the farming beds are located.

Area Related Capacity Limits. The overall size of the entire mussel farming industry within the German Wadden Sea area of Schleswig-Holstein has been limited to

3,000 ha and a finite plan has been developed to reduce this area to 2,000 ha by the end of 2006. For oyster culture (*Crassostrea gigas*) only one permit exists at the present time with a total area limit of 30 ha and under the present management scheme it is certain that no further licenses will be granted.

Habitat limitations. Placement of mussel plots above the mean low-water line of the spring tide or collection of seed mussels in the eulitoral zone are not permitted. The limitations are meant to protect the feed supply for non-diving marine birds within the National MPA. This has forced the industry to change their strategic plan to compensate for the loss of the option to obtain seed material. Further, a zoning approach for seed collection is effective in relation to the MPAs of Schleswig-Holstein.

Seasonal limitations. In contrast to oysters, harvesting of mussels is not permitted during the period between 15 April and 30 June. During the period, mussels usually have spawned in the Wadden Sea area and show very low meat content, rendering them unsuitable for marketing. Additionally, there exists a time limit for seed mussel placement, extending from 1 May to 30 June. This is the time of primary settlement of mussels in the Wadden Sea area; therefore, protecting recruitment of the resource.

Minimum growout time. There is a minimum time limit set for seed mussels to be maintained on growout grounds. Mussels being obtained from natural beds and relayed on licensed plots between 1 December and 30 April next year are not allowed to be harvested before 1 July the following year. Similarly, mussels relayed between 1 July and 30 November are not permitted to be harvested before 1 October the following year. This regulation replaces the previously employed minimum size at harvest regulation and provides maximum flexibility to respond to market demands while allowing for reasonable protection of recruits. For oysters there is no similar regulation.

Stocking culture plots with oysters. Only the culture of *O. edulis* and *C. gigas* is permitted. If spat are transferred from regions outside the watercourses of Schleswig-Holstein, it is prescribed that measures be taken to prevent the introduction of parasites, diseases and other nonindigenous species. The Fishery Authority requires an inspection certificate concerning the pathology and parasitology of the country of origin before placing the oysters into open waters.

Outlook and Perspectives

Going Offshore

The terms "offshore, open ocean and far out" are currently unknown or seldom used by the German public as the terms relate to aquaculture. Recently, however, these terms have become common catch-phrases in North America and elsewhere. In an effort to cover the immense demand for seafood products, new regions further away from coastal waters were sought to offer expansion areas. Such areas are located within the Economic Exclusive Zone (EEZ); that is, in federal waters, not those of the states. Currently, there are very few worldwide open ocean aquaculture businesses operating commercially because it is an international, emerging technology of aquaculture, requiring extensive development and testing. Our current research aims to ascertain the economic feasibility of an offshore marine aquaculture structure for the culture of marine organisms in the North Sea (Buck 2002).

In German territorial waters, a new stakeholder is in the process of setting up installations mainly in the EEZ and those activities are primarily concerned with offshore wind farms. More than 2,000 wind-generators are planned for installation in the EEZ of the North Sea before the end of this decade. Twelve are in the process of being installed. The offshore wind farms were chosen as a first possibility for installation in offshore locations.

Germany considers the combination of environmentally friendly wind-driven power generation with the environmental enhancement that aquaculture offers as a very important opportunity for the development of a multiple resource use concept. The research concentrates on open ocean aquaculture. Conventional onshore pond-based aquaculture or nearshore marine aquaculture with extensive reservoir and circulation systems are not covered.

Multifunctional use of offshore installations

Culture Conditions and Candidates. In offshore locations, the degree of mixing within the water column can be presumed to be high, inasmuch as the water masses are moved and exchanged continuously through tidal currents and are far away from urban usage. The concentration of pollutants, pesticides and near-surface agents can be considered as nonperilous. This provides a continuous supply of clean water having satisfactory levels of dissolved oxygen. The influence of salinity and temperature in these areas will be similar at all locations and is within the scope of tolerance of some candidates. However, the hydrodynamic conditions require resistant species that can withstand currents of about 1-2 m/s and mean wave heights of about 2-3 m (18 m every 100 years).

There are a variety of candidates that can be cultivated under such hydrodynamic and environmental conditions within the North Sea, and hold large potentials in the German market. Within the group of bivalves, the blue mussel and oysters are presumed to bear up those conditions. Additionally, mussels and oysters show high marketing potential in Germany.

Technique. Several types of cultivation can be used in the North Sea region (Figure 8). Longline systems are predominantly proposed for the cultivation of bivalves. Those are systems whereby submersible ropes provide the habitat on which the candidate species can settle. Other techniques, such as ring and cage constructions, which can be placed on the water surface and underwater. The Submersible Offshore Shellfish and Seaweed Cage (Buck 2002) can also be operated.

The advantage of submersible culture construction is the avoidance of the impact of harsh weather conditions and strong wave mechanics. Thus, a combination of these techniques with the main pillar (tripod or jacket) of the

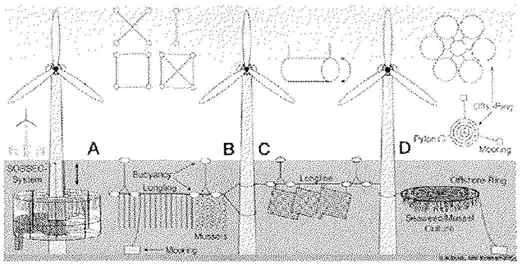

Fig. 8a-d. Side views and birdseye views from wind turbines combined with aquaculture techniques for mollusc culture. (a) SOSSEC (Submersible Offshore Shellfish and Seaweed Cage) for mussel and seaweed polyculture. Longline construction for (b) mussel and (c) oyster culture. (d) Ring construction for mussel and seaweed polyculture. Modified from Buck (2002)

windmill installation dispenses with the need for a sophisticated mooring system, which would impact strongly on the benthic ecosystem. Because of the solid construction of the windmills, such systems would be very safe.

Socio-economics. The outlined research points to the technical challenges and the importance of the skills any operator must possess. Furthermore, developing a new economic sector today requires that all users be addressed at the beginning of a new project so that consensus of all parties can be reached on conflicting issues such as user rights and duties to protect and support every user on equal terms (Buck et al. 2004). However, only by accepting the main idea of an integrated coastal zone management approach, an ecological and economically sustainable process can be launched and long-term success can be expected. Integration at all levels is required, not only of the different scientific fields, but also through community needs, external user groups and the responsible regulatory and planning authorities. The involvement of the latter two groups is commonly described as the step from the multi-disciplinarity to trans-disciplinarity (Buck et al. 2003).

Outlook

In early March 2002, a protected research area for aquaculture purposes was set up about 31 km offshore (Buck and Walter 2002). Because of the strong tidal currents at that location, wave heights can reach 3-4 m with a current velocity up to 2 m/s. The study area borders the zone of an applied wind farm, where the first windmills were to be installed by the end of 2003. Before technically elaborate and costly aquaculture systems will ever be fixed at or near offshore windmills, it is necessary to determine (a) their compatibility to requirements needed for other offshore installations and (b) the biotic and abiotic impacts, positive and negative, that such structures impose on the cultured species themselves. For this purpose, a longline system for mussel and oysters culture was installed.

Because onshore anchoring is not possible, both ends of the longline are securely tightened to heavy 4 t anchor stones (deadweight). A floating longline is attached and various types of culture systems are attached to the line for testing. These include lantern nets for oysters (*C. gigas*), collectors for larvae settlement and vertically hanging ropes for growout of mussels (*M. edulis*). As with the traditional bottom culture method in the Wadden Sea, the culture of offshore mussels depends on naturally settled larvae. These should settle on the given substrate provided by the collector or mussels and these structures could be attached to the ropes by man. These systems are preferred in high exposure areas.

In summary, there is an ample need for practical research pertaining to aquaculture development in the North Sea to overcome the current lack of knowledge on the performance of such new systems under given environmental conditions in the German offshore sector of the North Sea. The demonstration of its economic potential as an offshore aquaculture business will be a critical determinant for its future development.

Notes

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Appendix IV

Publication IV

Aquaculture and Environmental Regulations: The German Situation within the North Sea

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Abstract

The use of the North Sea is extremely multi-faceted and highly competitive. Within the vast variety of regulations inside the EU and in Germany, the regulative framework relevant to aquaculture is not yet complete. This chapter provides a short summary of the current legislative framework on international, national, and regional levels, which pertain to the development of aquaculture in Germany. Next, it highlights the question of decision-making in the coastal zone within an integrated coastal zone management (ICZM) approach. It can be shown that there is an ample need for sufficient regulations to optimise the management of marine resources, especially with respect to further ecological and socio-economic sound aquaculture development. Within the ICZM framework for aquaculture management in the North Sea, we propose a scheme for further development and the establishment of an independent regulatory/advisory body, which encompasses all spatial levels. Additionally, we show which tools, such as DSS (e.g. GIS) and active participation, could be used in such a scheme in the decision-making process and what outcomes are to be expected at which stage. The article closes with a call for integrative action in Germany for the further promotion of aquaculture development by endorsing the idea of ICZM in order to sustain the ecological and economic potential of the North Sea while providing an alternative livelihood for coastal communities.

Aquaculture and Environmental Regulations: The German Situation within the North Sea

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ABSTRACT

The use of the North Sea is extremely multi-faceted and highly competitive. Within the vast variety of regulations inside the EU and in Germany, the regulative framework relevant to aquaculture is not yet complete. This chapter provides a short summary of the current legislative framework on international, national, and regional levels, which pertain to the development of aquaculture in Germany. Next, it highlights the question of decision-making in the coastal zone within an integrated coastal zone management (ICZM) approach. It can be shown that there is an ample need for sufficient regulations to optimise the management of marine resources, especially with respect to further ecological and socio-economic sound aquaculture development. Within the ICZM framework for aquaculture management in the North Sea, we propose a scheme for further development and the establishment of an independent regulatory/advisory body, which encompasses all spatial levels. Additionally, we show which tools, such as DSS (e.g. GIS) and active participation, could be used in such a scheme in the decision-making process and what outcomes are to be expected at which stage. The article closes with a call for integrative action in Germany for the further promotion of aquaculture development by endorsing the idea of ICZM in order to sustain the ecological and economic potential of the North Sea while providing an alternative livelihood for coastal communities.

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1. INTRODUCTION

Aquaculture is presently one of the fastest growing aquatic food production sectors in the world and over the past two decades outputs have substantially increased within European Community (EC) countries. This development has been enhanced by a wide-ranging decline in fisheries yields accompanied by an increase in public demand for aquatic products. Due to limited availability of the conditions required for the development of modern aquaculture, Germany has seen a rather stagnant production level in this food sector.

The overall highly competitive use of the North Sea, for activities such as shipping (trade or private), recreational activities and tourism, extraction or disposal of gravel, marine missions, fisheries, offshore wind farms, cable lines, establishment of nature reserves and other marine and coastal protected areas, has highlighted the need for sufficient regulations to optimise the management of the resources within a multi-use context. In the marine environment, aquaculture production has a very short history and accordingly, regulatory frameworks in countries bordering the North Sea are diverse and still emerging.

The multifunctional sharing of marine waters must be regulated and safeguarded in order to provide all users with adequate user rights, while also protecting the marine environment and the environmental needs of all users. The emerging branch of marine aquaculture faces the same problems of every newcomer for which needs have not previously been considered. So far, a number of regulations are common to all users and are part of the European Union (EU) Directives framework, within which aquaculture will also have to find its place in national regulations.

This article intends to provide a rational summary how various levels of regulations are defined and may be interlinked to lead into recommendations for limited additional reference points within the national and existing international framework to accommodate a functional support system in which marine aquaculture can be integrated in multiple use concepts of the national coastal zone. It shall be demonstrated that an integrative approach to decision-making in the coastal zone would be highly beneficial for the further development of ecological and socio-economic sound aquaculture.

2. AN OVERVIEW OF THE PRESENT LAWS

(a) Historical Background

The principle of the freedom of the Seas (*mare liberum*) can be traced back to Hugo Grotius, who in 1608 claimed the Seas as *res commis* (Grotius, 1916). He asserted that things that cannot be seized or enclosed cannot become property. Grotius noted that use of the oceans for fishing or for navigation by one did not preclude their use by others. The oceans were created by nature in such a state that their usage could not be exclusive but belonged to all humankind (Grotius in Brilmayer and Klein, 2001).

This viewpoint indicated a natural right of mankind to utilise the resources of the Sea. Today the Sea is still generally regarded as commons. However, due to the growing awareness of resource depletion and limitation, the stage that

Hardin (1968) has defined as the "tragedy of the commons" has been reached. The development of the *UNCLOS* (United Nations Conventions on the Law of the Sea) agreement in 1982 can be seen as a move towards a change from this persistent commons perspective to a more regulative, protective rationing of international marine resources in the framework of sustainability.

International as well as national regulations and conventions concerning aquaculture within the EU are quite incomplete. While in some countries regulations for coastal aquaculture are well organised, the terms "aquaculture" and "mariculture" are often vaguely interpreted by regional and local authorities and do not comply with the Food and Agriculture Organisation of the United Nations (FAO) agreed definitions.

While in some countries aquaculture is defined and regulated under the agricultural laws, in others regulations are not centred in one lead agency. Germany is such a case where many regulations of several governmental bodies apply to aquaculture and are confusingly handled (individually and independently), leading to some uncertainty of the license process, not only for the applicants but also for the regulatory authorities themselves (e.g. federal, state, and local laws as well as EU and international regulations need to be addressed). Within the fragmentation of regulation applying to aquaculture there are no regulations concerning aquaculture within the German Exclusive Economic Zone (EEZ) at all (Czybulka and Kersandt, 2000; Buck, 2002). Furthermore, marine aquaculture in German territorial waters is presently very restricted with no hope for expansion, as regulations are stringent, and new licenses are extremely difficult to obtain (Rosenthal and Hilge, 2000). This is the case in particular for the licenses on bottom shellfish culture (Ruth, 1997).

(b) International Laws

Some international conventions, such as UNCLOS, *CBD* (Convention on Biological Diversity), and the *London Convention* (Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter) deal mainly with the protection of the marine environment and the prevention of pollution. Identification and monitoring of human activities that have an impact on the marine environment are included, while adequate environmental impact assessments are required to be carried out for any new development, followed by specific monitoring programmes. However, these regulations do not directly address marine aquaculture and do not therefore include specific aspects needed to fulfil the requirements of all interests. UNCLOS does not even mention the term aquaculture, but postulates measures to prevent, reduce and control pollution which might be originated by aquaculture (UNCLOS Art. 194 § 1, 1982). It also requires measures necessary to protect and preserve rare or fragile ecosystems including the habitat of depleted, threatened or endangered species (UNCLOS Art. 194 § 5, 1982). Like UNCLOS, CBD does not specify the term aquaculture. It primarily deals with impact assessments and avoiding or minimising adverse effects in general (§ 14; CBD, 1992). Within the London Convention an effective control shall individually and collectively promote all sources of pollution of the marine environment, and pledge themselves especially to take all practicable steps to prevent the pollution of the sea by the dumping of waste and other matter that is liable to create hazards to human health, to harm living resources and marine life, to damage amenities or to interfere with other legitimate uses of the sea. Again, aquaculture is not specified in this convention and is attributed to the term "others".

Only the *Agenda 21* explicitly alludes to the term aquaculture. In the Agenda 21, the impacts of aquaculture are discussed in the "Sustainable use and conservation of marine living resources under national jurisdiction" (Section II, Chapter 17, program area D). Coastal states are requested to conduct analysis of the potential of aquaculture and to implement mechanisms to develop mariculture and aquaculture within areas under national jurisdiction where assessments show that marine living resources are potentially available (17.79c, 17.83). Furthermore, coastal states should develop financial and technical co-operation to enhance the capacities of developing countries in coastal aquaculture and mariculture (17.87a). Agenda 21 suggests the following instruments for the implementation. The states should provide for the transfer of environmentally sound technologies to develop aquaculture and mariculture (17.92a) and accord special attention to mechanisms for transferring resource information and improved fishing and aquaculture technologies to fishing communities at the local level (17.92b). In addition, sustainable aquaculture development strategies should be established, including environmental management in support of rural fish-farming communities (17.94c).

(c) Regional Laws

Aquaculture is not mentioned in the *OSPAR*-Convention (*Oslo-Paris* Convention of the Protection of the Marine Environment of the North-East Atlantic), but within the OSPAR contracting parties it is identified as the technology to raise fish, molluscs and crustaceans (Czybulka and Kersandt, 2000). In addition to these convention articles, the Quality Status Report of OSPAR (QSR, 2000) records the actual condition of the impacts of human activities through aquaculture on the environment in terms of the release of metabolic wastes, antifoulants (copper), antibiotics, vaccines and parasites into the water column. Additionally, this report demands further work to assess the effect of implementation of the "ICES Code of Practice on the introductions and transfer of marine organisms" (International Council for the Exploration of the Sea) (ICES, 1984; ICES, 1988 and subsequent updates) and an assessment of the Recommendation 94/6 (PARCOM) concerning "best environmental practice for the reduction of inputs of potentially toxic chemicals from aquaculture use". Besides, the risk of spread of disease and the effect of escaped salmon on the genetic composition of wild stocks should be better documented.

Within the European Community there are several regulations which are relevant to aquaculture. The fisheries industry (including aquaculture) is directly dependent on environmental conditions, the quality of the farmed waters and product handling (in terms of hygiene conditions for the safety of human health) (Theodorou, 2001). However, specific European legislation relevant to limiting the effect of aquaculture on biodiversity is less well established than for capture fisheries. The EU public health provisions are related to the chain of activities involved in the production, harvesting and marketing of marine products for human consumption. EU legislation includes Directives and Council Decisions related to the infrastructure (usually composed of the public agencies of the Member States) capable of assessing water quality (classification), monitoring culture and harvesting activities, and providing adequate surveillance of the chain of supply from the point of production to the point of consumption (Theodorou, 2001). Among the applicable pieces of community legislation, there are (1) Directive 79/923/EEC, which concerns the quality of shellfish waters required to support shellfish life and growth of edible products and which applies to coastal and brackish waters (CEC, 1979; the parameters which are applicable to the designated waters are listed in the Annex) and (2) Council Directive 91/492/EEC and 97/79/EC, which lay down the health conditions and hygiene of live bivalve molluscs (CEC, 1991a; CEC, 1997a). (3) Council Directive 97/11/EEC on the assessment of the effects of certain public and private projects on the environment is also relevant to aquaculture purposes (amending Directive 85/337/EEC). It is mentioned in Annex II 1f concerning intensive fish farming, however, it is not definitely elucidated (CEC, 1997b). (4) The Council Regulation 1181/98/EC amending Regulation 3760/92/EEC, establishing a community system for fisheries and aquaculture, deals with similar regulations, such as the *Common Fisheries Policy* (CFP), which stressed the need for rational, responsible, and sustainable exploitation of fisheries and a more effective control of the whole fishing industry (CEC, 1998). In continuation of the amended Directive 3760/92/EEC, (5) Regulation 2847/93/EEC on control system applicable to the common fisheries policy was created (CEC, 1993). The *Green Paper* on the future of the CFP postulates the development of aquaculture in order to contribute to the supply of fish without increasing pressure on stocks in the marine environment. Aquaculture plays an important role in improving the socio-economic situation of coastal communities by providing alternative employment. The paper ranks priorities concerning the support for aquaculture. Issues addressed concern mainly training and control, research and development, treatment of waste water and the eradication and/or prevention of diseases. All these key issues will be supported by the *Financial Instrument for Fisheries Guidance* (FIFG). Most aquaculture activities are regulated by national legislation of each contracting Party to FIFG, which is influenced by a number of horizontal Community Directives, such as the (6) Water Framework Directive (2455/2001/EC amending Directive 2000/60/EC) (CEC, 2001b). (7) Directive 2001/18/EC (repealing Council Directive 90/220/EEC) on the deliberate release into the environment of genetically modified organisms covers both experimental purposes and the placing of such organisms on the market, which includes release of genetically engineered fish or shellfish (CEC, 2001a). (8) Fish and Shellfish Directive (91/67/EEC) controls animal health and the movement of animals, including infected animals, in order to prevent the spread of disease (CEC, 1991b). Furthermore, there are no regulations concerning aquaculture specifically relevant to the EEZ (Czybulka and Kersandt, 2000).

The International Conference on the Protection of the North Sea (NCS) does not take any position on regulation of aquaculture, but fosters the political impetus for the intensification of the environmental protection work within relevant international conventions, and ensures more efficient implementation schemes for the existing international rules related to the marine environment in all North Sea jurisdictions.

The *Trilateral Wadden Sea Plan* (WSP, 1997), formulated by Germany, Netherlands and Denmark, is aimed at limiting inshore aquaculture areas to the current area extension for mussel culture plots (Chapter 4.1.19). The existing permits specified for oyster culture will remain in force for traditional reasons. According to these permits, importation of seed oysters (whether bottom, rack or longline) is restricted to those from hatcheries that are under veterinary control. New permits will not be granted (Chapter 4.1.20).

(d) Laws in Germany

Within the Federal political structure of Germany, the Government enacts national orders which are mostly completed through the jurisprudence of the Federal States. The Federal States, called "Länder", are in charge and are responsible for the laws which deal with the use of water and with environmental protection. Within the Federal regulative framework, the *Sea Fisheries Law* concerning the open sea regulates the term fisheries, without covering aquaculture.

Concerning fish farm effluents, the *Federal Law on Water* (Wasserhaushaltsgesetz [WHG], 1996) is relevant for the licensing procedure (§ 2 and 7 WHG). However, the WHG does address primarily land-based systems which are considered point source emitters (looking at suspended solid load in terms of BOD [biological oxygen demand] and COD [chemical oxygen demand], oxygen deficit etc.), while water extraction and emission standards depend on numerous regulations. Open systems in coastal areas are dealing without standards being given. However, open waters within the EEZ are not covered. Cage culture systems in water-based marine or freshwater systems represent a matter of use, corresponding to § 3 (1) 4 WHG in connection with § 22 WHG. They need permission, should the situation arise (Schmid, 1993). Whether in freshwater or coastal marine systems, aquaculture regulatory measures under Federal Law (§ 7a [20] WHG and updates) cover land-based systems only.

The *Nature Protection Law* (Bundesnaturschutzgesetz [BNatSchG], 1998) does not include regulations concerning aquaculture in general, but indicates the rearing of fish for scientific purposes (§ 20g (6), 3 BNatSchG) with a restriction on the culture of endangered species (§ 26 (2),1 BNatSchG).

At a Federal State level, all "Länder" bordering coastal waters along the North Sea, such as Bremen, Hamburg, Lower Saxony and Schleswig-Holstein, have their own regulations concerning fisheries and partly on aquaculture within the *State Fisheries Laws* (Bremen: Bremisches Fischereigesetz [BremFiG, 1991]; Hamburg: Hamburgisches Fischereigesetz [1986]; Lower Saxony: Niedersächsisches Fischereigesetz [Nds.FischG, 1978]; Schleswig-Holstein: Landesfischereigesetz [LFischG, 1996]). However, only the State Fisheries Laws of Lower Saxony and Schleswig-Holstein regulate the cultivation of marine organisms, such as oyster farming and the combined mussel fishery-culture (§ 16 and 17 Nds.FischG, § 40 and 41 LFischG). Additionally, Lower Saxony and Schleswig-Holstein have *Coastal Fisheries Regulations* (Nds.KüFischO, 1992; KüFO, 1999), which regulate shellfish culture operations (§ 10 Nds.KüFischO and § 4 and 5 KüFO).

Along the German North Sea coastline a vast area of Natural Parks are designated as the *National Wadden Sea Park* of Lower Saxony, Hamburg and Schleswig-Holstein. Within these nature reserves *National Park Laws* are identified (National Park Law of Lower Saxony [2001], Law of the National Park of Hamburg [Gesetz über den Nationalpark Hamburgisches Wattenmeer, 1990], Nationalparkgesetz of Schleswig-Holstein [NPG, 1999]). These Laws, in combination with the State Fisheries Laws, regulate all aquaculture practices within the parks. While any kind of fisheries (including aquaculture) is prohibited in the nature reserves of Hamburg, the NPG refers to the LFischG to regulate specifically the culture of blue mussels and oysters (§ 6 (2) and (3) NPG) within the area. The cultivation of shellfish is allowed in specifically industrial areas within the park, but shellfish is restricted to blue mussel and oysters (Boysen, 1991). Therefore, raising other species, such as cockles, clams or scallops, is prohibited and therefore any development for shellfish aquaculture is extremely restricted.

Within the National Park Law of Lower Saxony shellfish cultivation is allowed and regulated in § 9 (National Park Law of Lower Saxony) while licences are maintained. When located within the Park area they will undergo changes in operational conditions within the next five years. These include long-range GPS-Satellite monitoring of all operational procedures which are restricted.

Marine fish farming is not specifically regulated in any of these Federal State or Coastal Fisheries Laws. Similarly, the cultivation of macroalgae or crustaceans is not mentioned in the regulations so far identified and described. Any application for a permit will therefore have to be handled as any other industrial application where outputs are limited. The difficulty is that water-based systems such as shellfish farms are incorporated in an ecosystem context in terms of uptake and release of nutrients and food organisms. Thus, conventional emission or immission standards do not apply. Similarly, fish farms operating cage flotillas are dispersed over a larger licence area and are considered as diffuse inputs as compared to point sources (GESAMP, 1996). One of the criteria to be taken as an environmental control aspect is the determination of the "assimilative capacity" (GESAMP, 1996; MARAQUA see below), which will sometimes be in conflict with effluent standards, as larger areas are included in conversion calculations.

Within the EEZ the regulation of marine facilities (Seeanlagenverordnung [SeeAnlV, 2001]) encompasses the erection, operation, and use of facilities which will be used by any offshore industry including mariculture (e.g. floating devices such as net pens and longlines or fixed structures such as cages).

Other laws and acts, such as the *Federal Regional Planning Act*, concerning Environmental Impact Assessments, a Municipal Landscape Plan and the County Landscape Plan, are relevant to both marine and inland waters, but are only defined for the latter (Bridge, 2001).

3. DECISION-MAKING IN COASTAL ZONE MANAGEMENT

Recently, a paradigm shift has taken place from predominantly ecological studies when considering the environmental impact of any activity to a stronger incorporation of socio-economic issues within the decision-making process in coastal areas. This has encouraged cross-sectoral discussions on coastal zone planning and management between different stakeholders, planners and regulators (Underwood, 1995; James, 2000; Kannen, 2000; Lakshmi and Rajagopalan, 2000; Welp, 2001). However, few clear structures on decision process guidance have yet evolved. Few approaches are tested as "virtual trajectories" across coastal systems (from upland to foreshore) with multidisciplinary and transdisciplinary inputs. However, more research efforts are required before evaluation criteria can be identified with sufficient confidence for these to be translated into regulatory measures. It is certainly questionable whether such criteria should result in strongly formulated regulations, as integrated management systems required the optimum resource mix, which requires general regulatory frameworks and objectives that may be adapted from case to case. Socio-economics are gaining importance in the overall assessment criteria (GESAMP, 1996; European Commission, 1999).

Decision-making within Coastal Zones is a complex process, which encompasses ecological, humanistic and economic needs and therefore must be managed jointly. A major role is played by the framework of environmental regulations promoting or limiting certain activities. Decision-making in the face of uncertainty is a common exercise for which skills within management are often as diverse and incomplete as our knowledge on the systems to be managed (Hogarth and McGlade, 1998). Thus, managers depend on good quality science for interpretation of both resource knowledge and uncertainties in a given coastal area.

To incorporate multidisciplinary knowledge requires a platform of communication on which a common denominator for all disciplines and interests involved can be identified (e.g. socio-economic, demographic, ecological, physical, climatic and technological disciplines). Such an approach acknowledges diversity in resource use demand, in views expressed, in terms of environmental and socio-economic interactions, while also opening opportunities for consensus building and/or agreed settlements over controversially debated issues. To implement such approaches, adequate tools are needed that are designed to optimise the benefits of the existing legal framework while identifying gaps to be filled for such optimisation. Although a holistic approach might be seen as one providing the most objective context to solutions (Richter *et al.*, 2001) there is still a need for pragmatic products to attract all stakeholders for the identification of realistic management options.

The limited success of ICZM (Integrated Coastal Zone Management) to date raises the question of why the available scientific information has not been used more effectively to inform the coastal policy, planning and management process (Burbridge, 1997). The development of robust tools to foster the ICZM process depends on a number of conditions within a given coastal region, where agreements and rules are initially based on trust and continuity. These develop over time and need to be amended in accordance with new multi-disciplinary data becoming available. Further such rules, once securely operational, need to be embedded in legal regulations. Thus, regulations are in part a product of the historically evolved functions which are merged with established regulatory procedures.

Richter *et al.* (2001) point to the current dialogue between ICZM managers, politicians, scientists and stakeholders which often suffers from lack of easy flow of relevant information in the right sequence.

So far, several tools have evolved on a test basis for promoting transdisciplinary interchange of information between different stakeholders, managers and the jurisprudence. Some of these that have been of influence on aquaculture development but are not an obligatory procedure and are not yet sufficiently well established at a bureaucratic level are briefly outlined below.

3.1. Decision Support System Analysis as a Tool in the Decision-Making Process

Several computerised Decision Support Systems (DSS) are available (Fabbri, 1998). For the development of a DSS to foster the establishment of sound management guidelines, monitoring programmes are of major importance, as they provide the data needed to install such computerised systems. The main goal of monitoring is to assess whether an activity has an unacceptable impact on the environment, the threshold of acceptability normally being decided on societal grounds. GESAMP (1996) define monitoring in a straightforward manner, as the regular collection, generally under regulatory mandate, of biological, chemical or physical data from predetermined locations, such that ecological changes attributable to, for example, aquaculture can be quantified and evaluated. Reviews, such as Fernandes *et al.* (2001) show how science could provide a monitoring strategy for marine aquaculture operations that is flexible enough to be applicable to a variety of locations, species and situations. They point out that traditionally environmental monitoring has concentrated on a few physical and chemical variables and organisms, somewhat reflecting the current state of the regulations in the coastal zone pertaining to aquaculture. However, there is a trend towards whole-system environment assessments (e.g. OSPAR, 1992; Fernandes *et al.*, 2001), including considerations of the assimilative capacity of specific systems. The current efforts in uniting the coastal zones of the Wadden Sea in the Netherlands, Germany and Denmark through the trilateral National Park agreement can be regarded as a first positive step. For example, the "Common Package" of the TMAP (Trilateral Monitoring and Assessment Program) promotes a unified parameter scheme for data sampling and management which supports recommendations for the development of management strategies on a trilateral basis (Marencic, 2002) and can be incorporated into a regional DSS.

These DSS assist in interpreting complex data sets for improved expert use. For example, SimCoast™ (Simulating the Coast) is one of these systems (Hogarth and McGlade, 1998). These do not affect the regulatory frameworks but often identify interactions of environmental impacts of various resource users and use-methods such as EIA (Environmental Impact Assessment) and EIS (Environmental Impact Statement) as an iterative process rather than a single exercise to determine site-specific limits.

One other commonly employed tool for decision-making in the environmental planning process is Geographic Information Systems (GIS). They are capable of storing vast amounts of data and of representing these in visual format, for example, in maps. Fabbri (1998) suggests that the integration of the GIS spatial information storage in a spatial decision support system would be the ideal way to promote consistent decision-making and to evaluate coastal development alternatives to ensure ecological sustainability in the coastal zone. Such systems support decisions and highlight areas of conflicting spatial demand.

Generally, DSSs are useful for scenario building to aid decision-makers (Warner and Jones, 1998) in their task of weighing the environmental, economic and social values of any one set of conditions against another, thereby presenting sound arguments for several options which are perceived as threads of benefits while identifying optimum solutions (consensus building). The level of certainty (or uncertainty) as well as the precision of data for parts of the scenario produces a negotiation base on which risks can be identified and assessed (through appropriate methods) and proposed solutions rejected or jointly carried. The usefulness of such tools depends on the quality of the data and the representativeness of the identified local or regional stakeholder needs. These are identified in rules and target objectives negotiated between all stakeholders. The level of participation is therefore crucial to success. Despite computerisation, the process is time consuming, complex and difficult to handle, but fosters a highly qualified and better informed decision process.

It has to be realised that such systems are presently under development. They are still in their infancy and require extensive effort in terms of research and further development. One of the advantages of such systems is that they permit a better use of existing vast data sets and the incorporation of other modelling approaches (e.g. numerical models).

3.2. Participation Techniques

The EU demonstration programme (European Commission, 1999) has shown that participation can be crucial. Nonetheless, does this vindicate the temporal, financial and social efforts of participation in terms of "output"? Participation has been perceived as a panacea for many ICZM approaches (Noble, 2000; Van Mulekom, 1999). However, one has to acknowledge that a consensus encompassing all stakeholder groups equally is extremely difficult to achieve and requires a substantial amount of time. Participation can be defined in various ways. Following Govan *et al.* (1998) and Glaser and Krause (2002), we distinguish between 3 different levels of participation:

- The *passive* participation with an exclusive information function, but without participation or informed decision warrants for directly affected groups;
- The *consultative* participation, which involves the stakeholders with limited possibilities and rights of hearing;
- The *active* participation, by which the affected stakeholder is qualified and entitled to make decisions and is liable for actions.

The main success of active participation, apart from the early mediation of emerging conflicts between different stakeholder groups (Warner and Jones, 1998), is in the establishment of rules through consensus-building at local and regional levels. Following the initial joint formulation of the rules by the stakeholders, these can be validated by DSS based on the background data incorporated by the multidisciplinary sciences. Following this validation, by which continuous informing of the participating stakeholders takes place, the rules can be embedded into the existing regulatory framework. This strategy achieves two goals. First, the jurisdiction adapts to the local conditions and needs, and fits the regulatory framework accordingly. Furthermore, as the rules have been initially formulated and agreed by the stakeholders, lower costs for the supervision of compliance with the verbalised regulations can be expected. Thus, policy changes are agreed to by the resource users and thus are more successful than those which are enforced by external entrepreneur activities.

Such approaches have been partially carried out in several countries, for example, in Brazil. Here, the concept of the "*reservas extrativistas*" (RESEX) (extractive reserves) was developed following the intense social clashes in the early 1980s in the Amazon region, between rubber plantation farmers and local traditional communities, which gained international attention through the murder of the community leader Chico Mendes (Allegretti, 1994). One of the ideas of the RESEX is, in brief, resource conservation through self-responsible use by the traditional local communities (Glaser and Krause, 2002). The latter encompasses groups for whom the use of the natural resource comprises economic as well as cultural values.

The process of the RESEX is carried out by *active* participation, by which defined user-rights are assigned to the traditional local communities and stakeholders, these being formulated by and between these groups and the environmental jurisdiction. This approach is led by the knowledge and priorities of the direct resource user. Their improved participatory involvement in the national development process is one of the main goals of the RESEX process. This approach is currently in expansion to the coastal regions of Brazil, but is hampered by a lack of financial resources and poor understanding of active participation in the first place. A more detailed review of the advantages and limitations of this approach is given in Glaser and Krause (2002).

This strategy provides an example of how participation can be carried out in practical terms, and what role the environmental regulations could play. However, one of the major drawbacks within this approach is that outsiders, such as financially strong companies that are common in the aquaculture business, are not included. Often these companies introduce their own value perceptions and economic interests to the coastal areas, and these are not necessarily based on the local conditions. On the contrary, activities of other stakeholder groups, which are likely to affect the proper functioning of an aquaculture farm (e.g. emission of sewage), are commonly not regulated and communicated in order to protect income generation through aquaculture.

4. ICZM FRAMEWORK FOR AQUACULTURE MANAGEMENT IN THE NORTH SEA

What are the lessons learned from the above brief review of the status of tools for decision-making for the environmental jurisprudence? Clearly, there is an ample need to enforce and support good practice in ICZM by the administrations at local, regional and Federal State level. There is an emerging demand for environmental law regulations that move away from the spatial-sectoral disposition of the ecosystem to a more realistic, dynamic and integrative legislation in the coastal zone. Especially in these areas such regulations are necessary, if the authorities wish to keep pace with the current tendency of enforced uses of the marine resources whilst following the constitutional precautionary principle.

To date aquaculture has not generally been considered as having equal rights of access to and use of natural resources in competition for sites in the coastal zone. Existing activities are often protected by legislative systems that are typically based on land laws that are not well suited for aquaculture (Burbrigde *et al.*, 2001). This current legislative state is hampering the further promotion of the aquaculture sector, especially in terms of the gradually increasing resistance to its development, through the non-involvement of other stakeholders during the early consultation and planning phase. As well as emerging conflicts over the control of natural resources, which inevitably arise when *active* participation does not take place between the stakeholders, the groups which retain their traditional access may find them less productive in the long run. There is therefore a need to establish clearer user (property) rights regimes (Burbrigde *et al.*, 2001) but also a well-defined, integrated juridical framework to support active participation and co-management in the coastal areas. Thus, laws concerning the use of marine areas for aquaculture operations have to be modified, or new regulations have to be established, to encompass, amongst others, aquaculture demands.

The above mentioned tools within the ICZM process are only some of the vast array of different approaches. This leads us to the question, at which stage should which tools be used and what would be the expected outcomes? Clearly, there is a need for integrative approaches, co-management, active participation, alternative livelihood scenarios and ecological corridors in order to sustain the Seas as viable ecosystems. In Figure 1, a scheme is proposed for a regulatory framework for aquaculture development in the North Sea.

This scheme shows that the marine management tasks cannot be accomplished by the current authority structure available within the North Sea Federal State communities. We propose the establishment of a multi- and transdisciplinary independent regulative/advisory body, which ties in on different spatial levels and encompasses the affairs of the various Federal State communities in the EU. Over a given timeline, successive activities concerning different topics have to be addressed. Following an interdisciplinary assessment, where we suggest the use of an array of different tools, such as monitoring and establishment of DSSs, an integrated conflict assessment in spatial perspective could be achieved. Following this outcome, the main focus is on the legislation to formulate regulations, from case to case, between the different stakeholders on a transdisciplinary level. Of major importance here

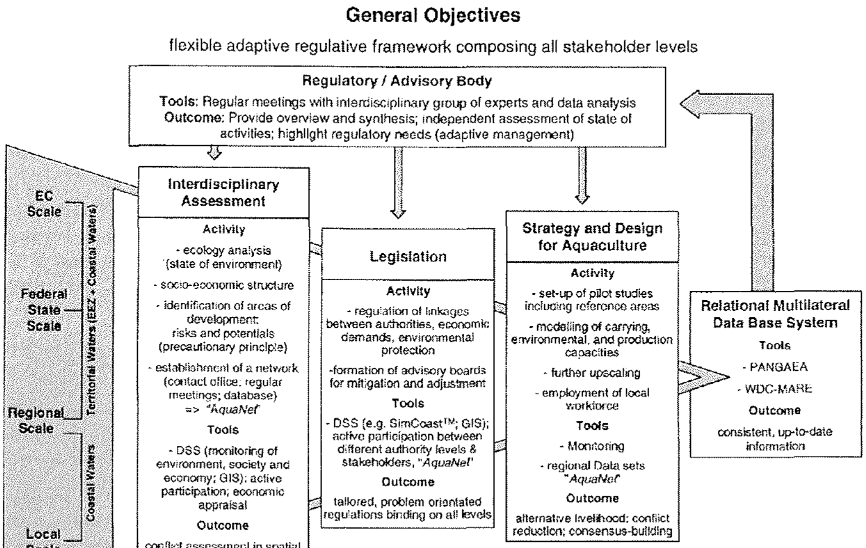

Figure 1. Scheme for the establishment of a flexible adaptive regulative framework comprising all stakeholder levels. The proposed regulatory/advisory body would provide expert knowledge, based on a relational multi-lateral data base, for the sectors "Interdisciplinary Assessment", "Legislation", and "Strategy and Design for Aquaculture" in the regulation and management process on a given timeline. For each of these sectors, several tools are proposed and desired outcomes outlined.

would be the formation of a platform for mitigation and adjustment between all groups involved. As tools for this procedure we suggest, among others, active participation and regular meetings between all stakeholder groups. This approach would lead to a tailored, problem-orientated set of regulations, which need to be binding at all levels. Having defined this framework, we can move on to formulate and test strategies and design of aquaculture at specific, previously assigned, sites. By continuous monitoring of the aquaculture site and reference areas, regional data sets are established, which flow into the relational, multi-lateral data base system. As the approach of the aquaculture is integrated, we expect outcomes to be based on consensus between the stakeholders and to provide alternative livelihoods for local communities. The different steps within the different spatial layers and sectors have to be repeated over time, which thus follows the generation policy cycles 1, 2 and 3 for ICZM proposed by Olsen *et al.* (1997).

5. DISCUSSION

In terms of the constantly increasing demand for marine products, aquaculture is one way out of the food impasse. To satisfy the increased demand for aquaculture products, this sector is currently undergoing a rapid development from a world-wide perspective. In the many considerations of the effects of aquaculture on the environment, the "precautionary principle" is frequently raised. Bengston *et al.* (2001) note that there is a requirement that all activities should be subject to prior review and authorisation. However, this principle should not be used frivolously to stop production if there is no impending environmental degradation. Tools, as outlined above, can be useful for elucidating ecological and socio-economic components and their interlinkages. This is especially timely with regard to the limited spatial resources available in the North Sea for development and extension of aquaculture. Questions pertaining to the number and type of species best suited to a balanced development of aquaculture should be addressed in close collaboration with experts as well as stakeholder groups and need to undergo well-defined decision-making process.

The existing regulations that have been listed above, which deal with aquaculture of marine organisms, have to be tied together or modified in order to provide a basis for straightforward integrative regulation for all stakeholders. First of all, the term aquaculture should be introduced into the regulative framework of all levels of institutions in concordance with the definitions within the Agenda 21, both in international conventions (e.g. OSPAR, 1992; UNCLOS, 1982) and in regional and State laws and directives. Furthermore, a simplification of EEC Directives and regulations should be realised in order to cover all sectors of aquaculture and the "grey areas" within the EEZs.

Regarding the current regulative framework in place for the German Territorial Waters, we suggest the creation of an overlapping comprehensive legislative body which is represented by an advisory board of experts on a multidisciplinary basis (see Figure 1). The cultivation of all potential marine candidates, such as fish, molluscs, crustaceans and macroalgae, has to be defined for all coastal zones of the Federal States as well as within the EU and the EEZ. Additionally, there is a need for regulations to protect and foster aquaculture development as well as to minimise impacts of other users on aquaculture.

A framework for developing new environmental law regulations, especially with respect to the emerging issues within aquaculture development, should incorporate the multi-dimensional interactions and ecosystem functions. It must be clear that for all types of human activities, ecosystems will set the limits as to how large an activity can grow in relation to its resource base. Within this ecosystem framework, the social system with all its institutional and cultural aspects will determine how fast an activity is approaching these limits. Thus, the definition of capacity thresholds on various levels is of importance for arriving at a well-defined scheme for sustainable development.

So far, from an international perspective, Canada has gone furthest in the regulation of aquaculture issues within the coastal areas (Fernandes *et al.*, 2000). Of the other States, the EU has made substantial efforts to establish a general framework of *Scientific Guidelines for Best Environmental Practice* in respect of aquaculture development, which could be widely applicable throughout the EU. The project "MARAQUA" (Monitoring and Regulation of Marine Aquaculture in Europe) is one example of this effort, which has been established and funded under the umbrella of the EU FAIR (Agriculture and Fisheries Programme) program. This two-year project, which commenced in 1999, was a "Concerted Action" and therefore did not involve new research but instead concentrated on a review of existing information and the establishment of agreed guidelines for the monitoring and regulation of marine aquaculture. Three workshops of expert groups, consisting of scientists, producers, regulators and voluntary organisations, took place, each focusing on different aspects of aquaculture development. MARAQUA has produced a critical review of the monitoring and regulation of marine aquaculture in the EU with reference to the implications of national and international regulation, and the role of codes of conduct, codes of practice and management systems in this process. Among other matters, the project analysed the socio-economic basis for approaches to improve the management of marine aquaculture (Fernandes *et al.*, 2000; Rosenthal *et al.*, 2000; Read *et al.*, 2001a; Rosenthal *et al.*, 2001).

The project raised some key issues, which need to be examined further attention in respect of the management and regulation of aquaculture. For example, MARAQUA highlighted aquaculture as an established marine activity which needs to fulfil environmental compatibility criteria in order to achieve sustainability, thereby meeting the social, economic and environmental needs and aspirations of society (Read *et al.*, 2001b). Additionally, the importance of promoting new policies for aquaculture that seek its full integration into an EU common strategy for the promotion of improved integrated planning and management of coastal development was emphasised.

We feel that the outcomes of such projects like MARAQUA provide a sound scientific basis for the further development of new, more integrated and comprehensive environmental regulatory framework to foster the establishment of sustainable aquaculture in the light of active co-management in the coastal zone.

6. CONCLUSIONS AND OUTLOOK

It could be argued that the current regulative framework in place in Germany does not support start-up companies in the aquaculture sector and does not attract potential investors. However, further promotion of aquaculture development should be carried out by the endorsement of the idea of ICZM in order for development to be sustainable and thus maintain the economic potential it holds for alternative livelihoods for coastal communities. This can be achieved by, among other things, considering risk-adverse behaviour and the "precautionary principle" of environmental management (Bodansky, 1991) and the implementation of adaptive management tools, which are suggested in the scheme above. In order to optimise for sustainable development, ICZM should consider both the short- and long-term impacts, which should be reflected in the environmental legislative framework. In this respect, environmental law regulations are of major importance for the promotion of integrated and transdisciplinary management. Legislative issues should encompass not only the direct "problem", for example, regulation of the establishment and maintenance of an aquaculture, but also the participation of the local stakeholders. This could limit the negative effect of external entrepreneur activities, which currently can only be minimally held liable for damages to the ecosystem, as well as to the local socio-economic system. Regulations should also support the establishment of new possibilities and user rights for the local user groups, for example, an imperative for fishermen training for future employment at aquaculture farms which are located on former traditional fishing grounds as a compensation measure. Additionally, a mitigation platform needs to be established where, from case to case, conflicts that arise can be addressed in an unbiased atmosphere and a consensus found. As well as the establishment of an information network, "*AquaNet*", there is a need for a lead agency (e.g. advisory board) in each country to be responsible for cross-sectoral regulatory framework development.

Active participation may influence the success of a sustained aquaculture development in the coastal zone. Herein lies the major role for the development of integrated environmental law regulations in order to minimise biased decision-making within an integrated coastal zone management framework and to support the idea of sustainability.

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Appendix V

Publication V

Extensive open ocean aquaculture development within wind farms in Germany: the prospect of offshore co-management and legal constraints

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Abstract

In the offshore region of Germany, human activity is increasing in type and intensity. Larger portions of the sea are sectioned off, dedicated for specific, often exclusive uses that cause rising conflicts between interests groups. One solution calls for stakeholder integration and the multifunctional use of space. This article focuses on two examples, offshore wind farms and open ocean aquaculture. It analyses their potential synergies within a co-management approach. It can be shown, that an integrated co-management strategy for offshore regions requires very different sets of rights and duties, as well as holding different types of conflicts, constrains and alliances, some of which are illustrated for the presented case study. The article closes with the conclusion that an integrated regulative framework is the most important basic precondition for a multifunctional utilisation of offshore areas and its sustainable development.

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Extensive open ocean aquaculture development within wind farms in Germany: the prospect of offshore co-management and legal constraints

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Abstract

In the offshore region of Germany, human activity is increasing in type and intensity. Larger portions of the sea are sectioned off, dedicated for specific, often exclusive uses that cause rising conflicts between interests groups. One solution calls for stakeholder integration and the multifunctional use of space. This article focuses on two examples, offshore wind farms and open ocean aquaculture. It analyses their potential synergies within a co-management approach. It can be shown, that an integrated co-management strategy for offshore regions requires very different sets of rights and duties, as well as holding different types of conflicts, constrains and alliances, some of which are illustrated for the presented case study. The article closes with the conclusion that an integrated regulative framework is the most important basic precondition for a multifunctional utilisation of offshore areas and its sustainable development.

1. Introduction

This note examines the conditions for potential sustainable schemes for a multifunctional use of marine resources in the Exclusive Economic Zone (EEZ) of Germany. The motivation is given by the intended development of offshore wind farms in conjunction with open ocean aquaculture within the German Bight.

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Without the solid foundations for the wind turbines as anchor points, economic installations of equipment for an extensive mariculture would not be possible in view of the high-energy environment in this part of the North Sea. For the aquaculture in this offshore region an extensive cultivation of blue mussels (*Mytilus edulis*), oysters (*Ostrea edulis*, *Crassostrea gigas*) and seaweed (*Laminaria saccharina*, *Palmaria palmata*) is considered.

In spite of the appealing potential synergy between the above completely different activities and the favourable motivation to establish alliances within the two potential user groups, conflicts between them and others are foreseen which deserve intelligent solutions by assigning clear rights that can be relied on. This aspect and the duties that have to comply with by all involved are discussed in this case example. The term "multifunctional co-management" is used in this context to describe the management of multiple uses, ranging from simultaneous utilisation of a certain area to jointly used infrastructure and sharing of economic input by various stakeholders, to which the authorities provide support and offer mutually agreed rules and duties.

Typically, there is a larger number of resource users in coastal waters than in high sea environments or on terrestrial grounds [1]. Their interactions occur at different spatial levels. If one attempts to minimise conflicts, integrated coastal management schemes must be commenced in a dynamic context with all interested and affected parties. The German North Sea territory and the EEZ (Fig. 1) hosts a situation of de-facto open resource access to a growing number of entrepreneurs while limited consideration is given to resource use interactions. This has given raise to several stakeholder conflicts, especially in the coastal zone [2]. In order to avoid the ever-increasing spatial competition and regulations in the coastal area, many stakeholders thus have moved or plan to move "offshore" into the EEZ [3,4]. One major incentive for this move is the still generally persisting view of the offshore regions as unregulated commons, which indicates a natural right of freedom of mankind to utilise the resources of the Sea without regulatory restrictions [5]. In fact, compared to the coastal zone, the *UNCLOS* (United Nations Conventions on the Law of the Sea) agreement for the EEZ contains considerable less protective rationing of the marine resources [6,7]. This agreement, however, can be seen as a first step towards a change in this persistent "commons perspective" to a more regulative, protective rationing of the international marine resources to achieve sustainability [6]. One major incentive why growing awareness on marine resource depletion and limitation occurs was given by Hardin [8] as he defined the "tragedy of the commons" which has now been recognised for many resources in offshore regions.

The article starts with an overview on the present state of utilisation of resources in the German Bight and the underlying legal framework before an account on recent development trends in wind farms and aquaculture in the German EEZ is given. As an introduction into the needed legislative portfolio for the new uses, a historical overview is presented and likely conflicting interaction patterns are discussed. Marine legislation for the EEZ in other countries is also consulted. The article closes with a discussion on some options of co-management strategies for an offshore aquaculture-wind farm synergy.

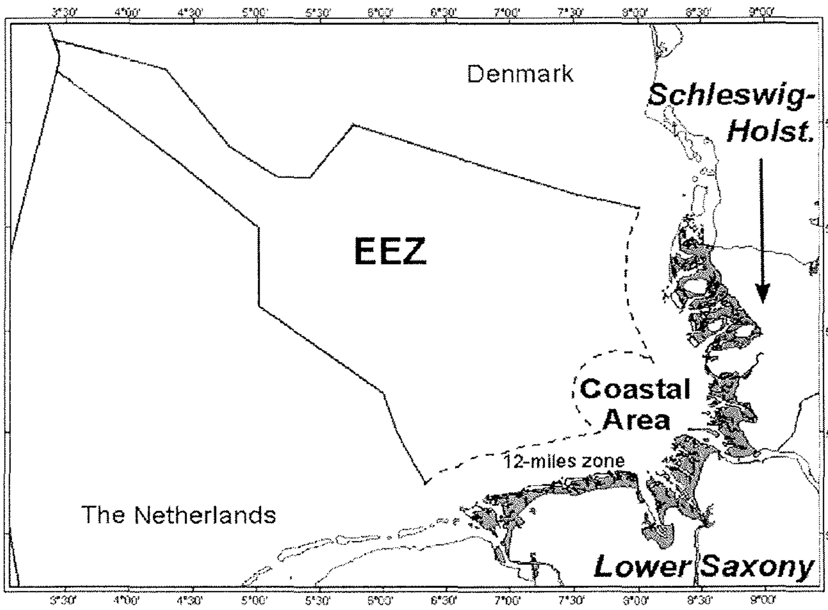

Fig. 1. Overview of the German North Sea sector indicating the coastal area (Territorial Sea) and the Exclusive Economic Zone (EEZ) and the States of Schleswig-Holstein and Lower Saxony. Shaded areas display the Wadden Sea, modified after BSH [10].

2. Multiple uses of the German section of the North Sea

The German North Sea waters host a highly competitive group of uses, such as shipping (trade or private), extraction or disposal of sand, navy exclusive areas, offshore oil exploration and exploitation as well as pipelines, cables, wind farms, nature reserves and other marine and coastal protected areas (Fig. 2). Recreational activities and fisheries are additional interests that deserve attention. These activities are not explicitly represented in this figure, which derives from the fact, that both, fishery and tourism, do not underlie any spatial restriction except mussel culture plots in some areas within the National parks. Marine aquaculture is not yet illustrated in Fig. 2 because of the minor role of this food production sector.

Due to this wide range of utilisation of the North Sea and its coastal marine environment, and partially in response to the requirements of the Water Framework Directive (WFD) [9], the Bundesamt für Seeschifffahrt und Hydrographie (BSH, Federal Maritime and Hydrographic Agency) developed a novel ocean data base, called Continental Shelf Information System (CONTIS) [10]. The CONTIS geodata are frequently updated and transformed into digital maps providing concentrated information about the coastal and offshore development of all uses. The system visualises, inter alia, the spatial extent of individual uses and interfaces with other

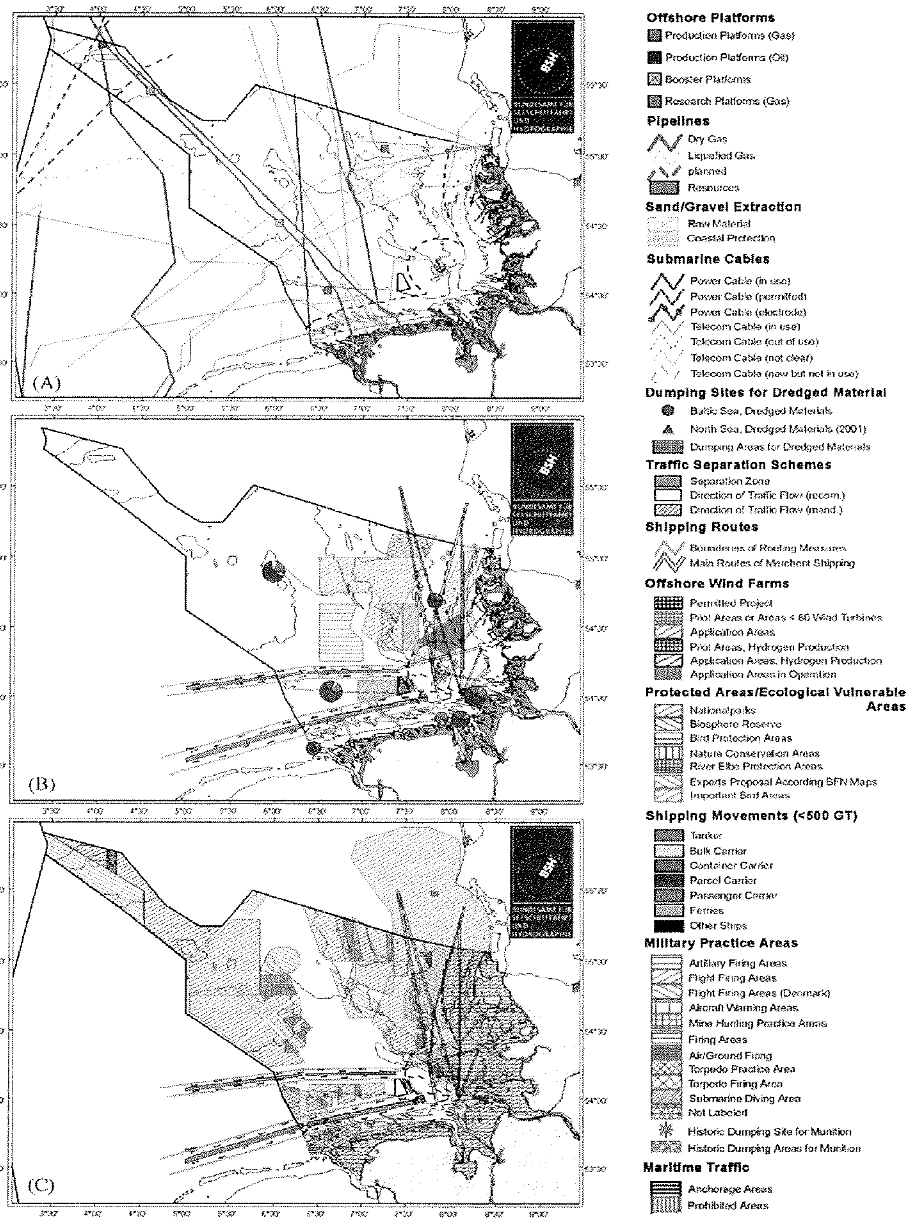

Fig. 2. Maps of current utilisation of the German North Sea. (A) shows pipelines, cables and areas of extraction, (B) includes maritime traffic schemes and frequency as well as military practice areas. (C) indicates all application sites for wind farm projects, natural reserves and other ecological areas. In (D) all uses, excluding fisheries and coastal tourism, are combined (source [10]).

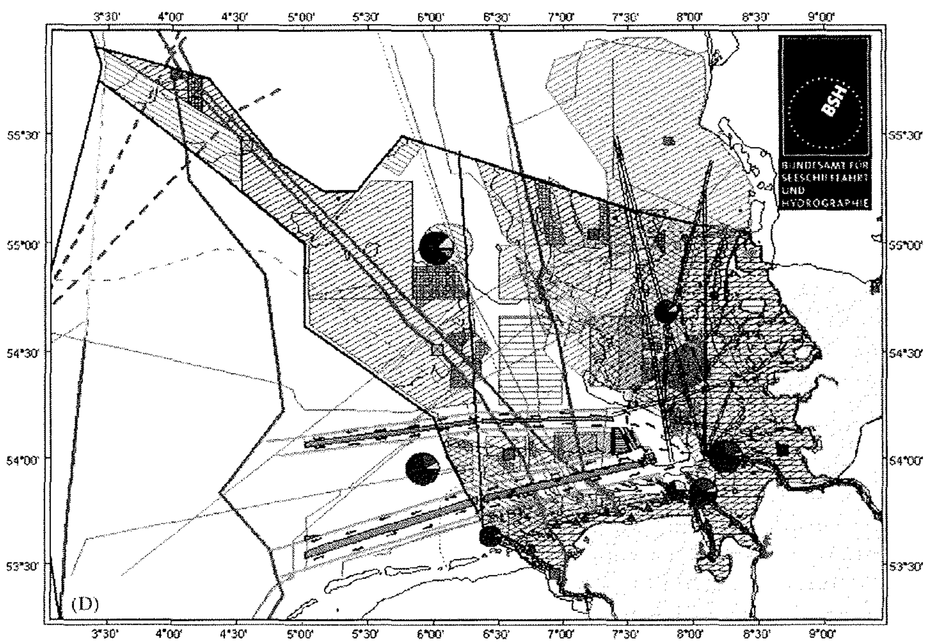

Fig. 2 (*continued*).

users as well as sea areas which are still free of any uses. The rapid development of these maps and the numerous utilisations of the marine areas highlights the need for regulations to adequately manage the resources within a multi-use setting. The limited space available for new activities, especially in the coastal zone, calls for new management initiatives, which follow the principle of equitable sustainable development, in which the socio-ecological system complex of the German Section of the North Sea will be maintained and its resilience enhanced in the light of future changes.

Within these manifold utilisations of the German Bight, only two examples of activities in near and offshore situations are considered in this paper, namely the emerging offshore wind farm operations and the extensive marine aquaculture at exposed sites. One of the main difficulties to date for these activities is their locations in different legal regimes, partly in the coastal waters of Germany but also within the EEZ. [4,11,12].

3. Offshore development trends in the German EEZ—a case study

3.1. Offshore wind farms

The first initiative in Germany to move towards an economy that predominantly utilises renewable energy resources was set by the governmental decision to gradually reduce the use of nuclear and fossil energy [13,14]. It is commonly believed that this decision contributes towards a sustainable development. This national policy also aims to reduce simultaneously the output of CO_2 to the atmosphere (Kyoto protocol), while fostering the efforts to produce more wind-generated energy [13,15]. So far, according to the Strategy Paper of the Federal Government of January 2002, this development has been successful to such an extent that almost 15% of the energy needs of the country are presently covered by this technology. Currently, opposition in the public is voiced against more wind turbines on land and/or along coasts with recreational value, because of aesthetics and interference with the landscape image. Therefore, the option for future expansions seems to be in truly offshore habitats in the North Sea, where views are not impaired, as these wind farms will be in such a distance that they are not visible from the shoreline. Furthermore, the potential to produce energy by wind is much higher in offshore locations. Plans for this new development are presently in progress.

The promotion of wind farms in offshore regions by the German Federal Government attracts competent and capable entrepreneurs. So far, 23 project applications have been filed for the German Bight with a total number of wind turbines per farm ranging between 80 and 500. Some applications cover small-scale pilot projects to allow the establishment of adequate criteria for an Environmental Impact Assessment (EIA), which has not yet been conclusively researched. It is anticipated that the finalisation of EIAs will take 2–4 years before permits for scale-up operations can be implemented. Due to the anticipated large-scale development of this offshore activity (e.g. high number of applications, supported by numerous energy company involvements), the Marine Facilities Ordinance [16] had to be amended to fulfil the regulatory requirements for this unconventional utilisation of offshore areas [17]. Additionally, several of the allocated sites are situated adjacent to busy shipping routes, e.g. the officially assigned traffic separation zones within the Weser and Elbe estuaries and off the Wadden Sea areas (Fig. 2). These require amendments to the already existing specific shipping safety regulations. However, the resource needs in terms of areas and geographic positions have not previously been considered, and their interaction with existing resource uses has not been adequately evaluated. So far, a number of regulations are common to all users and are part of several EU Directives pertinent to water habitats within which offshore wind farms will have to find their place also in terms of national regulations.

On November 9, 2001, the BSH granted the first approval for the installation of a pilot offshore wind farm. The Prokon Nord Company received the permit to install 12 wind turbines in the German EEZ of the North Sea with the option to expand the wind farm to a finite number of 208 wind turbines by the year 2010. On December 18, 2002, another company (OSB—Offshore-Bürger-Windpark Butendiek GmbH & Co. KG) obtained the authorisation to install 80 wind turbines until 2006. However, both permits do not include considerations for multiple uses of the same marine area, so that additional stakeholder interests are not yet adequately included (e.g. fisheries, aquaculture or shipping). For example, artisanal fishery in these allocated sites is so far prohibited, despite the fact that there may be sufficient space between wind turbines and waterways to be allocated for these purposes (Richert, pers.

comm.). However, passing through wind energy installations without special waterway identification would be prohibitive due to risks of collision in view of short distances between turbines (Dahlke, pers. comm.; Hoffmann, pers. comm.). One of the most intense commercial shipping traffic zones in the world lies within the EEZ areas of the North Sea of Germany and The Netherlands [18]. Therefore, safety needs will have to be clarified by modelled risk assessment methodology [19,20,21]. Because of diminishing space for commercial activities within the coastal and offshore zones, an increase in potential conflicts about space can be anticipated with other already well-established user groups, e.g. fisheries and commercial shipping. Such conflicts have already occurred. As the "wind farm newcomers" have presently powerful resources available to them and are also highly subsidised by the Federal government during the start-up period, the traditional users have voiced concern that they will be marginalised in the long run and will find less space and resources to maintain their current income sources.

3.2. Open ocean aquaculture

The potential newcomer of aquaculture in the open ocean is presently a very minor player among the German coastal resource users with little political support. This current situation is contrasting to the conviction that the commercialisation of open ocean aquaculture is an area of high future economic potential, resulting from an increasing demand on seafood products and the simultaneous harvest decline from wild stocks.

The rather stagnant development of coastal aquaculture can be partly explained by the harsh environmental conditions along the German North Sea coast, providing little incentive to entrepreneurs to take high risks (e.g. high water currents, strong wave action, harsh offshore wind conditions and very few protected habitats). Partly, this is also due to the vague interpretation of the terms "aquaculture" and "mariculture" by the regional and/or local authorities that do not always comply with the Food and Agriculture Organisation (FAO) of the United Nations agreed definitions [22]. This causes unclear or even total lack of supportive legal frameworks, which is in contrast to other countries, where regulations for coastal aquaculture are well organised.

The main barrier for open ocean aquaculture development in many instances is, however, the limited availability of suitable space. Apart from this obvious difficulty, there are additional legal problems involved in finding a suitable site. The nature of these problems varies between European countries, e.g. the granting of government permissions being hardest in Germany and easiest in Spain [23]. While in some countries aquaculture is defined and regulated under the agricultural laws, in other countries regulations are dispersed, and consequently the responsibilities are in the hand of several agencies (no lead agency). Furthermore, international as well as national regulations and conventions concerning aquaculture within the EU are yet incomplete [12]. In Germany this situation has lead to extended and long-lasting applications with often confusing management structures. This causes uncertainties for the licence applicants as well as for the local regulatory authorities themselves which also have to consider federal, state, and EU regulations. Therefore, aquaculture production in Germany does not enjoy the same support as elsewhere in Europe and does not participate in the otherwise fastest growing aquatic food production sector. It does not attract potential investors in this region.

The German aquaculture sector suffers from the negative public image. The unfavourable environmental conditions along the coasts prevent to employ conventional techniques. In addition, the expansion of marine protected areas and the influence of estuarine river run-offs, which often contain high organic and contaminant loads, have hampered the development of the industry in nearshore estuarine areas.

So far, marine aquaculture in German North Sea Territorial Waters is presently restricted to only one oyster farm (*C. gigas*) in the tidal flats of the island of Sylt backwaters and to a limited number of licences dealing with extensive bottom shellfish culture (*M. edulis*) in the Wadden Sea of the States of Lower Saxony and Schleswig-Holstein. All farms and cultured areas have little chance for expansion due to very limited site area availability [24]. This holds in particular for the licences on bottom shellfish culture for the coast of both, Lower Saxony and Schleswig-Holstein [25], where the number of licences will be maintained at constant low level.

The productivity of these extensive blue mussel cultures is subject to strong natural fluctuation; especially the spatfall with the following settlement of juvenile mussels in sublitoral areas shows strong annual variations. Traditionally, the fishermen dredge the sea bed on plots known to have a high spatfall and catch juveniles with a size of 0.5–2.5 cm. Afterwards, strong injector pumps on board flush out the seed mussels through hatches below the water line on to the licensed cultivation areas within the Wadded Sea (roughly 2.300 ha within Schleswig-Holstein) [26], where they require 600–700 days grow-out time to reach market size. Because this procedure is also subject to strong variability it causes an increase in potential fluctuation of yield and subsequent economic returns to the fishermen. For instance, in 2003 an enormous quantity of mussel larvae occurred in the Wadden Sea [27]. Due to successful settlement of the larvae, catches of spat resulted in high quantities of juveniles in the fishermen dredges that were used for reseeding. In the previous 4 years, however, only little yields of juvenile mussels were obtained, affecting production seriously [27,28]. This is in contrast to the research findings of Walter and Liebezeit [27], which revealed, that despite the annual low seed production seed mussels could be extracted with collectors in vast quantities directly out of the water column. It therefore can be concluded that a low spatfall ratio does not necessarily lead to a complete absence of mussel larvae, but is dependent on several other environmental factors, e.g. extraordinary seaward currents, seasonal high predation or starvation, which lead to a decrease of a successful settlement ratio. Thus, a proofed off-bottom culture with suspended ropes, which collect larvae directly out of the water column, could overcome the shortcomings of mussel larvae settlement at on-bottom culture operations.

In order to maintain an economic viable and vital business in the EU market area, fishermen and the processing industry are dependent on a reliable and steady spat supply as well as on successful growth of the seeded mussels to market size. Most of the capture, cultivation, and processing takes place in economic marginal rural areas of the State, where lack of alternative livelihoods is obvious, thus urges for the need of at least some stable economic activities. Therefore, from the mussel cultivators' point of view, a supplemental or alternative source of seed mussel supply and/or mussel production through offshore farming is seen as timely opportunity that should be utilised [28].

3.3. Potential synergies between wind farms and aquaculture

Initiated by the discussion on offshore energy installations the idea emerged to integrate these with the installation of open ocean aquaculture facilities. One of the main reasons for this linkage of open ocean aquaculture to wind farms results from the fact that aquaculture alone would not be able to afford expensive infrastructure facilities. While offshore wind farm structures do not depend on aquaculture *per se*, it is essential to open ocean aquaculture to rely on infrastructures provided by others in order to become commercially viable. As the areas of wind farms could be partly banned for other uses (especially fishing) for security reasons, the support of open ocean aquaculture installations creates a positive spin-off effect in providing alternative livelihood for the concerned fishermen communities, who would lose the access to their traditional fishing grounds. The need for infrastructure at wind farms that could serve simultaneously aquaculture has to be seen as one of the major incentives to apply multifunctional co-management procedures. However, the success of such a synergy depends on the installation of an effective regulatory framework (also in adjacent countries) that satisfies the needs for the emerging marine aquaculture industry. It has to be recognised that under multiple use scenarios, aquaculture is also vulnerable to the negative effects, which neighbouring resource users may produce. As shown earlier, the lack of a harmonious national as well as EU policy on aquaculture has drastically impeded its potential development so far.

For both of the above newcomers, legislative uncertainties to date seem to be the key factor in the difficulties the emerging branches are facing. If the rather vague regulatory system continues, the confused perception will also cause irritation among other users and potential partners. As the marine facilities ordinance regulates the installation of structures whose purpose is the production of energy from water, wind, and ocean currents or other commercial uses [16], it would be necessary to include the term "aquaculture" as an additional element into the legal framework, because this sector requires permanent offshore structures and can be regarded as a commercial activity. Thus, additional to the fragmentation of general regulations that are also relevant to aquaculture, there are no specific regulations for this sector within the German EEZ [4,11,12], which would be a prerequisite to a successful multifunctional co-management. Primarily, the legal system has to consider the prospects of the above mentioned potential synergies between industries if all are safeguarded by a multifunctional co-management approach in the offshore regions. In order to understand the shortcomings of the legal framework for potential offshore aquaculture investors and the uncertainties the industries presently face to safeguard jointly their development in offshore national waters, the historical development of the regulatory system and the status quo has to be briefly considered.

4. Development of rights and duties in the German North Sea region

4.1. Coastal waters versus offshore regions

First of all, a clear distinction must be made between the origin, context and dynamics of the utilisation of coastal and offshore waters, respectively. While the utilisation and management of the German coastal waters look upon a long historical development by local groups (e.g. fishing communities; mussel plot leases in the Wadden Sea), where traditional user schemes have had a long time to develop, the offshore waters have seen the emerging user context as a rather "recent" phenomenon, mainly based on (a) technological improvements in well-established industries such as ship constructions or oil platform installations and (b) on totally new and innovative developments such as wind farms and offshore aquaculture systems, which are still in their pilot and testing phase. For the most parts, financially powerful stakeholders operate in the offshore belt (e.g. oil companies, international shipping companies, etc.), whereas the coastal waters are utilised by a heterogeneous group of stakeholders ranging from local to international level (e.g. local fisher folk cooperatives, leisure sailing clubs, tourism entrepreneurs, harbour operators, etc.). Due to its historical origin, the latter region shows a well-established organisational structure and thus possesses sufficient social capital[1] in order to support the introduction of new multifunctional integrated co-management schemes. In contrast, the stakeholder groups in the offshore regions are not yet well linked in functional networks in both, the technological and social context, but have a high degree of political representation and persisting client mentality.

The fundamental differences between coastal and offshore regions call for a different set of rights and duties of the authorities as well as the users in the EEZ in order to provide a window of opportunity, where multifunctional co-management may emerge. In the following, a brief analysis of the current regulatory framework of regions within the EEZ is presented.

4.2. Major regulations for activities in the German exclusive economic zone

The German territorial coastal area extends 12 nautical miles seawards and is part of the sovereign territory of the Federal Republic of Germany. The EEZ includes the continental shelf area, which covers the seabed and sub-soil seaward domain of the Territorial Sea extending maximally 200 nautical miles from the coastline. Due to the federal structure of the State of Germany a specific problem emerges in the regulation procedures of these areas: within the German Federation, the states

[1] The term "social capital" refers to features of social organisation such as trust, norms and networks and to the richness of social organisation and social structure, following the definition in [29].

(called "Länder") are legally responsible for the territorial coastal areas. They approve or reject proposals for any type of installation and for nature protection regulations [12,17]. In contrast, in the areas of the EEZ the Federal State holds the main authority in the decision-making process.

Below and in Table 1, the current situation within the regulative framework concerning the German EEZ is documented:

Legal issues surrounding the private use of federal waters have not been sufficiently addressed. To date, there is only one regulation, the "Seeanlagenverordnung" (marine facilities ordinance), explicitly designed to marine offshore area utilisation, regardless of the purpose or type of activity within the German EEZ [16]. Under this ordinance, the BSH grants approval for site-specific construction and operation, including the use of offshore structures (e.g. wind turbines, oil platforms). The approval procedure includes consideration of the German mining law regulations dealing with the exploration and exploitation of various non-living resources together with the regulations for safeguarding commercial shipping routes within the areas under German jurisdiction. Included are interests of the German navy as well as fisheries, environmental protection, and operators of submarine cables and pipelines. The plans are laid open for public information and comment, which is a mandatory part of the approval process enabling citizens to make proposals and involving also the interest concerns at local and municipal level [17].

With the amendment of the Federal Nature Conservation Act, the German parliament has made a first move towards a regulative framework [30]. Consequently, areas suitable for e.g. wind farms, aquaculture or other activities will be formally allocated in future.

Spatial planning of sea areas belonging to the territory of Germany has not yet been implemented so far. Laws and acts, such as the Federal Regional Planning Act, a Municipal Landscape Plan and a County Landscape Plan, which could be relevant to offshore waters, are only defined for inland waters (i.e. rivers, lakes) [31]. The validity range of the Federal Regional Planning Act covers only partly the sea areas up to the 12-mile zone with respect to offshore wind farms, but in fact, no new aspirant areas have been claimed. Further detailed planning of areas for offshore wind energy usage are only fragmentarily present and have not been bound into regional plans so far.

Within the EU there is currently a debate, whether directives regarding to the protection of birds [32] and habitats [33], should apply beyond the 12-mile zone [34] though, at present, these regulations are juristically not relevant to the EEZ. However, apart from that, the structure and implementation of the EU Water Framework Directive (WFD) [9], which is presently under development by all EU countries, will be of particular relevance. The EU considers to establish a framework for the protection of *all* waters (including inland surface waters, transitional waters, coastal/offshore waters, and groundwater), which includes for coastal water the following objectives:

- to prevent further deterioration of water resources,
- to promote sustainable use of water based on long-term protection of water resources,

Table 1
Regulations concerning offshore installation, such as wind farms and open ocean aquaculture in the EEZ, modified after Czybulka and Kersandt [11] and Buck [12]

	Major regulation	Wind farms	Aquaculture
Marine facilities ordinance [16]	Section 2a postulates an environmental impact assessment	Applicable	Applicable
	Section 3 counteracts any adverse effects concerning sea marks, navigation, waterways, pollution of the marine environment and bird migration	Applicable	Applicable
Nature protection law [30]	Section 20g, 6.3 indicates the raise of fish for scientific purposes (except endangered species	—	Applicable
	Section 38 regulates the assignation of marine protected areas	Applicable	—
Water framework directive [9]	Directive is not yet passed	—	—
UNCLOS (only in marine protected areas, MPA's) [6]	Art. 1, Section 1 postulates "no dumping"	Applicable	—
	Art. 145 requires effective protection for the environment from harmful effects, which may arise from such activities	Applicable	—
	Art. 194 Section 1 postulates the prevention, reduction and control of pollution	Applicable	Applicable, but the term "aquaculture" not specifically mentioned
	Art. 194, Section 2 requires that activities are so conducted as not to cause damage by pollution	Applicable	—
	Art. 194, Section 5 postulates the protection and preservation of rare or fragile ecosystems	Applicable	Applicable, but the term "aquaculture" not specifically mentioned
CBD (only in marine protected areas, MPA's) [46]	Art. 7 c postulates the identification of processes and activities, which could have adverse impacts on the conservation and sustainable use of biological diversity, and monitor their effects	Applicable	Applicable, but the term "aquaculture" not specifically mentioned
	Art. 8 f postulates the rehabilitation and restoration of degraded ecosystems and promotion of recovery of threatened species	Applicable	Applicable, but the term "aquaculture" not specifically mentioned
	Art. 8 i postulates the endeavour to provide conditions needed for compatibility between present uses and	Applicable	Applicable, but the term "aquaculture" not specifically

Table 1 (*continued*)

	Major regulation	Wind farms	Aquaculture
	the conservation of biological diversity including the sustainable use of its components		mentioned
	Art. 8 1 postulates, that regulations or management of relevant processes and categories of activities have to be done, if effects on biological diversity have been determined	Applicable	Applicable, but the term "aquaculture" not specifically mentioned
	Art. 14, Section 1 deals with impact assessments and the avoidance or minimisation adverse effects in general	Applicable	Applicable, but the term "aquaculture" not specifically mentioned
OSPAR (only in marine protected areas, MPA's) [37]	Art. 2 V postulates the necessary measures to protect and conserve the ecosystem and the biological diversity	Applicable	Applicable, but the term "aquaculture" not specifically mentioned
	Art. 3, Section 1 V postulates to draw up programmes and measures for the control of human activities and their effects on ecosystems	Applicable	Applicable, but the term "aquaculture" not specifically mentioned
	Art. 4, Section 1 requires regulation as prerequisite for the use on, or the discharge or emission from, offshore installations of substances which may reach and affect the maritime area	Applicable	—

- to enhance protection and improvement of the aquatic environment through specific measures for the progressive reduction of discharges, emissions, and losses of priority hazardous substances.

The concept central to the WFD is *integration*, which is seen as key to the management of water protection within the river basins. Although mainly focussing on coastal and inland waters, spin-off effects to more exposed ("offshore") areas are obvious as these are invariably interlinked with coastal activities.

There are a number of actions required by Germany and other EU countries having coastal zones to achieve the objectives and these include:

(a) the identification of "river basins" which include coastal/shelf habitats lying within the national territory of member states while also assigning them to River Basin Districts (RBD) and identify competent authorities (already in 2003; Article 3, Article 24);

It seems that there are still significant uncertainties in the definition of what constitutes a water body in the German national coastal and offshore habitats, and it is unclear whether the national authorities will define water bodies of sufficient size to allow for aquaculture to be considered as one of many pressures on water quality within a large body of water. The size of the management units (districts) will influence the complexity or simplicity of interacting regulations for all users, particularly in coastal zones.

(b) the identification of pressures, impacts, and economics of water uses in river basin districts, including a register of protected areas lying in them by 2004 (Article 5, Article 6, Annex II, Annex III);

(c) intercalibrate together with the European Commission the ecological status classification systems by 2006 (Article 2(22), Annex V);

In relation to the classification of water bodies it is not presently clear how the national schemes, and subsequently the inter-compared schemes, will accommodate differences in the values of biological or hydro-chemical elements within water bodies. How this is to be done is clearly of importance to aquaculture activities in marine waters, as aquaculture sites will present pressures on the immediate environment, and some of the elements of the assessment will be below reference status at these sites. However, this has to be done until 2006 (Article 2(22), Annex V), and scientific studies that integrate the various interacting resource users in relation to classification are urgently needed.

(d) install or complete the necessary monitoring network and make it operational by 2006 (Article 8);

Considering the monitoring requirements for the WFD (Article 8), the present development towards offshore wind farms and aquaculture seems to come just in time to simultaneously develop the adequate and necessary monitoring schemes to fulfil the WFD-obligations while also serving the multi-use concept. This may include simplification of the monitoring programme through combination of efforts by multi-use stakeholders.

(e) prepare River Basin Management Plans (RBMPs) for each River Basin District, including the designation of heavily modified water bodies. This should be completed and published by 2009 (Article 13, Article 4.3);

The approach proposed in this paper towards multifunctional co-management contains already several aspects that could be effectively used in structuring the RBMPs (as required under Article 13 and Article 4.3) for coastal and national offshore waters/habitats. There is a need to clarify to what extent large-scale wind farms are considered as significant "water body modifications".

(f) develop a programme to cost-effectively achieve the WFD environmental objectives by 2009, based on the analysis of monitoring results for the river basin (Article 11, Annex III);

(g) to implement water-pricing policies that enhances the sustainability of water resources by 2010 (Article 9).

The WFD approach, which should achieve the environmental objectives by 2009 and implement the pricing policies by 2010, contains elements that reflect also some of the considerations that have been offered by the ICES Working Group on Environmental Interactions of Mariculture. They propose concepts towards integrated coastal zone management and multiple-use assessment methodologies [35]. The EU member states' national competent authorities are now in the process of implementing guidelines associated with the WFD (e.g. BSH CONTIS as tool for zoning; see Chapter 2). It is not unrealistic to assume that in some countries pollution control authorities consider to use much smaller water body units that allow for a direct relationship between individual significant sources of pollution. This would have serious consequences for aquaculture systems with their discharges as the assimilative capacity of the receiving water becomes extremely small in cases where the area specific water quality classification becomes very stringent. For example: options for "integration" of multiple-use concepts require the permit to discharge a certain output of nutrients (e.g. fish farm) to "serve" the integrated downstream operation (e.g. shellfish farm; seaweed farm) so that these operations gain the critical amount needed to achieve a reasonable (viable) productivity. These nutrient discharges may exceed the permissible level identified by the habitat classification system within the WFD. Such permits can only be envisaged if the two co-operating industries are considered as an area unit within which nutrient flows are managed to fulfil all stakeholder requirements while the pertinent habitat classification regulations would fully apply outside the overall licence area co-assigned to the integrated partners. This principle holds not only for offshore resource users but also for coastal systems (e.g. artificial wetlands with agricultural crops along-side riverine systems). It is therefore necessary to provide sound scientific data for identifying minimum sizes for both, coastal basins districts (CBDs) in coastal areas and river basin districts (RBDs; e.g. artificial wetlands) in riverine systems coastal areas) that allow multifunctional uses while maintaining the overall Environmental Quality Standards (EQS) as outlined in the objectives of the WFD. So far, no provisions have been made to accommodate multi-use scenarios.

Again, this question is not confined to aquaculture but applies also to many other human activities that result in waste discharges and habitat use in coastal and offshore waters. The fact that they are subject to the same uncertainties should be considered as an opportunity to cross-link with these stakeholders at an early stage to discuss and prepare schemes, where mutual interests and "integration" become potentially an option, particularly when considering wastes from aquaculture production as a *new resource* for nearby users. The importance of this consideration is the fact that to become a *new resource*, certain wastes (organic solids, nutrients) must have a minimum concentration (mass) to be considered a suitable resource. Discharge from aquaculture farms feeding downstream stakeholders must be considered differently from those not having this conversion linkage. Such strategies can—however—only be employed if the area units designed as "Districts" are not too small. From an aquaculture viewpoint it would be desirable and more consistent with the philosophy of the WDF, if national pollution control authorities would define "water bodies" of sufficient size so that one can deal with each potential polluter in relation to other activities operating within and impacting on a restricted area either in the coastal zone or within the riverine basin.

While the process to consider measures to improve ecological quality of water bodies (particularly mitigation measures) are just starting, it would be useful that the aquaculture research community becomes pro-active in participating to formulate these measures, because it can be anticipated that additional management and mitigative actions may be required from aquaculture operations in some areas, where good ecological status has not been achieved.

4.3. Other international considerations

The international maritime legislative framework has developed extensively during the past decade [36]. International conventions, such as UNCLOS or CBD (Convention on Biological Diversity), include regulations for installations and structures, but do not specifically identify or mention the term aquaculture or mariculture. To raise fish, crustaceans or molluscs is only sporadically described within the OSPAR-Convention (Convention for the Protection of the Marine Environment of the North-East Atlantic) [4,11,12,37,38].

Generally, the major issues that have not yet been adequately addressed in the public policy arena relate to the need to ensure security of tenure for the project (i.e. conveying property rights in public waters that are traditionally free and open to all) while fulfilling public trust obligations, minimising/mitigating impacts on other users, and ensuring that other governmental policy objectives, such as environmental protection, are not jeopardised [39].

If different stakeholder groups are involved in the management of limited resources, as in this case study of limited spatial offshore resources, the potential of emerging conflicts and alliances increases. In the following, some of the conflicts and potential alliances and their relevance for offshore co-management are discussed.

5. Stakeholder perspectives in the offshore region

In regions, where different types of stakeholders exist, the question of their driving interests, conflicts and alliances need to be analysed in order to successfully implement a co-management approach. For the offshore region of Germany, the lack of long-term and total system planning is noteworthy and similar to current regulatory regime situation in other countries, e.g. for offshore activities such as aquaculture in the EEZ of the USA [39]. The policy to date appears to be made by granting permits on a case-by-case basis, usually with no provision for examining cumulative impacts. This increases the potential of surfacing conflicts between different user groups. However, latent or actual conflicts and alliances affect the relative probability of priority fulfilment for individual stakeholders, especially in the EEZ regions, where little surveillance of individuals' compliance with e.g. environmental rules can be undertaken. The investigation of conflicts and alliances in coastal management thus facilitates strategic assessment and integrated planning of co-management approaches [40,41].

5.1. Conflicts

Due to the legal inconsistency in the designation of official responsibility for marine waters, latent and actual conflicts over interests, responsibilities, and powers in planning, decision-making and implementation can be observed. Maybe the most prominent conflict arenas are the economic and political interests, which encompass very different types of stakeholders some of which are exemplified below.

Most economic conflicts in the offshore regions concern the question of production and marketing of resources. In this context, the type of resource and territorial access are crucial. The to date strictly isolative consideration of each offshore installation application by the marine facilities ordinance [16], which is a mandatory licence procedure, provokes conflicts with other agents and their interests, as no regional integrative planning procedure is followed and thus other stakeholders easily overlooked. This leads to conflicts between e.g. the governmentally supported and thus powerful offshore wind farm entrepreneurs and commercial fisheries (except mussel fisheries, which inherit a different line of production) or commercial shipping interests. These examples pertain in addition conflicts between local versus non-local resource users. For example, it could be observed, that many fishermen believe in the concept of inherited "home waters", which does not necessarily follow the legally defined spatial boundaries in coastal waters and offshore region [42]. The notion of "home waters" and their implied territorial rights gives rise to further conflicts with other fishermen groups, who are by legislation allowed to fish in "their" waters, e.g. in the "home waters" in some regions beyond the 3 mile zone between Germany, the Netherlands and Denmark (pers. comm. Schmidt; pers. comm. Hagena). The most prominent economic conflict in Germany is, however, mirrored in the classic contrast between development and conservation, which appears between a number of official and civil society institutions. The conflict between environmental conservation and the quest for a socio-economic quality of life surfaces in the attempts by official conservation units when implementing heavily debated environmental laws (e.g. Wadden Sea National Park zoning regulations), as well as in the often less than cordial relations between conservation implementation agencies and ecosystem users (e.g. Wadden Sea National Park authorities protecting marine wildlife versus local fisher groups).

The latter described situation points out to the political conflict arena, in which spheres of influence and management are the most prominent. Without a lead agency for offshore development, conflicts between different regulatory agencies are inevitable. There is competition for influence and authority, voters and client constituencies between various official and civil society institutions. One example is the political conflict of Federal versus State authorities (Federal Law rules over State law). The Federal Environmental Ministry supports wind farm "clients", whereas National Park authorities and State conservation agencies reject wind farm installations and pursue nature conservation interests. Thus, likewise observed by Cicin-Sain et al. [39] for the USA, conflicts arise between industry assistance of the Ministry of Commerce and the protection interests of the Ministry of the Environment. Furthermore, the political policy may even differ among divisions within the same agency, e.g. the division of the Ministry of the Environment representing the interests of uses that may be in conflict with EEZ development, such as marine mammal protection, and other divisions promoting environmental sound renewable energy technology. However, as the current political agenda is strongly focusing on the reduction of CO_2 emissions, frustration in the part of the authority to fulfil its mission on safeguarding marine life in an efficient way emerges. Another example is the prevention of offshore wind farm development by local environmental and nature conservation organisations due to its potential impact on the marine ecosystem, which contrasts the viewpoint of other nature conservation organisations, such as "Greenpeace", which support the installations.

This brief analysis documents, that political conflicts arise mainly between influential institutions, while economic conflicts exist mainly between local and regional producers and stakeholders. This is in concordance with the findings of Cicin-Sain et al. [39] and of Glaser and Oliveira [40].

What are the consequences of all this to aquaculture? This is a question that requires a closer look on the potential synergies an alliance between these stakeholders would generate for coastal communities.

5.2. Alliances and synergies

Overlapping interests that create scope for alliances in the offshore region also exist. However, the interpretations of alliance objectives can differ between the potential alliance groups, even if the overall objective appears similar. In the following, some examples of such alliances and their innate unresolved issues that hold the potential for future conflicts are given, followed by an outline of suggested synergies for the case study.

Economic development interests in marine waters are pursued by a number of Federal and State Development authorities, as well as by private companies, such as wind farm operators, and local politicians. These form alliances among themselves, but also with local stakeholder groups (e.g. local fisher communities). The unresolved question in this alliance is, however, what type of economic development, e.g. short-term profit or long-term sustainable revenue, is at aim.

Within the political arena, marine conservation interests form the scope for an alliance between Federal and State conservation authorities as well as marine biologists or ecologists and environmental NGOs. This holds the potential to foster alliances with small-scale local fisheries (extensive capture fisheries) and extensive mariculture, such as mussel or seaweed cultivators. The positive ecological effect of the limitation of planktonic load, nitrogen (NO_2^-, NO_3^-, NH_4^+) and phosphorus (PO_4^{2-}) in the water column caused by the filter activities of mussels and the uptake of nutrients by algae, next to the simultaneous prevention of feeding and vaccination renders potential alliances with the conservation authorities. The major unresolved issue is, however, if habitat preservation should be carried out for human needs or nature protection for its own sake.

Thus, the danger of the creation of alliances resides in the fact that the believed common interest may not be a sufficiently stable tie, if difficulties emerge. This is mainly due to their underlying unresolved agendas. For successful cooperation in the framework of integrated co-management, it is necessary to communicate these innate issues in order to avoid future conflicts between different parties.

In the case of offshore wind farming and open ocean aquaculture, approaching new activities jointly holds the potential for future cost-benefits, e.g. through the combination and joint use of existing structures under the viewpoint of "what need has the marine aquaculture?" or "what can the wind farm operators offer"? Here, a programme of alliances for multifunctional cooperation can be suggested. Potentials of such alliances and how close cooperation could be implemented are multifaceted for our case study.

The following options are proposed: (a) maintenance of wind turbines and aquaculture facilities, (b) training and capacitation, (c) technological multi-use of fixed structures, (d) environmental impact assessments, (e) maritime traffic, (f) transport and supply and (g) economic cooperation.

(a) Maintenance of wind turbines and aquaculture facilities

Existing fishing vessels could be made available as servicing craft for wind turbines. Additionally, the harvest of mussels and seaweed by operation vessels of the wind farm operators, which are specifically designed to fulfil both purposes, could be a multi-use approach.

(b) Training and capacitation

In order to take advantage of the existing pool of local knowledge on the environmental conditions of the North Sea, local fishermen, who are well familiar with the natural offshore conditions and thus require less training, could be employed. Next to the maintenance of the local knowledge, local economy and alternative livelihood is promoted.

Due to the continuing decline in commercial fisheries in the long-term perspective, the training of local personnel holds the future potential for the establishment of their own aquaculture enterprises. By their involvement and capacitation from the very early stage, spatial conflicts between the fisher associations and the wind farms could be minimised.

(c) Technological multi-use of fixed structures

The technological development for detached aquaculture offshore structures is far from being satisfactorily solved. The underwater constructions of wind turbines thus offer themselves as a cost-effective, alternative solution to fix cages, longlines or offshore-rings and to provide some storage for the maintenance of aquaculture facilities. This prevents the loss of expensive culture material caused by strong currents, heavy weather and shifting of anchor stones. Fig. 3 suggests some potential multifunctional constructions.

(d) Environmental impact assessments and ecological aspect

By German and EU law, environmental impact assessments are a mandatory process, which have to be carried out for every activity and construction. Due to the sharing of the same construction and area, time and money are saved for both users and thus attracts potential investors.

The prevention of fisheries within the farm areas and the effect of artificial reef build up by the pylons of the wind turbines and the moorings of the aquaculture

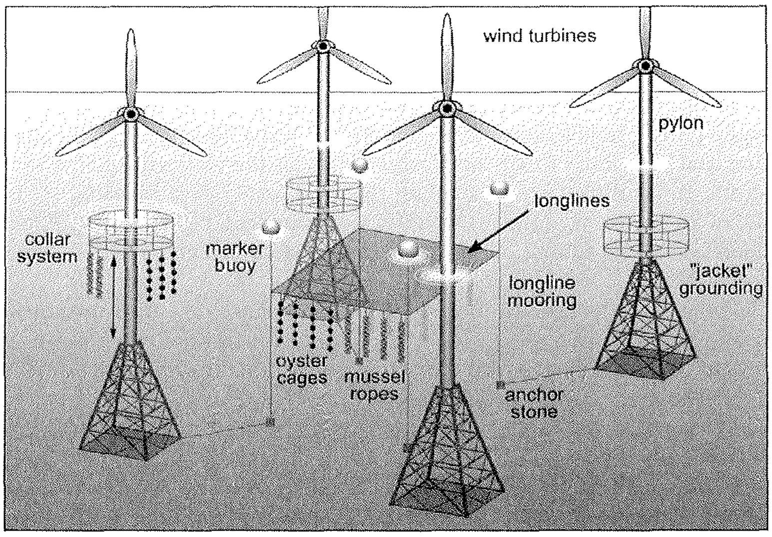

Fig. 3. Potential multifunctional use of the fixed underwater structures of offshore wind turbines for the maintenance of aquaculture facilities. Alternative solutions include oyster cages and mussel collectors attached to longlines in the inner section of the wind farm or offshore-rings (collar systems) attached directly to the pylon. The latter system can be submersed in case of wind turbine set-up.

systems renders the preservation of existing spawning and breeding grounds. Hence, productivity and diversity of the ecosystem could increase.

(e) Maritime traffic

Traffic rules are required in order to provide safe access to each of the wind turbines (planned amount ranging from 80–500 turbines per farm area) in a respective wind farm. If these turbines are used in a multifunctional manner by combination with offshore aquaculture facilities, traffic rules need to be reconsidered in that respect, that access is provided to the aquaculture facility as well as to each turbine. Thus, security is given to the wind generators in the form of keeping out of the vicinity of the turbine area and of the aquaculture systems and thus minimising the risk of destroying floating structures by running over them.

A possible solution could be, that clear working spaces are defined (e.g. separation zones), including access patterns for aquaculture areas with a regular alternation of parallel one-way waterways. Furthermore, boats could be designed with low draught in order to move well over aquaculture structures, if shuttle services between several turbines are necessary. In Fig. 4, some examples of possible traffic routings are given.

(f) Transport and supply

Centralising the supply and maintenance operations holds a high amount of cost-effectiveness, as sharing reduces ship time to and from the installations. In addition, boat constructions could be developed in such a way, that the ship simultaneously can support the technical maintenance of the wind farms as well as the harvest of the aquaculture production. This would provide a powerful incentive for alliances,

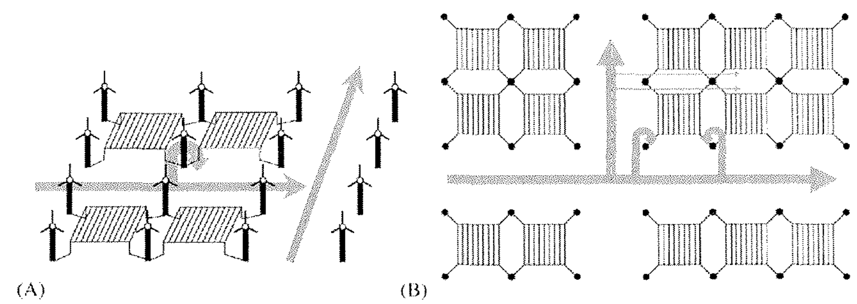

Fig. 4. Potential multifunctional maritime traffic zones in offshore wind farms. Arrows mark access and servicing routes to each wind turbine. Gridded boxes in the inner section of the wind farm represent parallel attached longline systems, which are separated from the major waterways. (A) shows a side view and (B) a bird's eye view.

especially between the to date conflicting parties of fisheries and wind farmers. Additionally, tourism could create another scope of alliances, by sightseeing tours to the offshore wind- and aquaculture farms, where local mussel and algae dishes are served.

(g) Economic cooperation

Offshore aquaculture constructions, such as longlines, rings or lantern nets, will have to be much larger than their counterparts in nearshore areas to compensate for the sizeable additional costs of larger moorings, the connection to the pylons of the windmills and the greater distance from the mainland, and thus to enable economical sound operations.

Additionally, modern offshore farming systems require expensive infrastructure and services normally not needed in fairly protected nearshore habitats. It seems reasonable to defray parts of the extra costs through sharing such infrastructure with potential users of other resources in the marine environment. Offshore wind farms require also frequent servicing and control and thus, the opportunity exists to join forces and gain cost effectiveness.

In the case study, the main incentive for synergy is due to the agreement on economic cooperation, as financial aspects are highly relevant to such new technologies, where the revenue is yet unclear. Especially for the emerging branch of offshore aquaculture the availability of financial capital is a major problem. As Cicin-Sain et al. [39] point out, the uncertainty of short-term revenues hampers the interest for investors to support aquaculture. Banks and financial institutions typically demand that crop ownership should be well defined and that all permits should be obtained in advance. Furthermore, they typically require a track record of profits and significant prior experience in the field. Both of these are in short supply; especially the emerging offshore aquaculture does not fulfil these demands.

A major political alliance incentive for the Federal and State conservation as well as commerce authorities to support such a multifunctional use pertains the limitation of the ever-increasing consumption of spatial resources. Next to providing more unutilised areas for marine reserves, future development of other commerce areas so far not foreseen are still possible.

The need for sufficient regulation and integration also arises now because of the EU Water Framework Directive [9]. In light of open ocean aquaculture within this Directive, one of the above-mentioned integrative measures has the potential to simultaneously *affect* and *protect* aquaculture and fishery even beyond coastal waters and, therefore, requires careful attention in research and development to properly identify the true interests and potentials of the aquatic food production sector. The aim to "integrate" all water uses, functions, and values into a common policy framework will require studies that identify criteria related to environmental needs, water for health and human consumption, water for economic uses, transport, leisure and water as a social good. In fact, many of the integrative processes can methodologically addressed through the application of appropriate ICZM (Integrated Coastal Zone Management) tools, which are presently under development. It is worth mentioning that the WFD considers under "integration" not only ecological and water quality aspects but also a wide range of measures such as pricing and financial instruments in a common management approach for achieving the environmental objectives of the Directive.

6. Potentials of and constraints to multifunctional offshore resource uses

The synergy of two different stakeholders, the so-called multifunctional utilisation of marine areas, can be viewed as a new concept by the implementation of integrated, consensus-based resource planning conditions. A common interest in new forms of management has thus arisen among ecosystem users and state administrators. The outcome of a recent first forum meeting in which the mussel cultivators, scientists, several responsible authorities, and wind farm operators discussed jointly the potentials and chances of mariculture in the offshore wind farms highlighted a strong interest in cooperation and shared responsibilities.

However, as it was demonstrated in Chapter 5, there are several dangers and constraints involved in the implementation of co-management schemes in offshore regions. Besides the difficulties of establishing a consensus-based management scheme among the users, the spatial remoteness of offshore regions holds the further difficulty that "invading outsiders" cannot always be controlled. Thus, the legal right to closed, defined user groups cannot always be guaranteed and therefore a major incentive for co-management is eliminated. The latter situation has been addressed within the fisheries management under a rights-based regime in New Zealand. Hereby, fisheries are managed largely through the quota management system (QMS) since 1986, in which New Zealand's EEZ was divided up into a number of management areas known as Quota Management Areas (QMAs). The quota owners have a defined right of access to a defined share of the yield of a stock, which is set annually by the Minister of Fisheries for each fish stock in each QMA. If different interest groups enter the arena of the EEZ the government has proposed a trade-off regime, in which the different right holders and interest groups have to negotiate directly with each other and to agree to defined, secure rights. Uncertainty about the tenure of marine farming rights under the governmental proposal reduces the incentives for commercial fisheries rights holders to negotiate a long-term agreement, in which both parties have their equal share [43]. The alternative example from New Zealand highlights the importance of clearly defined and secure rights to the stakeholders, in which the right holder must be clearly identifiable, either individually or collectively.

Thus, legitimate constraints seem currently to be the key issue in all development and management issues of the EEZ areas. For example, the US National Aquaculture Act (NAA), passed in 1980, found that legal concerns prevented aquaculture operations from becoming established or operating efficiently. While many environmental and marine laws passed after the NAA contemplated an aquaculture industry, they have generally failed to provide mechanisms to organise the rules and develop such an industry. Although several US states have applicable aquaculture statutes with co-ordinating regulations, the permitting process is far short of being streamlined. The absence of such implementation rules can impede the progress of ocean aquaculture development as much as too many regulations impede other industries. This has resulted in the situation, in which the need for legislative and regulatory action in the US is highlighted by the conflicts, which aquaculturists experience with other established uses of the ocean such as commercial fishing, navigation, and recreational boating and swimming. Coastal states must protect such uses under the Public Trust Doctrine of the US, which requires a balancing of interests to ensure that one activity does not severely infringe on other uses [44]. Thus, the US federal permitting procedures appear to be disjointed for open ocean aquaculture.

It has been shown in several examples, that institutional arrangements are a major impediment to effective implementation of necessary user changes. Obvious rifts between regulators and those being regulated has reduced opportunities to overcome major challenges [45]. Contrasting the findings of Cicin-Sain et al. [39] and Fletcher and Weston [44] for the US EEZ, some overall planning of the management, development, and conservation of the EEZ in Germany has taken place through the establishment of the geographic information system CONTIS by the BSH. This database provides a suitable visualisation and planning tool, revealing what areas are best suited for marine aquaculture in terms of the requirements of the marine aquaculture activity itself and in terms of avoidance of environmental risks and of spatial conflicts with other uses. Nonetheless, the lacking legislative framework causes a high degree of uncertainty among the stakeholder groups, which makes the urgency for a legible common framework apparent. Within the vast variety of international (EU), national, and regional regulations concerning German territories, the regulative framework promoting synergies within the aquaculture sector are yet incomplete [12].

However, it must be emphasised here that the EEZ-concept holds potential for alternative management structures, as little regulation has been developed so far. In addition, there are few considerations on how the organisational arrangements currently in place could be impediments to co-management and how e.g. fisheries organisations could be better arranged to lead to the implementation of this management tool [45]. For example: wind farms would arrange the positioning of and distances between units in compliance with the physical/aerodynamic conditions and the navigational regulations/safety standards. They would not like to see any complication that inflicts with the control of their operation or would require joint responsibilities with other stakeholders unless these are strictly regulated and assigned. Likewise, the aquafarmer would follow technical/operational safety standards as they pertain to the bio-technological system's operations. Operating in the same area and sharing resources and even infrastructure that one or the other primarily provides would require more than just gentleman arrangements for co-management. It needs strictly defined responsibilities and liabilities as well and goes as far as implicating the design criteria of either of the cooperating industries. Fig. 4 indicates a simple example of regulating the waterway laws (e.g. separation zones) and handling guidelines (e.g. boat approaches to platforms). The regulation also needs to address the layout of the service boats and the technical handling of longlines or other structures to satisfy safe operation for both users.

The existing decision process in the EEZ for most countries is characterised as a linear decision-making process whereby each of the protagonists contribute in an independent fashion to the final decision, its implementation and its consequences. The lack of coordination, inappropriate sharing of responsibilities, feedback and accountability are persisting and renders the potential of emerging conflicts.

If formal partnerships are indeed to be considered, such as co-management of offshore areas, then what is required is nothing short of a significant change in the law that would permit direct involvement of regional authorities, communities, industry, and private stakeholders to responsibly manage their common affairs and identify jointly the regulatory requirements which authorities must include into the legal framework. Lane and Stephenson [45] propose in this context a two-track approach: in the longer term, participants must contribute to and be represented in policy settings for strategic levels. Furthermore, they must be involved at intra-seasonal levels and this should be undertaken in a participatory co-management manner. The disadvantage to this approach lies in the process itself, which may be too complex, but as the case example of New Zealand suggests, there may be alternative routes of addressing management issues in a participatory manner. Therefore, to overcome the shortcoming that complexity inherits, co-management approaches have to be confined and grouped to specific geographical areas or topics in order to be manageable. This confinement, such as the organisation in local area management teams, makes information sharing possible and still permit a bottom-up participatory approach [43,45].

The governmental support for further offshore development has provided an incentive for new management approaches such as the potential introduction of multifunctional co-management schemes in Germany. However, the lack of sufficient regulations for the EEZ and contrasting interests of the conversation authorities restricts these approaches. The major difficulty in this endeavour resides in the weakly defined assignation of authorities that are jointly responsible for the permit of wind farm facilities and open ocean aquaculture in the EEZ. So far, permits are carried out under the auspice of the Federal Maritime and Hydrographic Agency and are requested to follow the EU Water Framework Directive [9]. The EU enforces the implementation of an integrated approach endorsing the ICZM philosophy in recognition of the overall highly competitive functions and uses of the North Sea (NE-Atlantic). The need for sufficient regulations to simultaneously safeguard technically all interacting users and to optimise the management of the resources within a multifunctional and multi-use(r) context is appealing incorporating an integrative consideration of land and sea territory.

7. Outlook

Each of the points raised here gives way to different sets of potentials, issues, and constrains, which are beyond of the scope of this article. For instance, the technological aspects of the offshore installations, either offshore wind farms as well as offshore mariculture, is yet far from being solved and still much research has to be undertaken to develop sound techniques, which will withstand the severity of the potential impacting physical forces offshore. If culture techniques are designed to fulfil the requirements of offshore weather conditions, the next step is to address the question, how these techniques can be combined with wind farm installations.

The described situation calls for expansion (modification) of the legislative schemes that endorse the idea of multiple area use, equal user rights, and mutual (simultaneous) protective measures for all partners active in offshore areas. Community management and user-oriented co-management may provide key terms in the debate on how to optimise resource use. However, effective co-management requires increased transparency and consensus on the rights of local users before current ambiguities become obstacles. Only then the economic potential fundamental to open ocean aquaculture can be calculated as this requires the inclusion of all points raised beforehand.

The EU-Water Framework Directive (WFD) may offer some potential to optimise procedures for open ocean aquaculture in a multi-use context. However, in this context it is of concern that the EU commission has removed the coastal zones from the WFD research programme, which was supposed to also support links with ICZM research initiatives. Therefore, a window of opportunity may have been closed, where the potential of future multifunctional use would gain sound scientific support.

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Appendix VI

Publication VI

The offshore-ring: A new system design for the open ocean aquaculture of macroalgae

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Abstract

Mass culture of benthic macroalgae under rough offshore conditions in the North Sea requires rigid culture support systems that cannot only withstand rough weather conditions but can also be effectively handled while at the same time retain the cultured species. Various carrier constructions and different mooring systems were tested. *Laminaria saccharina* grew on all of these carriers with initially high (up to 14.5% per day) and later decreasing length increments. Longlines, ladder and grid systems had certain disadvantages and these are discussed. The study results led to a new ring carrier (patent pending), first used in 1994/1995, which was gradually improved until 2002. This system now emerges as being superior, since it resists not only rough weather conditions (2 $m \cdot s^{-1}$ current velocity, 6 m wave height) but also permits ease of handling when compared to other constructions. The ring allows various operational modes and can be equipped with culture lines that can be collected offshore or transported to shore facilities for harvesting. The modular nature of the tested ring system lends itself for future use in integrated aquaculture systems located in or attached to offshore wind farms.

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The offshore-ring: A new system design for the open ocean aquaculture of macroalgae

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Key words: *Laminaria*, length change, length increment, offshore aquaculture, ring construction

Abstract

Mass culture of benthic macroalgae under rough offshore conditions in the North Sea requires rigid culture support systems that cannot only withstand rough weather conditions but can also be effectively handled while at the same time retain the cultured species. Various carrier constructions and different mooring systems were tested. *Laminaria saccharina* grew on all of these carriers with initially high (up to 14.5% per day) and later decreasing length increments. Longlines, ladder and grid systems had certain disadvantages and these are discussed. The study results led to a new ring carrier (patent pending), first used in 1994/1995, which was gradually improved until 2002. This system now emerges as being superior, since it resists not only rough weather conditions (2 m s^{-1} current velocity, 6 m wave height) but also permits ease of handling when compared to other constructions. The ring allows various operational modes and can be equipped with culture lines that can be collected offshore or transported to shore facilities for harvesting. The modular nature of the tested ring system lends itself for future use in integrated aquaculture systems located in or attached to offshore wind farms.

Introduction

Aquaculture is presently one of the fastest growing aquatic food production sectors in the world due to the rapidly increasing demand and declining global fishery yields. Compared to the rapid augmentation of 117% (1993–2002) in fish, crustacean, and shellfish aquaculture, the cultivation of seaweeds still plays a less important but increasing role in the industry. The worth of the seaweed industry has grown about 26% between 1993 and 2002 to 6 billion US$ (McHugh, 2003; FAO, 2004).

Traditionally, mariculture of seaweeds has been conducted mainly in Japan and China for more than three centuries mainly for human consumption (Kawashima, 1993; Tseng, 1993, 2001; Ohno and Critchley, 1997; Critchley and Ohno, 1998). The culture of marine algae can be traced back to 1690, when the first recorded attempts to culture seaweed on the fences of fish cages were carried out in Japan (Tamura, 1966). Yet, scientifically supported culturing techniques resulting in a much more successful commercial production (Scoggan et al., 1989) were not initiated until as late as the early 1950s and then mainly in relatively protected inshore waters. In 2002, production levels of algae have been reaching 18.6 million tonnes (FAO, 2004). The FAO notes that in 2002 Europe had only a 6.3% share of the global production of brown algae (362 000 t FW) and about 0.3% of red algae (9400 t FW) with less than 200 t macroalgae produced in aquaculture. Norway, France, and Iceland are the main suppliers of brown seaweeds in western Europe, since their rocky coastal areas, unlike that of the German Bight, provide enough hard substrate to accommodate extensive kelp forests. This has given rise to a traditional harvest of naturally grown algae in these EU countries (Kain, 1991; FAO, 1998). However, the economic gains are low, due to limited access to the natural beds, harsh weather conditions and an unavoidable mix of species harvested in the field (Kain and Dawes, 1987). Contrastingly, 97% of the Asian production of brown seaweeds is grown as monocultures in aquaculture (Fei et al., 2000; FAO, 2004). This approach avoids the disadvantages of the traditional European fishery-based production systems that yield a high variability in terms of quality and composition. Often, a partial destruction of the seaweed beds accompanies this collection fishery.

Outside Asia only few algae are consumed directly, but many products marketed globally contain phycocolloids, extracted from algal cell walls that are used as stabilisers and emulsifiers in the food and cosmetic industries (De Roeck-Holtzhauer, 1991; McHugh, 2003). The long chains of algal polysaccharides can make up to 40% of dry weight (Smidsrød and Christensen, 1991). The global market for phycocolloids that include agar, carrageenans and alginates is estimated to be worth annually 585 million US$ (McHugh, 2003). Moreover, *Laminaria* can be used for waste water treatment and the partial recycling of nutrients particularly near fish farm effluents (e.g. integrated culture systems) Subandar et al., 1993). They have also been employed to absorb heavy metals from industrial sewage (Sandau et al., 1996; Stirk and van Staden, 2000).

In western countries macroalgal farming of brown algae in the sea was tried out at the Californian coast (Neushul and Harger, 1985; Neushul et al., 1992) and in Europe near the Isle of Man and Ile d'Ouessant (Kain, 1991; Perez et al., 1992). In Germany, a feasibility study on offshore algal mariculture in the North Sea was launched by the German Government in 1993 and conducted at the marine Station of the Biologische Anstalt Helgoland (BAH) off the island of Helgoland, North Sea (Figure 1). The study lasted for two years. One major component of this feasibility study was to develop an appropriate technical device to grow macroalgae. The system had to withstand the

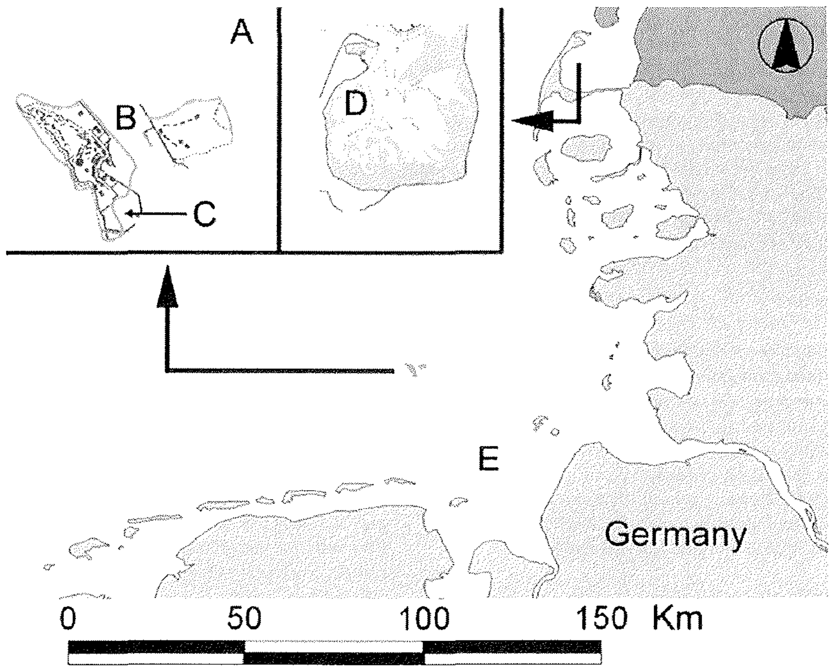

Figure 1. Map of the German North Sea region including the enlarged island of Helgoland (upper left) with the test locations (A) Helgoland farm, (B) Helgoland Roads and (C) Helgoland Harbour. The enlarged northern part of the island of Sylt (upper right) illustrates the test location (D) in the Sylt tidal flats backwaters. Location E indicates the Roter Sand test area.

harsh environmental conditions of the German North Sea shelf, where maximum wind speeds can be 150–180 km h^{-1} and wave amplitudes commonly reach 5–8 m during storms. Investigations were resumed in 2002 as part of a doctoral thesis (first author) aiming at using this new aquaculture technology in conjunction with offshore wind farms. Sheltered nearshore areas, suitable for mariculture, are already largely used as established nature reserves or as protected areas in general. Thus, future commercial cultivation of seaweeds will have to move to more exposed offshore areas.

Several known carrier designs for algal culture were built and deployed, subsequently resulting in the final modular construction used in this study. The performance of the various test designs under offshore conditions, length changes and, where possible, the biomass yield of *Laminaria saccharina* on these constructions were investigated at different locations.

The results are of high importance for the future utilisation of exposed offshore locations, especially when considering multi-user concepts combining wind farm installations with mariculture. Such projects as are currently developed along the German coast (e.g. Buck, 2002; Buck et al., 2003, 2004; Krause et al., 2003).

Material and methods

Study site and environmental conditions

Experimental mariculture of *Laminaria saccharina* was conducted in 1994 and 1995 at Helgoland, in 2002 near the island of Sylt and in the outer estuary of the river Weser (Figure 1). The study sites are characterised by various hydrographic features. Depth, condition of the sea bottom, salinity, turbidity and light, wave exposure, current velocity and significant wave heights (Mittelstaedt et al., 1983; Asmus et al., 2000; Dring et al., 2001; WSA, 2002) are shown in Table 1. Furthermore, nutrients (ammonium, nitrate and phosphate) and water temperature (Table 2) at the study sites were monitored for unusual events by examining the BAH's and WSA's long running time series of measurements (BSH, 2002; BAH, 2002, 2003; NLÖ, 2003). Peak wind velocities of ≥6 Beaufort and ≥8 Beaufort were noted down during years of the experimental studies.

Sporadically, photosynthetically active radiation (PAR) was determined with an 'Underwater Quantum Sensor' (LI.COR [μE m^{-2} $s^{-1} \approx$ mmol m^{-2} s^{-1}]), which recorded the light intensity in air near the water surface and underwater at the culture rope. Additionally, water temperature was recorded during the experiments.

Experimental plants and pre-cultivation of young sporophytes

For "seeding", reproductive specimens of *Laminaria saccharina* with a thallus length from 90 to 150 cm were collected by divers from nearshore areas around the island of Helgoland (Hgl; 54°11′N, 7°54′E) (Figure 1) from a water depth of 1–4 m in the winter months.

In order to obtain sporophytes attached to culture lines, zoospores were released from the sporogenous tissue (sori) of *L. saccharina* that had been meticulously cleaned by brushing in three pasteurised water baths. Sori from up to 12 different plants were

Table 1. Site-specific conditions at nearshore and offshore test locations.

Location	Depth at low tide (m)	Sea bottom	Salinity (psu)	Turbidity	Light (PAR) (mol · m^{-2} · s^{-1})	Wave exposure	Current velocity (m · s^{-1})[a]	Significant wave height (m)[b]
Offshore								
Helgoland Farm	12–14	Sand	29–33	Low	No data	Exposed	0.3–1.2	0.5–4
Roter Sand	12	Mud/silt-sand	25–32	Moderate	100–1750	Exposed	0.5–2.1	0.5–5
Nearshore								
Helgoland Roads	6	Coarse gravel	29–33	Low-high	100–2590[c]	Partly exposed (strong currents)	0.3–1.5	0–3.5
Helgoland Harbour	5	Mud (clay)	29–33	High	No data	Sheltered	0.1–0.3	0–1
Tidal flats of Sylt	1	Mud (clay)	32–34	High	0–1600[d]	Sheltered	0.4–1.0	0–1.5

[a]Mittelstaedt et al. (1983).
[b]WSA (2002).
[c]Dring et al. (2001).
[d]Asmus et al. (2000).

dried in a moist chamber at 10 °C over night and allowed to sporulate the next day in fresh seawater. The spore suspension was poured into a 3000 L basin containing five large plastic frames, segmented for stability. Each frame was wrapped with more than 350 m of culture line. In a previous test various culture lines had been tested. Among 15 different lines a 6 mm polypropylene line, three-strand right hand soft lay, proved to be most suited to fulfil the requirements: This line was not toxic and ready for use after only two rinsing steps; the diameter of 6 mm was acceptable for space-saving at "seeding" time, but also strong enough to carry larger plants, which therefore did not have to be transferred to thicker ropes. The frames were arranged vertically and reversed every second day to accomplish a more even exposition to the artificial sunlight generated by Power Star HQI-TS 150W/NDL Neutral Weiss lamps by Osram, which yielded 10 μmol photon m^{-2} s^{-1} in the centre of the basin. The light regime was 10 h light per day. The seawater was filtered and supplemented with either Provasoli's solution (Provasoli, 1968) or 100 mmol L^{-1} $NaNO_3$ and 10 mmol L^{-1} sodium glycerophosphate once a month. At "seeding" and once per week for two weeks germanium (IV) oxide was added to prevent diatom growth. Approximately two months after seeding, the first cultured laminarian sporophytes reached an average length of 1 cm and were placed in the sea.

Design of the carrier systems

Four different cultivation systems were designed and deployed in the study area in order to find the most suitable design for offshore use: these included longline, ladder (tandem longline), grid and a ring-shaped design for attachment of algae seeded culture lines (schematic Figures 2a–2c and 3a–3c). Each of these different constructions varied in mooring design, floatation and culture units. Concrete blocks of 2.5, 4 and 4.5 tonnes were employed in a single, twin or radial mooring geometry in order to securely moor the carrier constructions. The ladder and grid constructions were oriented parallel to the main direction of the tidal current. Starting from the anchor stones, chains with a service load (SL) of at least 8 tonnes were used to connect the concrete with the mooring line (SL 12 tonnes). The service loads corresponded to a threefold collapse load. The mooring line itself held the culture unit, which was designed to float at or below the water surface. The floating system consisted of ball-like floaters or fenders, which were connected by ropes to the culture unit to provide sufficient buoyancy. All connections between ropes, chains, floaters and concrete blocks contained triple rings (SL 6 tonnes), shackles (SL 6.5 tonnes), warbles (SL 6.5 tonnes) and thimbles, in case of eyes at rope ends.

The *longline* consisted of a 50 m long, horizontal carrier rope anchored by a 4 tonnes twin mooring

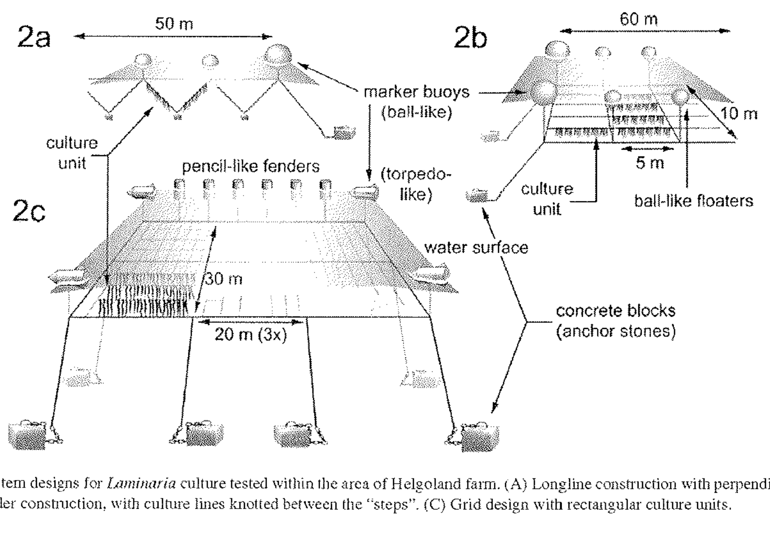

Figure 2. System designs for *Laminaria* culture tested within the area of Helgoland farm. (A) Longline construction with perpendicular culture unit. (B) Ladder construction, with culture lines knotted between the "steps". (C) Grid design with rectangular culture units.

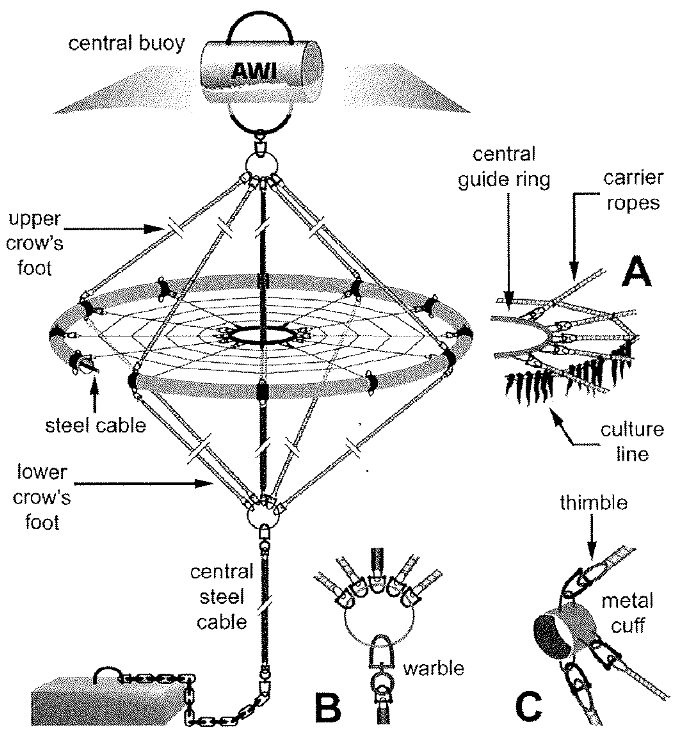

Figure 3. The successful ring design for the culture of *Laminaria* at offshore locations. The major elements of the system design are magnified: (A) central guide ring with attached carrier rope and culture line, (B) the transition between central steel cable of the mooring and that of the lower crow's foot, (C) metal cuffs, to which the crow's feet and the carrier ropes are attached.

system. It served to fasten culture lines perpendicular to the water surface, each kept straight by a concrete weight (2.5 kg) (Figure 2a). This method had been successfully employed by Kain and Dawes (1987) and Perez et al. (1992). Between December 1994 and April 1995, a total of 140 culture lines each 5 m long, with young *Laminaria* sporophytes were transferred from the laboratory and knotted at 3 m intervals to the horizontal carrier rope. Later, two adjacent 3 m long culture lines were connected at their lower ends (V-shape). *L. saccharina* on these lines were 2–3 mm at transplantation.

The *ladder* construction was 60 m × 10 m in size and was positioned horizontally 1 m below the sea surface by 24 concrete weights (each 1 kg under water) and air-filled buoys on the surface (Figure 2b). Ball-shaped buoys of 110 L at the corners of the ladder construction were meant to keep it afloat. It was suspended between four anchor stones (4.5 tonnes) in a double twin mooring shape. Five metres long culture lines were knotted in between the "steps". Experience from the "ladder" went into the construction of a grid system.

The *grid* systems had been in use off the Isle of Man (Kain, 1991) and in Brittany (Perez et al., 1992). Based on the above and our own experiences, a grid system depicted in Figure 2c was set up. The grid measured 60 m × 30 m and was submerged at a depth of 1.2 m. The grid was designed to hold 1400 m of culture line in an area of 0.18 ha. A radial mooring system was used with 10 concrete blocks (2.5–4.5 tonnes). The frame material employed here was "Herkules" rope, which is commonly used in commercial fisheries. This rope contains in its core several subcores, each made of six strands of steel. This way the rope was heavier than the surrounding seawater, which reduced the risk of potential damage at the weight attachment points. The inner supporting ropes of the construction were made of Polystar, a mixture of polypropylene and polyethylene, a material with excellent references in steel grades. Four metal torpedoes served as buoyancy devices at the corners, another 72 floats were pencil-like fenders with 23 kg buoyancy each.

The *ring* construction (patent pending) had a total diameter of 5 m and consisted of a polyethylene tube with a 10 mm thick wall and a diameter of 110 mm that was welded to rings. The rings were weighed down by a steel cable (30 mm in diameter) inserted into the tube and obtained their buoyancy through eight elongated fenders (23 kg buoyancy each). They consequently floated at a depth of 1.2–1.5 m. Carrier ropes were suspended radially and 80 m of culture line could be fastened like cobwebs on each ring. A crow's foot was used to fasten the ring on a common mooring system. Due to permanent chafing of the carrier ropes with the fender ropes and because the fenders themselves got entangled with each other a modified system was developed (Figures 3a–3c). This consisted of one centre buoy (300 kg buoyancy) with a connected reverse crow's foot and a centre guide ring to prevent chafing of the mooring line with the carrier ropes. Furthermore, all radial splices, which connected the carrier ropes to the polyethylene tube, were replaced with metal cuffs. Three loops were welded to these cuffs, one to the centre to fix the carrier ropes and the other two to the bottom and the top of the cuff, to connect both crow's feet.

An important feature common to all constructions was their ability to adjust the depth of culture lines to 1–1.5 m as this appeared to prevent possible PAR and UV damage to the young plants, while providing enough light for successful photosynthesis. Moreover, the most turbulent upper meter of the water column could thus be avoided.

Location for test deployment

In order to find the most suitable place for kelp cultivation in the German Bight different locations were selected which are considered to be representative of those where offshore aquaculture may develop and where depths, seabed material data, sedimentation load, current velocities and wave climate, light intensities, nutrient concentrations and distance to the main land varied. Two offshore and three inshore locations were tested during this study (Figure 1). The main testing area (offshore algal farm) was located 3.5 nm north-east of Helgoland (54°13.00′N, 7°57.00′E). Longline, ladder design, grid system and a ring construction were installed there. Additionally, another offshore location at the lighthouse known as "Roter Sand" was chosen (53°49.9′N, 8°8.7′E). The performance of the ring construction was tested at three nearshore test sites, Helgoland Roads (54°11.4′N, 7°53.8′E), Helgoland Harbour (54°10.4′N, 7°53.9′E) and in the tidal flats of the island of Sylt backwaters (54°59.5′N, 8°23.4′E). Table 1 gives an overview of site-specific conditions of all test locations.

Sampling and harvesting techniques

In the Helgoland experiments (1994–1995), sporophytes were collected at sea individually from the culture line for measurements of frond length in the laboratory. Few data are thus available for assessment of biomass m^{-1} of culture line over time. In the experiments performed at Roter Sand (2002) 1.5 m of culture rope was removed each month for frond length measurements. In all samples sporophytes ($n = 30$ in 1994/1995; $n = 40$ in 2002) of the largest size class were measured. Blade length was measured from stipe/blade transition zone to blade tip. Initial attempts to use the established technique of punching holes in the laminarian blade for calculation of growth rates (Parke, 1948; Kain, 1979; Lüning, 1979) had to be abandoned because of rough sea conditions.

To harvest seaweeds from longline, ladder or grid constructions, small boats were employed. To harvest the ring construction the rings were towed to shore and lifted by cranes. Harvest at sea was performed by divers or by boat-based cranes.

Calculation of length changes

The length change (LC) per day was calculated on the basis of mean blade lengths of *Laminaria saccharina* at each sampling date (t_1, t_2) modified according to the formula usually used for calculation of relative growth rates (Kain, 1987):

$$\mathrm{LC}(\%/\mathrm{day}) = \frac{\ln L_{t2} - \ln L_{t1}}{t_2 - t_1} \times 100 \qquad (1)$$

Statistical analysis

For all data, standard deviations (SD) or confidence limits (CL; $f = n - 1$, t-factor $= 95\%$) were calculated and applied in graphs as appropriate and shown as bars in the figures. Significance levels were determined using the Student's t-test ($p < 0.05$).

Results

Site-specific conditions at test sites

The temperature was above 19 °C on 3 days (4, 8, 11 August) at Helgoland in 1994, between 18 and 24 August in 1995, and at Sylt during 9 days in summer 2002. Nutrient (ammonium, nitrate, phosphate) concentrations varied between location and season (Table 2). Nevertheless, in all the experiments there was sufficient N and P in the surrounding water to sustain algal growth.

Technical results for different constructions

Longline. Only 65 of the 140 culture lines which had been fastened on the longline system were retrieved and 20 of these were evaluated. Due to very stormy weather between October 1993 and May 1994 the farm was visited only infrequently. However, every chance during calm weather was used to exchange horizontal carrier rope and supply it with new culture lines. The study revealed, however, that the weights on the culture lines were insufficiently heavy, so that they were frequently tossed across the carrier line resulting in the removal of the young *Laminaria* by friction and causing them to become entangled. Other culture lines, consisting of three twisted strands, were untwisted by the current and turbulences and consequently the individual strands were torn. Some improved performance of the longline was obtained by connecting pairs of only 3 m long culture lines at the lower end like a V-shape. Length data were taken from these lines.

Ladder. The ladder construction revealed problems in the durability of the frame material, the attached weights being potential breaking points. Moreover, the 110-L buoys at the corners were very instable and had to be exchanged several times. These drawbacks were taken into account for the development of the grid system.

Grid. The grid system proved much more stable compared to the "ladder" even though the mooring ropes could not be adjusted to their optimal length to accommodate the full tidal differences. The use of elongated fenders instead of ball floats protected the

Table 2. Nutrient concentrations and temperature at nearshore and offshore test locations.

Location	Months	Nutrients (μmol/L)			Temperature (°C)
		Ammonium	Nitrate	Phosphate	
Offshore					
Helgoland	Dec.–Feb.	3.0–6.8	12.5–110.3	0.8–1.1	2.2–9.0
Farm	Mar.–May	1.0–6.2	13.8–73.8	0.1–1.5	4.8–11.5
	Jun.–Oct.	1.7–10.4	0.4–24.8	0.1–1.1	11.1–20.2
	Sep.–Nov.	2.9–5.7	1.3–8.1	0.5–1.2	9.4–17.8
Roter Sand	Dec.–Feb.	0.3–4.4	1.1–13.4	0.1–0.4	1.8–5.0
	Mar.–May	1.8–5.9	6.1–55.4	0.2–0.9	6.1–11.3
	Jun.–Oct.	0.9–6.5	0.2–49.3	1.3–1.7	14.1–18.8
	Sep.–Nov.	0.3–6.6	0.9–10.2	0.1–0.5	18.2–2.1
Nearshore					
Helgoland	Dec.–Feb.	1.2–9.3	10.6–80.7	0.6–2.7	2.2–9.0
Roads	Mar.–May	0.7–7.0	29.0–136.0	0.0–1.2	4.8–11.5
	Jun.–Oct.	0.7–7.1	0.1–58.8	0.0–1.4	11.1–20.2
	Sep.–Nov.	3.5–8.8	0.6–32.5	0.7–1.9	9.4–17.8
Helgoland Harbour		No data	No data	No data	No data
Tidal flats of sylt	Dec.–Feb.	3.0–12.9	22.8–64.8	0.8–1.4	1.4–2.5
	Mar.–May	0.2–4.6	5.2–68.2	0.1–1.0	2.6–14.2
	Jun.–Oct.	0.4–4.5	0.1–4.0	0.1–1.0	14.8–19.9
	Sep.–Nov.	0.2–12.5	0.1–25.3	0.6–1.1	6.2–14.3

Data were provided by the long running time series of the BSH (2002), BAH (unpublished with reference of J. Van Beusekom), BAH (2003), and NLÖ (2003).

construction by better riding the swell which resulted in continuous vertical movement, while the balls used previously had resulted in jerking behaviour that created substantially more stress on all the materials. Culture lines were knotted into the grid from a small rowing boat, a procedure that needed smooth sea and calm weather and could only be managed during the period of slack tide (maximum 30 min). Culture lines (880 m) were transferred to the grid, but only some samples were retrieved. Unfortunately, the test unit was destroyed by the crew of a yacht who ignored the official signs, got entangled in the ropes and cut themselves out destroying also the frame construction. The weakened grid system no longer supported the culture lines, which led to their loss.

Rings. Individual rings of 5 m diameter showed a superior performance in comparison to the other tested carrier constructions. They remained stable and in place during all weather conditions, provided their moorings were tended regularly, at least after storms which imposed some wear on them. In addition, they allowed equipment with culture lines to be performed onshore, the rings subsequently being towed to their mooring locations and fastened relatively quickly during slack tide.

With the ring construction the harvesting period could be prolonged by moving complete rings onshore. Moreover, sampling of the seaweed culture was more easily done due to the possibility of heaving up the ring construction with a ship's crane.

Kinetics of length changes and biomass yield of Laminaria saccharina

The data on length changes (LC) of *Laminaria* fronds are presented in Figure 4, with the first column of diagrams showing results from all carrier constructions in the area of the algal farm near Helgoland in 1994–1995 (Figures 4a–4d), and the second column with data on ring carriers at different locations and years (1995, 2002), but during the same season (Figures 4e–4h).

Basically, LC were high immediately after transplantation, when *L. saccharina* sporelings were still small, and decreased with progression of the grow-out phase. The early differences in LC are concealed in the diagram of the 1994 ring "farm" (Figure 4d), because only one measurement 90 days after transplantation was possible and LC had to be equalised over the whole period. On the longline (Figure 4a) *L. saccharina* hardly grew in the month of July (days 63–93), while during the same month frond length increased by 9.4% d^{-1} (days 5–35) in the ladder system (Figure 4b), and on the farm ring (Figure 4d) increases were noticed as well. It should be noted that the culture lines for all three systems had been inoculated with the same mixture of zoospores on the same day (04.03.94), but transplanted into the sea at different dates. A minimum in length increment occurred in August with a slight increase again in September on the longline as well as on the ladder system (Figures 4a–4b). In the grid system (Figure 4c), supplied with algae on 8 May 1995 (inoculated on 6 February 1995), the algae did not perform as well as on the other three carrier systems (Figures4a–4b, 4d) in terms of adherence to the culture lines, susceptibility to fouling and growth.

In the ring experiments performed in 1995 or 2002 and all started in December or January (Figures 4e–4h), the values for length increase from December to February ranged between 5 and 15%. The maximum value of 14.5% d^{-1} occurred on the Harbour ring at Helgoland (Figure 4h) from December to January, while at the same time at Helgoland Roads (Figure 4g) less than half of this value was recorded, and in early April the obvious superiority of the harbour location at this stage became striking (Figure 5). Lower values of 5–7% d^{-1} were found for February seven years later at Sylt and Roter Sand (Figures 4e–4f). In all, but the harbour experiment, positive length changes were recorded until the end of the experiments between June and August (Figures 4e–4g). The Harbour experiment showed negative length changes from May to June parallel to heavy fouling by various epiphytes and epizoans, mainly *Ciona intestinalis*. In the end, many algae were basically reduced to the meristematic area in the Harbour ring.

Outside the harbour conditions clean blades with an average blade length of 1.5–2.0 m were obtained between June and August at different locations and in different years, while the blades in the harbour deteriorated (Figure 6a). The algae on the ring moored at Sylt exhibited lower increases in blade length throughout spring but reached a similar size to algae on the ring at Roter Sand and Helgoland Roads in summer (Figure 6a).

After three months of grow-out time at Roter Sand, significant differences ($p < 0.05$) were detected between blade length on the outermost culture line and the inner parts of the culture unit (Figure 6b). The same was true after two months at Sylt (data not shown).

The ring from Helgoland Roads was towed into the harbour in June 1995, lifted by a land-based crane (Figure 7), and the culture line with adhering algae

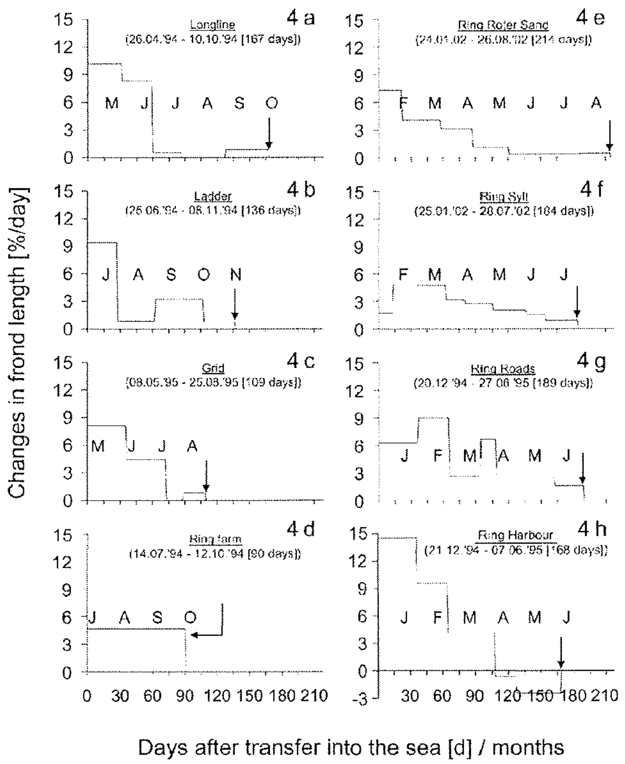

Figure 4. Kinetics of length changes (LC) in *Laminaria*. The left column shows results from the four system designs tested at the Helgoland farm, the right column demonstrates the results from the ring systems at four locations (a–d, g–h: $n = 30$; e–f: $n = 40$). Sampling days are indicated by the perpendicular lines. Arrows indicate the end of the experiments. Capital letters along the abscissa indicate months.

was retrieved. About 75% of the 84 m long culture line were fully covered by *Laminaria saccharina*, with a total fresh weight of 304 kg after six months of grow-out phase in the sea. Average biomass m^{-1} of algae covered culture line on the various culture constructions was 4 kg (mean value $\pm$ 1.1 SD, $n = 18$).

Discussion

An encouraging finding of the investigation was that *Laminaria saccharina* did grow on artificial substrates in all the carrier systems used, even under very rough circumstances (Koehl, 1998). Major key conditions for offshore culture were fulfilled such as the pre-cultivation of healthy plants that were well attached to the culture lines. Another key factor, the reduction of mechanical abrasion, was a major problem on the longline system, because of high turbulence. Longline systems are hence considered unsuitable for macroalgal culture under open North Sea conditions. The ladder system was more apt to damage than the improved grid system, e.g., at the fastening points of weights, and should therefore also be rejected in future considerations. A further problem of all carrier constructions except the rings was the necessity to fix them at permanent offshore sites. This led to the logistic and cost problems of efficient transfer of sporelings from the laboratory (or hatchery facility) to the grow-out location as well as appropriate tending of the carrier system under the prevailing rough weather conditions. Labour requirements were also enormous. Every single culture line had to be fastened to the carrier system from

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Fig. 5

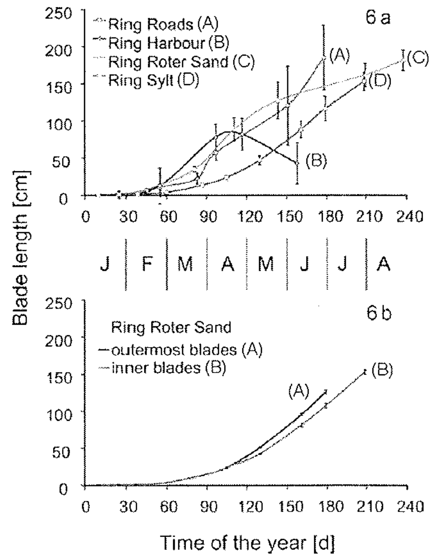

Fig. 6

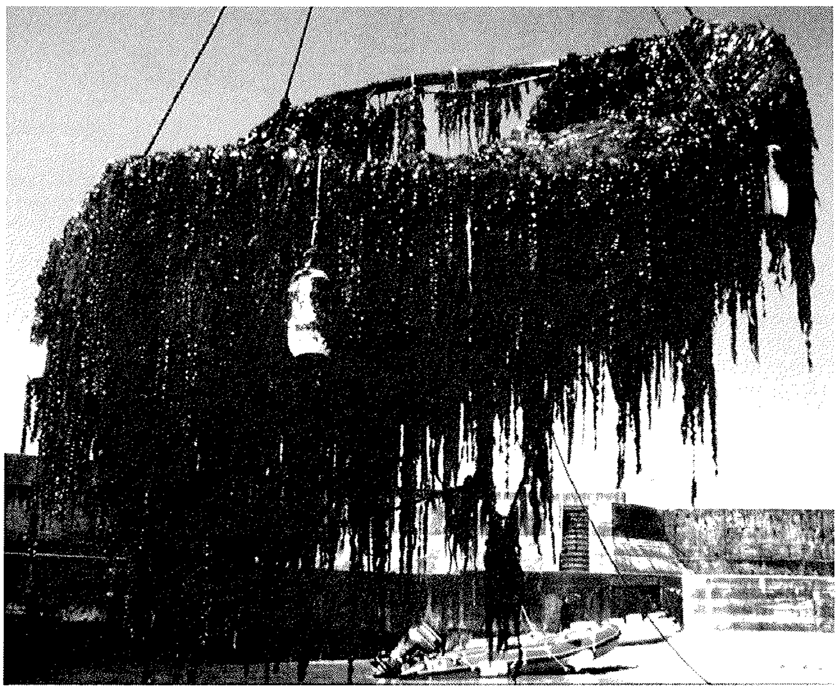

Fig. 7

a small rowing boat, and this was only suitably done during slack tide. Work was seriously impaired by the difficulty of getting ship time and divers, while also waiting for calm seas and all of this at the 30 min of slack tide and during working hours.

The ring construction using its present dimensions has proven stable in offshore conditions (Helgoland farm, Helgoland Roads, Roter Sand). The new ring construction, with a central steel cable and central buoy, reduced tractive power and tension in high velocity currents and when being moved for sampling or harvest. The two crow's feet with the metal cuffs greatly prevented torsion of the ring when lifted. The depth of a ring could be adjusted by insertion of steel ropes into its cavity and the buoyancy of the central buoy could also be adjusted by changing its size. This way the ring could be kept at an appropriate depth to avoid exposure to stressful surface turbulence and admit sufficient light for algal photosynthesis even with increasing weight of algae.

A major advantage of the ring system compared to the other systems was that the ring could be equipped onshore with 80–100 m of culture line and subsequently towed to the mooring site, where it could easily be moored by the ship's crew. The reverse took place at harvest time and was also most advantageous. The ring diameter of 5 m could be managed by cranes from relatively small vessels (12 m in the case of RV "Aade"). This way the algae on the ring construction could be examined at most dates and at harvest while in the worst case it was at least possible to tow the ring into the harbour, where a larger crane could lift it onshore. The described characteristics and the modular nature of the ring construction promise to make it a sensible and effective choice to be used in aquaculture situations where offshore wind farms are located (Buck, 2002; Buck et al., 2003, 2004; Krause et al., 2003). Moreover, one could transfer the technique to less developed countries using suitable materials, e.g. bamboo or rattan, and the craftsmanship of local people. However, lifetime and stability of the ring systems using materials of these countries will have to be tested before large-scale employment.

In our mass cultivation the difficulties to relocate marked algae at the next date of examination prevented the use of the common method of punched holes for assessing growth rate in laminarian blades (Parke, 1948; Kain, 1979). We could only measure blade lengths, thereby integrating tissue production and distal blade loss over the preceding period between sampling dates. Laminarian blades behave like moving belts of tissue, eroding at the tips while growing at the bases, so that a total year's growth may amount to 1–5 times the initial length (Mann, 1972). As an example, the frond area lost in *L. saccharina* during the first year of life in the sea near Helgoland at 2 m water depth below chart level may amount to 70% during the period from May to October (Lüning, 1979). As another example, during the winter period *L. longicruris* lost almost 70% of the blade tissue grown in the previous summer (Chapman and Craigie, 1978). For practical and commercial purposes, however, exact data on growth rate and distal blade loss are not as important as the actual blade length and harvestable biomass at a given time, which are reported in the present investigation. Moreover, it seems possible and should be further investigated that distal blade loss in first year laminarians cultivated upside down in the pelagial on longlines or rings is probably not as prominent as in algae growing in the rocky intertidal, where they are mechanically battered on the rocky substrate by tides and wave action.

The length increments of young sporophytes of *L. saccharina* were initially high after transfer from the laboratory to the sea in the beginning of the year. This coincides with the well known rapid phase of seasonal growth during the first half of the year in *Laminaria* spp. as described by Parke (1948), Kain (1963, 1979) and Mann (1973) with optimum environmental temperature, nutritional and light requirements and a suitable phase of endogenous seasonal rhythmicity for active growth (Lüning, 1993). During the second half of the year, i.e., the period of slow growth (Parke, 1948; Kain, 1979), sporophytes of *L. saccharina* or *L. digitata* still exhibit noticeable growth activity although with a progressive decrease from month to month (Lüning, 1979; Creed et al., 1998), and this was again evident in

Figure 5. Photograph of *Laminaria saccharina* sporophytes taken from the ring constructions and Helgoland Harbour (left) and Helgoland Roads (right) on 7 April 1995 after 3.5 months in the sea.

Figure 6. Average blade length of *Laminaria saccharina* on ring constructions at different locations (a), or at Roter Sand in the outer or inner parts of the ring (b). The numbers on the time axis indicate the day of the year. (a: mean values $\pm$ SD, $n = 40$; b: mean values $\pm$ CL, $p < 0.05$, $n = 40$).

Figure 7. Preparation of *Laminaria* harvest from the ring formerly located at Helgoland Roads in the harbour of Helgoland. The ring was lifted from the water by a land-based crane.

the length increments recorded on the various carrier systems in the present investigation.

The temperatures above 19 °C in August may have contributed to the reduction in length increase in the case of the algae dispatched on the longline and ladder in 1994, but cannot explain the poor performance of those plants attached to the grid, because in 1995 the high temperatures were found too late to be included in the experiment. In the case of the ring at Helgoland Roads the small length increment between day 55 and 83 of the grow-out phase was probably due to the unusually stormy weather in March 1995 with 13 days of winds of ≥ 8 Beaufort (mean of 30 years: 2 days). January was also very stormy and overall conditions did not allow for the same high length increase as was observed for algae from the same spore suspension and seeding badge on an identical ring in the harbour.

At Helgoland, storms resuspend a lot of sediment in the water column and can almost reduce light intensity in the water to zero. The calm waters of the harbour are less turbulent and allow faster re-sedimentation and consequently better light conditions in surface areas. Therefore, the algae at Helgoland Roads were probably light-limited at certain periods while those in the harbour were not. Light-limitation was also evident at Sylt, where the concentration of suspended material is always high due to the tidal currents in the backwaters. The shading effects did not prevent growth, but slowed it down. Additionally, the ring at Sylt had been exposed to air and had weighed down on some of the algae, battered by the receding and incoming tide causing blades to shorten. Due to the particularly nutrient-rich waters and the limited water exchange in the Sylt backwaters as well as in the Helgoland harbour, fouling occurred by organisms such as blue mussels, ascidians as epizoans and epiphytes, like *Fucus* and *Enteromorpha*, which settled on both rings and cultured algae. At Helgoland Harbour the heavy load of epizoans contributed to the loss of algal material and accounted for the marked negative length change. At Roter Sand and Helgoland Roads the strong currents largely prevented settling of fouling organisms. The high current velocities did not result in substantial loss of algae.

The results on changes in blade lengths showed that all algae eventually attained the same length. Standard deviation was higher in algae harvested from the 1995 rings, because smaller samples were collected, since small groups of *Laminarians* were plucked from the ring sometimes under harsh weather conditions. The rationale was to save a quantity as high as possible for the final harvest. The 2002 rings were sampled by regularly cutting out about 1.5 m of culture line and the choice of the largest size class to be measured was therefore greater. The algae on the ring at Helgoland Roads grew in the best conditions, they reached the greatest length a month earlier than the others. The slower length increase of Roter Sand sporophytes might be explained by stress through variations in salinity and also sometimes turbid water. The longer blades on the outer rope of the culture unit can be explained by the superior availability of space and light in contrast to shadowing by neighbouring plants among inner parts of the culture unit. Similar observations in 1995 served as an argument against singling out punched sporophytes at the periphery for conventional growth measurements.

The yield of 300 kg FW *L. saccharina* on the harvested ring may certainly be increased. The percentage of *Laminaria*-covered culture line could be raised by continuous movement of the spore collectors to allow efficient light harvest from the whole culture mat. On the covered part of the culture line sporophytes grew quite densely, thereby showing effects of intraspecific competition. This phenomenon, reported for *L. digitata* by Creed et al. (1998), resulted in different size classes of *L. saccharina* on the lines, an unwelcome feature biologically and for economic reasons. The largest size class competed successfully for light and constituted most of the biomass at harvest. Optimum density of sporophytes on the culture lines is still unknown and requires further well-designed investigations. It should leave sufficient space for the individual laminarian specimens to grow but also deny space for smothering by diatoms or macrophytes that compete for substrate. Besides the density problem at the start of the culture, harvesting can easily be scheduled too late. As was shown in later experiments with *L. digitata* (Buchholz, unpublished), further culturing could have resulted in "overgrowth" of phylloids by bryozoans. A timely harvest is an important objective to be incorporated into any logistic work plan.

Concerning the most favourable location for aquaculture of macroalgae, our experiments suggest that fairly exposed sites with rough conditions are suitable, however, only if the carrying support structure is sufficiently rigid to withstand the rough to extreme conditions encountered in most of the trials. Aquaculture in sheltered waters must avoid shallow areas, like in the Sylt backwaters, because of possible contact with the seabed and the high siltation and suspended solid load which creates low light conditions. Any location selected for seaweed culture should have a minimum depth of 5–8 m. Offshore areas like Roter

Sand and Helgoland Roads seem to be well-suited. Concentrations of dissolved O_2 and CO_2 and a good transparency of the water column stimulate algal growth. High current velocities provide sufficient nutrient supply, prevent fouling but do not impair plant performance. Sites like Helgoland Harbour could serve at times to pre-cultivate algae or store ring modules for some time before transferring them to offshore areas for grow-out.

As to the possible costs of seaweeds produced by open ocean culture on rings, one may expect a value of 40 € per ring, as based on a yield of 40 kg dry weight (corresponding to approx. 400 kg fresh weight) on 100 m culture line per harvested ring. If the costs for the fully mounted ring are 1000 € and the ring lasts for ten years, 100 € investment costs would be required per ring per year without any labour and ship costs. However, the situation would be changed if the present price of approx. 1 € kg^{-1} dry seaweed (e.g. Sandau et al., 1996) became substantially higher. Higher prices for seaweeds may be expected for several reasons. Fresh seaweed biomass may be sold as food to restaurants or as raw material to cosmetic companies at much higher prices than 1 € kg^{-1} dry seaweed. Examples are the successful production of the red alga *Chondrus crispus* in Nova Scotia (Canada) as exported food to Japan (Nakamoto, 2002) or the production of the red alga *Palmaria palmata* or the brown alga *Himanthalia elongata* in northern Spain (CMC, 2004) again as food. In addition, supply of seaweeds from natural stock in Europe may become legally restricted for environmental protection reasons, and open ocean aquaculture may help fill the gap.

Outlook

The combination of several ring modules requires some investigation into coupling techniques and the consideration of sea wave lengths exerting stress on the construction. The destruction of culturing devices by commercial shipping or pleasure yachts is unfortunately a rather frequent phenomenon offshore and has yet found little consideration in the planning of such constructions. The problem can probably be overcome by utilising offshore areas in a multi-functional manner. A combination of aquaculture with offshore wind farms (Buck et al., 2003, 2004), where strong legal shipping regulations are enforced, seems to be sensible. The pylons of the wind generators are fixed structures in the seabed and could serve to fasten culture modules like the rings in an offshore area.

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Appendix VII

Publication VII

Experimental trials on the feasibility of offshore seed production of the mussels* Mytilus edulis *in the German Bight: Installation, technical requirements and environmental conditions

Buck BH (in press) Helgoland Marine Research

1 2 3 4 5 6 7 8 9 10 11 12

Abstract

This study summarizes the activities and findings during a two-year study on the grow-out of blue mussels (*Mytilus edulis*) and the technical requirements to withstand harsh weather conditions at an offshore location. The experimental sites were two different chartered test areas, 5 ha in size, in the vicinity of the offshore lighthouse "Roter Sand" located 15-17 nautical miles northwest of the city of Bremerhaven (Germany). Two versions of submerged longline mooring systems were deployed; a conventional polypropylene-based longline in 2002 as well as a steel hawser-based longline in 2003, both featuring different versions of buoyancy modes. The spat collectors and grow-out ropes were suspended perpendicular from the horizontal longline for several months beginning in March of each respective year. The farms were visited on a monthly basis using research vessels. Larval abundance was determined in the surrounding water column and reached numbers of up to 1,500 individuals$\cdot$m^{-3}. Post-larval settlement success varied through the entire experimental period, ranging from 50 to 700 ind.$\cdot$m^{-1} of spat collectors. Growth of settled mussels reached a shell length of up to 28 mm 6 month after settlement and at the end of the grow-out phase (market size) shell length was measured to be 50 mm after 12-15 month. Settlement after 6 months reached 4,400 ind.$\cdot$m^{-1} and harvestable production was 10.9 kg$\cdot$m^{-1}of collector rope, respectively. The polypropylene line resisted storm conditions with wind waves of up to 6.4 m and current velocities of 1.52 m$\cdot$s^{-1} and was retrieved in autumn of 2002. In contrast, the steel hawser-based line did not withstand the harsh weather conditions. The steel-based line consisting of six twisted strands was untwisted by strong currents and turbulences, and consequently the individual strands were torn. Additionally, the line was accidentally cut by a yacht in July 2003. The biological study revealed that the tested location near "Roter Sand" has potential for offshore seed production as well as for grow-out of mussels to market size. In light of the technical results, recommendations for mussel culture using polypropylene longline system are given.

Experimental trials on the feasibility of offshore seed production of the mussel *Mytilus edulis* in the German Bight: Installation, technical requirements and environmental conditions

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Abstract

This study summarizes the activities and findings during a two year investigation on the grow-out of blue mussels (*Mytilus edulis*) and the technical requirements to withstand harsh weather conditions at an offshore location. The experimental sites were two different test areas, each 5 ha in size, 12-15 m in depth, in the vicinity of the offshore light house "Roter Sand" located 15-17 nautical miles northwest of the city of Bremerhaven (Germany). Two versions of submerged longline systems were deployed: a conventional polypropylene longline in 2002 as well as a steel hawser longline in 2003, both featuring different versions of buoyancy modes. The spat collectors and grow-out ropes were suspended perpendicular from the horizontal longline for several months beginning in March of each respective year. The test sites were visited and sampled on a monthly basis using research vessels. Larval abundances in the surrounding water column reached numbers of up to 1,467 individuals·m^{-3}. Post-larval settlement success varied through the entire experimental period, ranging from 29 to 796 individuals of spat per meter of collector. Settled mussels reached a shell length of up to 28 mm six months after settlement. Based on the growth rates observed for the seed, it is projected that mussels would reach market size (50 mm) in 12-15 months post settlement, and at the observed densities, each meter of collector rope could yield 10.9 kg of harvestable mussels. The polypropylene line resisted storm conditions with wind waves of up to 6.4 m and current velocities of 1.52 m·s^{-1} and was retrieved in autumn of 2002. In contrast, the steel hawser-based line did not withstand the harsh weather conditions. The steel-based line consisted of six twisted strands that were untwisted by the strong currents and turbulences and consequently the individual strands were torn. Additionally, the line was accidentally cut by a yacht in July 2003. The biological study revealed that the tested location near "Roter Sand" has the potential to become an offshore seed production site as well as being exploitable as a grow-out site for mussel production to market size. In light of the technical results, recommendations for mussel culture strategies using a polypropylene longline system are given.

Keywords: mussel farming, submerged longline, culture design, offshore aquaculture, larvae distribution, settlement

Introduction

Presently, a number of species of mussels are farmed globally, the most common of which is the blue mussel (FAO 2004). Following the data recorded by the FAO, China is now the largest producer of blue mussels where its culture technique depends on a high proportion of spat being produced from hatcheries. Other important producers of blue mussels are Spain, the Netherlands, France, and the United Kingdom followed by Ireland and Germany (FAO, 2004).

In Europe, blue mussel farming started early in the past century and was based mainly on the raft method. Other off-bottom culture techniques are pole (France), rack (also France and Tahiti) and longline (e.g. Ireland, Norway, New Zealand, China) systems (Hickman 1992). In Germany, the Netherlands and Denmark, mussels are cultivated using the on-bottom culture method (Seaman & Ruth 1997). Mussels are collected from natural beds and transferred to licensed culture plots, where environmental conditions are suitable for growth and fattening. However, the intertidal and subtidal bottom culture plots are subject to predation pressure, such as ducks (e.g. *Somateria mollissima* [Hamilton 1997, Hamilton 1999]), starfish (e.g. *Asterias rubens* [Kristensen and Lassen 1997, Reusch and Chapman 1997, Dolmer 1998]) or crabs (e.g. *Carcinus spp.* [Leonard et al. 1998]). Furthermore, this technique depends on the availability of seed mussels obtained from wild habitats in the Wadden Sea (Seaman and Ruth 1997). Additionally, due to the nature reserve status of almost 98 % of the German North Sea coast, the development and scale-up of the mussel aquaculture sector is limited. Culture plot sizes are decreasing in order to follow the mussel management plans of Schleswig-Holstein and Lower-Saxony (e.g. CWSS 2002, Buck 2002) with no new licenses being approved in the future.

In most places in Europe the development of mussel culture has taken place almost exclusively in protected nearshore waters and estuarine habitats. In Germany, sheltered locations are rare and because of stakeholder conflicts the development of coastal aquaculture is rather stagnant. However, it is widely believed that the commercialization of ocean mariculture in more exposed locations, in the open ocean, has tremendous future economic potential (Buck 2002, Ewaldsen 2003). In 1998, the University of New Hampshire initiated the Open Ocean Aquaculture Demonstration Project to investigate the commercial potential of environmental responsible seafood production, employment opportunities, engineering solutions and operational methodologies of offshore aquaculture (Bucklin & Howell 1998). As part of the project Langan & Horton (2003) deployed two 120 m submerged longlines for shellfish culture 10 km off the coast of Portsmouth (New Hamshire) in the south western Gulf of Maine, where the biological and commercial feasibility of *Mytilus edulis* cultivation were tested.

In the German North Sea, offshore cultivation of some candidates, such as the two seaweed species of *Laminaria digitata* and *L. saccharina*, showed promising results (Buck & Buchholz 2004; 2005). However, no attempts to use the open ocean in the North Sea for mussel aquaculture were established yet. Since 2000 a new industry enters the scene: the offshore wind farm operators in the German Bight. These new stakeholders are seen as a chance to combine renewable energy production with cultivation of organisms, thereby the idea for synergistic resource uses in form of offshore aquaculture was born. While the offshore wind farm areas are closed for commercial shipping and fishery, aquaculture constructions can be installed within these wind farms utilizing the same protective benefits (Krause et al. 2003). Additionally, the wind generators themselves represent infrastructure to which aquaculture constructions can be linked (Buck et al. 2006, Buck et al. 2004).

Offshore sites in the North Sea are exposed to high waves and strong currents, requiring engineering structures that can survive the largest wave formations at a site while at the same time supporting the growth of the cultured organisms, preventing detachment and subsequent loss. Numerous environmental conditions are important to the success of an offshore mussel aquaculture operation, such as phytoplankton biomass represented by chlorophyll content and the C/N-ratio, to obtain good growth rates, physico-chemical parameters within optimum range to prevent losses due to mortality, predation, and a reliable seasonal occurrence of abundant natural larvae and juvenile spat fall for settlement on collectors. Until today, there are no data available on an overall offshore design of constructions for mussel longline cultivation in the North Sea. In this case, the term "offshore" will be defined (1) being in an area fully exposed to all kinds of environmental conditions (Ryan 2005) and because of tremendous stakeholder conflicts (Dahle et al. 1991) in coastal areas (2) being at least 8 nautical miles off the coast (Buck 2004).

This is the first study in European territorial waters where a new longline-design was installed to resist an extremely high energy environment, to test system strength and to focus on site selection criteria. Further, the biological and technical feasibility of mussel spat collection at an offshore location adjacent to a planned offshore wind farm was investigated. To follow some important biological aspects in this study several parameters were routinely measured, such as the concentration of mussel larvae in the water column and the settlement success. Furthermore, a biological supporting programme was carried out to determine local conditions, such as chlorophyll concentrations and C/N-ratio to indicate food availability and quality, temperature and salinity to indicate conditions within the water body as well as some oceanographic data, such as current velocity and wave height to test system strength. The technical feasibility was tested by employing two promising versions of longline constructions. The techniques were designed to withstand harsh conditions while also supporting suitable operational requirements such as maintenance and retrieval techniques for mussels grown to market size. In addition, the system should be commercially feasible and operate a durable longline and mooring system.

Material & Methods

Location of the study sites and local environmental conditions

Two study sites (12-15 m in depth) were established in the vicinity of the offshore lighthouse "Roter Sand", which is located 17 nautical miles NW of the city of Bremerhaven (Germany). This marine area, commonly called "Nordergründe", was chosen because of the adjacent offshore wind farm, planned from the company "Energiekontor" (Fig. 1). Because of an option contract between the wind farm operator and the responsible Water and Shipping Agency (WSA) a permit at the same site could not be obtained. An approval in the vicinity of the planned wind farm site for the utilisation of the study sites was obtained in January 2002.

The wave climate, the current velocities and direction at the study sites were under continuous observation of the Federal Maritime and Hydrographic Agency (BSH) and the local Water and Shipping Agency (WSA), which deployed a wave-following buoy (Waverider, Datawell) and an acoustic doppler current meter (RCM 9, Aanderaa) and shared the data sets obtained during the study period.

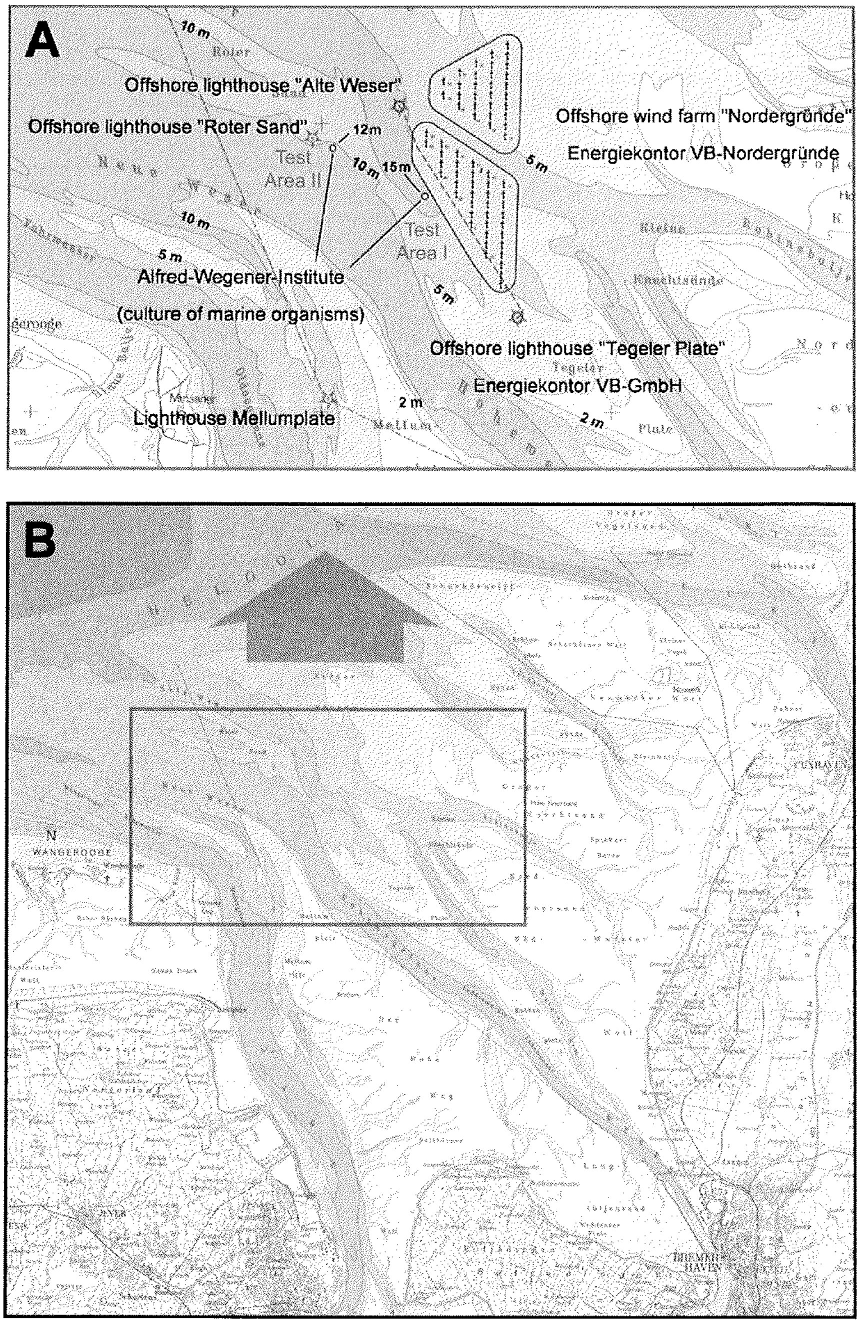

Fig. 1 Map of the southern German Bight. The enlarged red inset illustrates the test area No. I, "Nordergründe", and the test area No. II at the offshore lighthouse "Roter Sand". The wind mills indicate the planned offshore wind farm "Energiekontor".

Design and construction of the longline and mooring system

Longline shellfish culture involves a system of horizontal ropes anchored to the seafloor with buoys to provide flotation, to which vertical droppers are attached. The specific design of the system dimensions depends on site conditions. Here, longlines were used for both, spat collection as well as for the grow-out of juvenile mussels. Two different anchored longlines (Fig. 2) were installed in order to test their suitability under open sea conditions in terms of material and functionality: (1) a polypropylene- based design in 2002 and (2) a steel hawser-based design in 2003. In a first test the longline systems and their mooring devices were modelled and designed. A local cable and wire manufacturer supported the engineering development for the culture design. All components were selected and procured to start the preparation and assemblage of the longline during winter time.

Both culture systems were based on the same fundamental setup (Fig. 2). The longline operated in a submerged mode at a depth of about 5 m horizontally below the surface to avoid the destructive effects of surface waves. The longline had at both sides a 10 m "undisturbed end", which could not be retrieved when sampling or harvesting. Buoys were fixed along the longline in combination with suspended mussel spat collectors. The 3-stranded collectors (*Galician* type, 2.5 m long, Fig. 3a-b), equipped with horizontal inserted pegs to prevent attached mussels to be shaken off through current and wave forces, were suspended every 2 m perpendicular from the longline in a parallel manner. Each collector had a weight of approximately

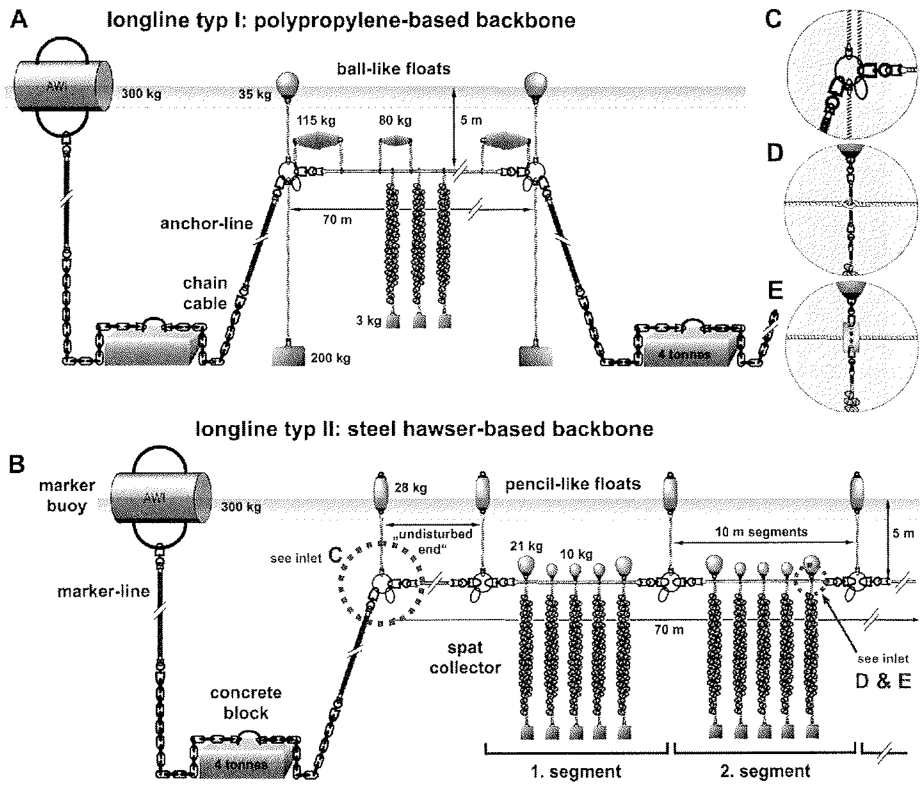

Fig. 2 Submerged longline system designs with spat collector harness: (a) polypropylene-based longline above (longline I) and (b) a steel hawser-based longline. The insets show the (c) coupling elements and (d-e) the connection of floats and collectors. (c) polypropylene and steel hawser, (d-e) steel hawser.

3 kg at the bottom end and was on the top end hooked into the longline by shackles. Tufts of unravelled polypropylene lines (Tortell 1976) were also connected to the longline (Fig. 3c) to determine the settlement of mussel post-larvae (Fig. 3d). The longline was secured at each end with an anchor consisting of a 4 t concrete block. A chain cable attached to the concrete block was connected to the anchor-line, which itself holds one end of the longline. Additionally, each concrete block was equipped with a marker-line and a marker buoy (300 kg). The marker line had a service load of several tonnes that it could be used to tauten the longline and to retrieve the concrete block at the end of the project. All mooring components were selected and sized for the use in muddy sea bottom and for long term durability. All longline segments had spliced eye loops with embedded galvanized thimbles at the ends and at all coupling elements shackles and swivels were used (Fig. 2a).

The 3-stranded polypropylene-based longline (ø = 32 mm) was made of two 35 m long segmental parts connected to each other. To keep the longline afloat each segment was equipped with one 80 kg buoyancy barrel in the centre and with 115 kg barrels at the coupling to the anchor-line. Further, a few 35 kg ball-like surface marker floats were fixed to a 5 m rope, which was connected to the longline. Three steel barrels filled with concrete (200 kg) tightened the longline to the sea bottom at the coupling to the anchor-line and in the centre.

The 3-stranded steel hawser-based longline (ø = 20 mm) had a similar set up as it was described for the polypropylene line, however, the longline consisted of more sections: seven 10 m long segments with each three 10 kg submersed floats in the centre and at each coupling elements 21 kg submersed floats. All floats were connected to a short wire element, which itself was spliced perpendicularly into the hawser and squeezed by one of the hawser's strands (Fig. 2b). An alternative attachment was the use of flat steel panels tightly fixed to the longline to which both, the floats and the collectors, were attached (Fig. 2c). Due to the weight of the steel wire the longline had more floaters than the polypropylene-based longline and no additional weights were attached to the longline. At all coupling elements pencil-like fenders (28 kg) were attached to mark the longline at the surface.

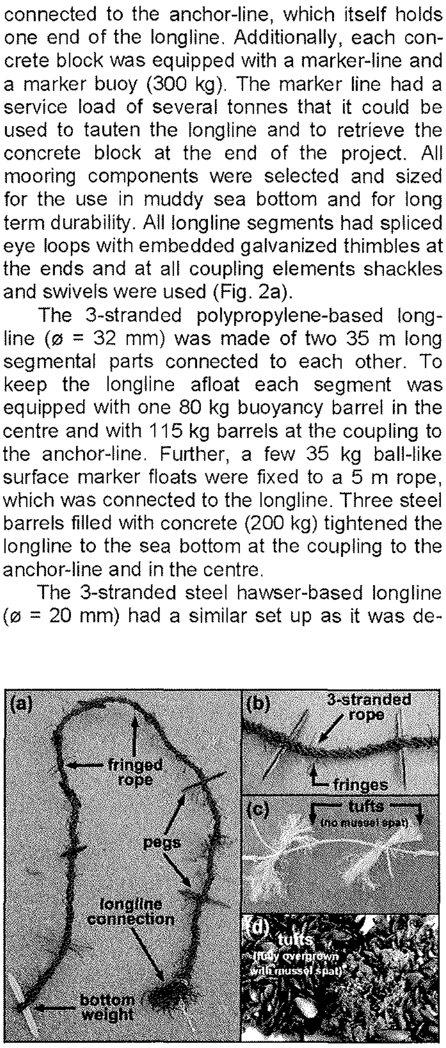

Fig. 3 Collector and tuft design for the settlement of *Mytilus* larvae. (a) shows a collector rope (Galician type) for the settlement and grow out of blue mussels, (b) shows an enlargement of the collector rope to display attached fringes which ease larval settlement, (c) presents a tuft for larval settlement and (d) demonstrates a tuft fully overgrown by juvenile blue mussels.

Deployment of the entire longline system and maintenance

The Water and Shipping Agency (WSA; Bremerhaven) provided assistance to deploy the moorings and to install the entire longline by using the buoy tender *Bruno Illing*. Both longlines were deployed in March, the polypropylene-based line in test area I (2002) and the steel hawser-based longline in test area II (2003) (Fig. 1). Marker buoys were deployed to establish the corners of both chartered test areas in order to mark and protect the site for navigation purposes. In test area II marker buoys were lighted. In the area of Nordergründe the main current direction is bidirectional from NW to SE depending on tides. To avoid high drag forces on the longline we decided to deploy the entire longline parallel to the flow.

The polypropylene longlines were installed when the concrete blocks with the chain cable and the anchor-line had already been deployed at sea. The anchor-line had already been connected to the 115 l barrel to keep it afloat. Afterwards, each part of the two 35 m longlines, which were fully equipped with collectors and floats, were deployed at sea and connected to the anchor-lines and to each other in the centre.

The steel hawser-based longline was fully equipped with floats and collectors ahead of time and prepared on board of the servicing vessel *Bruno Illing*. One end of the longline had already been fixed to the chain cable of one mooring. While lowering the first concrete block to the sea bottom the longline was carefully paid out until the second concrete block was deployed. Later, the longline was tightened by pulling the concrete block with the marker-line until all longline-floats were submersed.

From March to November 2002 and March to July 2003, monthly cruises were made to the study site for servicing purposes and data collection. Upon inspection and at harvest time the upper portion of the longline was raised to sea level. Fouling (except mussels) on the collector ropes and other deployed parts of the longline was not removed in order to follow how fouling develops and to determine how increasing weight impacts the total load on the longline. As the grow-out of mussels increases the suspended weight buoyancy was calculated and flotation was added do prevent the longline from sagging.

Biological supporting programme

Post-larval settlement was observed by individually retrieving collectors and tufts to take mussel samples. In the lab, numbers of settled post-larvae of *Mytilus edulis* were counted and measured in size under a stereomicroscope and transformed into mussel abundance per cm of rope.

Temperature and salinity profiles were taken using a CTD sensor (OTS 124, ME Kiel). Data describing chlorophyll contents and nutrient concentrations (nitrite, nitrate, ammonium, phosphate) of the surrounding water column were used from data provided by the BSH (2002/2003), the NLÖ (2003) and using the findings of Buck and Buchholz (2004). The nutrient concentrations were additionally used to describe the local conditions for phytoplankton growth in terms of site selection criteria.

On each cruise, seawater samples (3 replicates) were taken in a depth of 2-5 m to determine C/N-ratio and larval concentrations. 5 l of seawater were pumped for particulate organic carbon (POC) and particulate organic nitrogen (PON) analysis and were stored deep frozen and analyzed in the laboratory. C/N analysis was modified after the methodology described by von Bodungen et al. (1991). Samples were filtered over precombusted (450 °C, overnight) glass fibre filters (Whatman GF/C®), washed with 2 ml distilled water and dried at 65 °C. After weight determination the samples were acidified with 1M HCl to remove inorganic carbonates and redried. C/N was then determined by high temperature combustion (Nitrogen Analyser 1500, Carlo Erba Strumentazione). Acetanilide was used as calibration standard. To assess the abundance of mussel larvae prior to settlement, 50 l of seawater were pumped from 5 m below water surface. Water samples were then filtered through a metal plankton net (mesh size: 125 µm) and fixed in buffered formaldehyde (4 %) for later analysis. In the laboratory, larval samples were transferred to a grid chamber and larval concentration counted using a stereomicroscope.

Statistical analysis of data

Means and standard deviations (mean ± SD) of data on current velocities, wave heights, salinity, particulate organic carbon, particulate organic nitrogen, chlorophyll, larvae numbers, shell length and settlement success were calculated and some are presented in graphs as appropriate using Microsoft Office Excel 2003 software; these are shown in bars.

Results

Environmental conditions

Current velocities measured at "Nordergründe" ranged from 0 to 1.52 $m \cdot s^{-1}$ (n = 5188) showing a pronounced diurnal tidal variation (Fig. 4a). The current direction showed a bidirectional flow from NW to SE (314° ↔ 114°, y = -1.0497x + 4.5078) (Fig. 4b). The mean significant wave height during a 280 day measurement campaign in 2002 was recorded at 1.49 m ± 1.01 (n = 2259) with a maximum wave height of about 6.46 m (Fig. 4c). Temperature data varied throughout the year from 1.8 to 22.4 °C as well as through tidal effects by 2.4 °C (Fig. 4d, 1). Likewise, salinity was affected by the tidal regime and ranged from 26.7 to 31.1 ppt (Fig. 4d).

Particulate organic carbon concentrations ranged from 198.53 ± 17.6 $\mu g \cdot l^{-1}$ (July) to 515.58 ± 176.5 $\mu g \cdot l^{-1}$ (Jan./Feb.) and 549.85 ± 385.8

Tab. 1 Data of environmental conditions at the offshore test locations in 2002

Months	Nutrients [µmol/l]			Temperature [°C]	POC [µg/l]	PON [µg/l]	Chl. [µg/l]
	Ammonium	Nitrate	Phosphate				
Dec.-Feb.	0.3 - 4.4	1.1 - 13.4	0.1 - 0.4	1.8 - 5.0	35.2 - 84.3	543.3 - 669.7	3.3 - 3.7
Mar.-May	1.8 - 5.9	6.1 - 55.4	0.2 - 0.9	6.1 - 11.3	48.2 - 84.1	335.7 - 549.8	4.5 - 33.6
Jun.-Aug.	0.9 - 6.5	0.2 - 49.3	1.3 - 1.7	14.1 - 18.8	29.4 - 34.3	174.7 - 217.1	4.9 - 16.4
Sep.-Nov.	0.3 - 6.6	0.9 - 10.2	0.1 - 0.5	18.2 - 2.1	50.1 - 65.4	327.1 - 450.6	3.9 - 5.3

$\mu g \cdot l^{-1}$ (April). Particulate organic nitrogen ranged from 31.86 ± 2.6 $\mu g \cdot l^{-1}$ (July) to 66.69 ± 21.6 $\mu g \cdot l^{-1}$ (Jan./Feb.) and 84.1 ± 48.7 $\mu g \cdot l^{-1}$ (April) (Tab. 1), respectively. This resulted in a POC/PON ratio ranging from 6.2-7.7 throughout both years. Highest concentrations occurred in spring/early summer, reflecting the spring phytoplankton bloom which is typical in this area (Walter et al. submitted). Total chlorophyll concentrations varied throughout the entire project period being lowest in January/February 3.45 ± 0.18 $\mu g \cdot l^{-1}$ and September 4.63 ± 0.65 $\mu g \cdot l^{-1}$ and highest in April 33.61 ± 1.56 $\mu g \cdot l^{-1}$ (Tab. 1).

Concentrations of nutrients (ammonium, nitrate, and phosphate) analysed by the BSH and the NLÖ and according to Buck and Buchholz (2004) varied over an annual cycle as shown in Table 1. From these data it can be concluded that nitrogen and phosphate concentrations in the surrounding water were not limiting at any time of the test period, thus providing sufficient nutrients to allow phytoplankton growth.

Larval concentration and spat settlement

In April 2003, 25 ± 5 mussel larvae per m^3 ($ind. \cdot m^{-3}$, n = 3) were recorded in the water column at "Nordergründe". Highest larval densities were determined in May with 1,467 ± 455 $ind. \cdot m^{-3}$ (n = 3), while a following gradual decrease in larval abundance attained 267 ± 110 $ind. \cdot m^{-3}$ (n = 3) in early September.

Wild mussel spat was found to settle abundantly in dense colonies on collector ropes, which appeared to compete successfully for space and food against fouling organisms over time. At the end of July, significant mussel growth was observed during site visits, but these mussels were too small for consumption.

During the last site visit in September 2002, the crew on board the RV *Uthörn* stripped a vast quantity of mussels from several collectors. Upon rising of the submerged longline to a position above sea level alongside of the RV *Uthörn* in September 2002 an amazingly large growth of

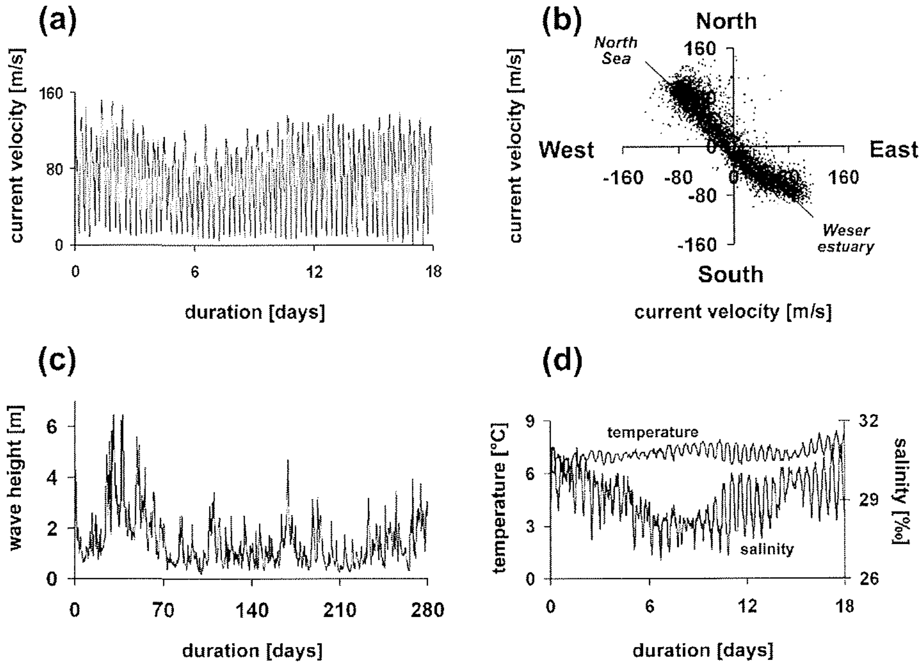

Fig. 4 Environmental conditions near the test location "Nordergründe" over a duration of 18 days in April (a, b and d) and 280 days (c). (a) shows the local current velocity influences by the tide, (b) shows the current velocity as a function of direction and tide, (c) demonstrates wave height and (d) displays the temperature and salinity regime influenced by the tides.

self seeded mussels was discovered. The 32 mm diameter longline had grown to up to 15-20 cm in diameter with marine growth during its six months submerged exposure at the offshore farm site "Nordergründe". Growth patterns along the line varied in mussel density, but the frequently large accumulations of mussels were always associated with abundant colonies of fouling organisms. The density of mussels on the grow-out lines ranged between 55 ± 17 (March) to 700 ± 197 (May) ind.$\cdot$m^{-1} line length during the first year of spat collection (mean 397 ± 374 ind.$\cdot$m^{-1}) and ranged between 29 ± 20 (July) to 796 ± 400 (May) ind.$\cdot$m^{-1} in the second year. That yielded to an average of nearly 10.9 kg of mussels per meter collector rope. Mussel spat was 28 ± 9.2 mm in size within six months of growth. These results indicate that a single longline of a dimension similar to that used for this project can yield up to 700 to 1000 kg of mussel seed in a six months grow-out period and would last 12-15 months to bring those mussels to market size.

Longline design

Problems encountered during the project include material failure, heavy fouling on the collector lines and other infrastructural units resulting in large ballast weights, while heavy predation on mussel seed by sea stars was also encountered. Another difficulty was maintaining proper headline depth as the mussels grow and add weight to the line.

On the engineering side the field experience with the deployment and servicing of units has been invaluable. Specific assets and drawbacks in both longline constructions were found, and this holds true for both, the polypropylene-based longline as well as the steel-hawser-based longline. Most problems emerged by lifting of the longlines manually as well as by the cranes of the vessels. While all segments from the steel wire line had steel rings (mostly chain links) at all coupling elements to ease the hook up of the line, the saving of the polypropylene line often failed. The segmentation also allows the replacement of spare parts. Unfortunately, the transverse wires, which hold the floaters above and the collectors below, were quickly weakened and frequently broke because they were permanently being bended through the tidal currents. These stress forces affect the lifetime greatly. The polypropylene line was resistant to the high energy environment of the North Sea, but chafed within the inner parts of the eye loops and therefore some of the thimbles were lost.

The weight of the suspended collector harness increased significantly with time, and extra floatation had to be added to support the buoyancy of the longline. However, the time intervals chosen for service were too long (particularly during the summer growing season) so that parts of the collector harness including the floats submersed fully and touched the seafloor. Additionally, (in both constructions) loss of buoyancy resulted in a lowering of the total construction.

There is another lesson to be learned. Despite operating in an officially closed area encounters with sea traffic is not out of option. Unfortunately, a private yacht ignored the navigation marks and entered the test area in July 2003. With the attempt to cross the test area, the boat got entangled in the longline and some of the buoyancy ropes, which resulted in cliping the longline. An immediate retrieval of the entire longline to save samples and parts of the construction was not possible due to harsh weather conditions. Some days later only a fully destroyed longline could be heaved from the sea bottom. Due to the tidal currents the collector harness touched the sea bottom and chafed of the sediment, which resulted in the loss of all settled mussels.

When the longline was retrieved the concrete blocks were broken easily out of the clay at the site and raised by the anchor chain. On all mooring components heavy mussel growth was found. More mussels were recorded on the undisturbed ends of the longline at each side.

Most of the mooring system, in particular the longline and its harness, was later inspected onshore. On a few spots near the eye loops some slight damage of the material was found, but most of the line, after removing the fouling, looked intact and almost new.

Discussion

Mussel larvae numbers and post-larval settlement

At "Nordergründe" the cultivation of blue mussels can only be successful following a regular and reliable supply of *Mytilus* larvae originating from

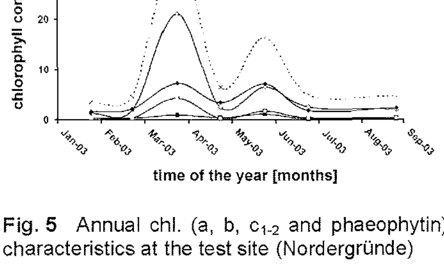

Fig. 5 Annual chl. (a, b, $c_{1\text{-}2}$ and phaeophytin) characteristics at the test site (Nordergründe)

local spat fall. These two characteristics are the basis of every mussel culture enterprise and have been investigated even in countries, where mussel farming today is not yet established (Ekaratne 1987, Menzel 1991). In terms of mussel farming in Germany, mussel settlement has been found to be quite variable from year to year and from site to site (e.g. Walter and Liebezeit 2001, Ewaldsen 2003). Generally, however, late spring and early summer (Pulfrich 1997) is deemed to be the best time to collect spat on the pegged downropes used for on-growing (Walter and Liebezeit 2001,). In addition, these scientists found out that even in years with a low spat fall determined on bottom culture plots mussel larvae are in vast quantities in the water column and are able to settle on suspended substrates.

Due to the anti-clockwise tidal currents in the North Sea (Becker et al. 1992, Ducrotoy et al. 2000) the settled post-larvae may originate from inshore mussel beds along the Lower-Saxonian coast and, in some cases, from the intertidal areas from the Dutch Wadden Sea. Data of larvae numbers determined in the water are equivalent to those reported by Dobretsov and Miron (2001) for the White Sea and Cáceres-Martínez and Figueras (1998) for NW Spain being $\approx 1.3 \cdot 10^3 \cdot m^{-3}$ and $1.2 \cdot 10^3 \cdot m^{-3}$, respectively. Due to a dilution effect long drifts to offshore sites result in declining densities of mussel larvae in the water column (Young et al. 1998, Metaxas 2001, Buck 2004, Bos et al. 2006). While nearshore distribution and larval numbers within the water column are well known in the North Sea (e.g. Walter & Liebezeit 2001), only a few data are as yet available in offshore areas and are fragmentary (Buck 2004, Walter et al. 2006). However, if suitable substrates are available pediveligers settle and grow, while recruitment success and growth rates depend on environmental conditions.

The larval peak at "Nordergründe" timely coincides with highest larval concentrations found by Heiber (1988), Pulfrich (1995), Pulfrich (1997), de Vooys (1999), and Walter and Liebezeit (2001). However, the peak varies within the White Sea, NW Spain and the test location. While in the White Sea larval concentrations are highest in early August and in Spain between March and April the findings in this study show the most larval numbers in May. The reason for the differing regional spat falls may result from the water temperature reaching 12-14°C in March/April in Spain and at the same level first in May at "Nordergründe". In the White Sea, 12°C is first reached in August, which explains the late spat fall in Russia. The temperature peaks and the therefore resulting high concentration of *Mytilus* larvae are due to latitudinally differences. In southern regions the reproductive cycle starts earlier in the year due to increasing water temperature than conspecifics further north (Gabbott 1975). That explains the late spat fall in Norway in July-September (Lande 1973).

It is also reported that food supply determines the reproductive cycle of *Mytilus edulis* (Kautsky 1982, Seed & Suchanek 1992). As a value to measure food supply the concentration of chlorophyll in the water column as well as the POC/PON ratio was used. Here, the findings support this suggestion showing chlorophyll concentrations being highest in April/May and POC/PON ratios being around 6.8 and reflecting a "healthy planktonic organism community" (Kraul 1994). Additionally, nutrients were at no time a limiting factor to sustain microalgal growth.

Settlement of mussel spat on tufts reached ≈ 700-800 ind.$\cdot m^{-1}$ of the Galician type collector rope. Unfortunately, there are no data from offshore sites to compare these data with. Results from inshore sites at the Jade estuary at the German coast were determined by Walter and Liebezeit (2001) ranging between 10,000-70,000 ind.$\cdot m^{-1}$ rope. This location has numerous natural mussel beds and culture plots in its vicinity which explains the vast quantity of mussel spat per meter of rope. Nevertheless, the settlement data coincide with spat numbers used for re-seeding after thinning out of spat collectors for the grow-out phase in offshore cultures (Langan 2001). Finally, if the natural settlement of ≈ 800 ind.$\cdot m^{-1}$ at the longline site proves to be a reliable annual event, it can be suggested to eliminate the costly step of thinning and re-seeding the mussel spat. The growth rate determined at "Nordergründe" was approximately 5 mm per month, which denotes that grow-out from settlement to ≈ 30 mm can be achieved in 6 months. To cultivate mussels to market size (< 5 cm according to the Hagena [pers. comm.], including a decline in growth rate during winter time), a growth period of at least 12 months can be calculated. Thus, a full production cycle from spat settlement to market size can be reached within 12 to 15 months.

Mytilus larvae in the water column and post-larvae settling on collectors were recorded. Ideally, grow-out locations for post-larvae are situated away from heavy spat settlement areas to avoid layers of spat attaching to larger mussels. At the location "Nordergründe" the spat fall is low compared to findings of Walter & Liebezeit (2001), thus, preventing heavy overgrowth of free living post-larvae on newly suspended ropes with grow-out mussels.

Environmental factors

Temperature: While increasing growth of mussels ranges between 3 and 20°C, a reduced growth above 20°C and below 3°C was examined by Almade-Villela et al. (1982). They further determined that *Mytilus edulis* is well-adapted to constantly changing environmental conditions, which is the case at "Nordergründe" in the Weser estuary, where temperature ranges annually from 1.8 to 22.4°C and tidally about 2.4°C. The relatively warm waters at "Nordergründe", partly originating from the river Weser estuary and diluted with offshore waters (Fig. 4b), provide long term mussel growing conditions and may enable aquaculturists to collect mussel spat as well as to grow mussels out to a marketable size within short time.

Salinity: When salinity falls below or above a certain value (15 ppt / 50 ppt, Wilson & Seed 1974) for prolonged periods filtration rates decrease (Widdows & Donkin 1992, Gosling 2003). In worst cases, high mortalities within the cultivated mussels may occur (Almada-Villela 1984, Gruffydd et al. 1984). Decrease in salinity levels is usually the major and frequent problem, mainly caused by the influx of large volumes of fresh water from the river Weser or land runoff during the rainy season. Blue mussels may survive reduced salinity up to 4-5 ppt for a short time, however, those concentrations limit the mussel's growth rate and could lead to high mortalities (Kautsky et al. 1990). Such a drop in salinity will not occur in the Weser estuary at the location "Nordergründe", which range from 26.7 to 31.1 ppt.

Maintenance, sampling and harvest

The vessel used during this project, mainly the *RV Uthörn*, is too large to manoeuvre within the test area or to handle the longline system. Additionally, no special equipment normally used to lift longlines, to harvest mussels or to inspect the entire system were available. Thus, inflatable boats were used for maintenance works and sampling procedures. The longline, however, had to be lifted by hand to sample the collectors. The handling of the gear and the use of the smaller boats even at waves of "only" 2 m in height or within the short period during slack time made the offshore work difficult, even in some cases, weather conditions made the servicing and sampling procedure impossible.

The presence of fouling organisms is undesirable because they compete for food and space and critically increase the weight of each hanging unit. Generally, there is a need to remove these organisms (Bussani 1983). This laborious process, however, is not required in this particular site, as the increasing density of mussels over time take over space and force fouling organisms to detach or kill them by overgrowth. Further, total biomass of fouling can be reduced by deploying the longline and the collectors in early May prior to larval settlement to prevent the settlement of other organisms drifting in the water column in March to early May.

At "Nordergründe" the natural time from settlement to a size of 28 mm was measured to be approximately 6 months. At this time, one has to decide to grow mussels to market size or to supply the on-bottom culturists with spat. Only the latter technique requires a change of the set up. As already described above, it can be suggested to avoid this laborious procedure and follow an extensive way of mussel cultivation by leaving the settled mussels on the ropes until they reach market size. To follow the second possibility the culture season ends with seed harvest and mussels are planted on bottom culture plots in inshore areas. In this study, the mussels were harvested once when retrieving the entire longline and did not follow a grow-out period to determine, if suspended mussels do have thinner shells, which can lead to a shell damages.

The longline design: polypropylene versus steel hawser

The longline system design is probably the method that has been mostly used world-wide, especially for *Mytilus* cultivation (Polk 1996, Hesley 1997, Stickney 1998, Bridger & Costa-Pierce 2003). Similar to mussel rafts, the longline has been frequently modified over the course of time. In contrast to rafts operating in a floating mode on the water surface (Hickman 1992), making themselves unsuitable for high energy offshore environments, longlines can be deployed in a submerged mode at various depths to avoid some of these forces at near surface levels (Danioux et al. 1997). Such a flexible system was chosen for the German Bight and moored at the offshore lighthouse "Roter Sand" for long-term monitoring and testing.

These two longline systems were deployed in order to determine if offshore mussel growth at the location "Nordergründe" was feasible at a rate that it might become a form of offshore shellfish aquaculture. In comparison to other culture constructions, the longline system was chosen due to the easy deployment and the cheaper investment costs in comparison to other culture systems (Gosling 2003). Longlines can withstand relatively strong wind and wave action due to the flexibility of the system itself (Lovatelli 1988) and can resist harsh winters (Gosling 2003). Furthermore, growth rates of mussels are reported to be better using longline systems (Chaitanawisuti & Menasveta 1987, Hickman 1992). The only study where growth of mussels were investigated at three different culture designs, the pole, the on-bottom and the longline method, the longline cultivated mussels demonstrated the best growth rates (Garen et al. 2004).

This can be explained by the fact that longline mussels are fully suspended in the water and do only have a little hard substrate in the collector's centre and are therefore flushed by phytoplankton-rich seawater at all time.

Both, the polypropylene as well as the steel hawser longline, showed advantages while at the same time disadvantages. Maintenance work at both lines was complicated due to the submersed mode. Here, the polypropylene line with its surface floats eased the retrieving of the longline by lifting the floatation ropes to reach the harness. A lack of specific equipment, as it was described above, caused these problems and not the submerged design of the longline. On the contrary, the use of ball-like floats at the polypropylene line caused an increase in drag force, friction and tension on the entire system. Elongated fenders would protect the construction by better riding the swell to result in vertical movements, while the ball floats had resulted in jerking behaviour that created substantially more stress on all the materials and could further result in a loss of mussels by shaking them loose. However, it is necessary to reduce surface floatation as much as possible. Floats used in the submerged mode (steel hawser line) did not affect the longline greatly. But floats, which are attached to submerged parts of the longline should have in-compressible mantle, thus, no additional pressure due to water depth can limit the buoyancy.

Due to heavy weather conditions accomplished with strong currents and high wave action both systems were partly damaged. Tangling of the growing lines occurred and mussels were shaken off at times, when the longline was not submerged. While strands in the eye loops despite the inserted thimbles untwisted by the current and turbulences the longline could be retrieved easily. The segmentation of the steel hawser line showed advantages in the construction period and favoured the change of segments at sea stage. Unfortunately, the spliced wires with loops, to hold the collector on the bottom end and its buoyancy on the top end did not withstand the current. All wires were untwisted or broken and parts of the harness, such as collectors and floaters, lost. The replacement of the wires by metal plates resisted the current and wave actions and protected the harness from damage or loss.

Finally, we suggest eliminating the use of wire which can result in chafing of polypropylene lines and will not be able to resist permanent movement due to currents and waves. Connection materials such as shackles, thimbles and swivels bring a lot of weight which have to be absorbed by adding more floatation, increase investment costs and could also cause chafing of lines and collectors.

Site selection: Nordergründe

Depth and aerial exposure: Water depth is not usually a limiting factor in mussel culture, however, it will determine what culture method can be used and depth ranges between 1-15 m, at some instances up to 50 m depth (Loste 2001, Langan pers. comm) have been commonly reported as being useful. In areas where the mean tide level is usually less than 1.5 m, on-bottom culture on the seafloor or on other materials (racks, bamboo sticks) can be practiced. Probably the most important aspect with regard to water depth in tidal seas is to avoid long exposure periods to air during the extreme low water spring tides. Long exposure periods increase the culture period mainly due to the fact that during these periods the molluscs stop feeding and growth declines with aerial exposure duration (Yamada 1989) while also being exposed to rapid temperature changes (particularly during sunny days). For suspended culture methods, such as the deployed longlines, mussels feed continuously and therefore grow rapidly (Seed 1968). Water depth can be a limiting factor in tidal seas as usually a minimum water column height is essential during the low water spring tides due to variations in food availability within the water column (Rodhouse et al. 1984, Page and Hubbard 1987). At the site Nordergründe, we suggest to submerge the longline at least 6-7 m to avoid the energy forces from waves. Sites with a depth of > 20 m would have a lesser impact on the longline system and would further allow longer collectors to guarantee economic return. Furthermore, the hanging harness should never touch the bottom mainly to prevent predators such as crabs and sea stars from reaching the bivalves, avoid exposing the mussels to high water turbidity near the seabed, and also avoid losing the mussels at the lower end of the collectors as a result of their friction with the ground. Therefore, a longline system was designed, which fits exactly to the location and its physical demands. The location "Nordergründe", where the longline design used in this study was deployed has a water depth at low tide of about 12 m. The collector harness suspended along the submerged longline in a depth of 5 m below the surface has a length of 2-3 m. Therefore the culture ropes are at all sea stages above the sea floor (at least 4 m) also during extreme low water spring tides or at harsh weather conditions with wind waves of up to 6 m.

Food availability: The annual chlorophyll concentrations indicate a distinct early phytoplankton spring bloom followed by lower summer values. There was a sufficient chlorophyll concentration in the surrounding water to sustain mussel growth (Sara et al. 1998). The determined seasonal availability of inorganic nutrients as an indicator for phytoplankton growth conditions became at no time limiting. The data are, even though at present not effectual for site selection criteria, sufficiently indicative to be used for correlations between phytoplankton density and composition, survival and settlement of larvae and growth of mussels.

Currents and waves: In the Wadden Sea current velocities of up to 1.5 $m \cdot s^{-1}$ usually generate high turbidity and high siltation rates (Ehlers 1988, Brown et al. 1989). The presence of suspended materials above a certain level hinders the filtering activity of bivalves which often remain closed to avoid tissue damage and becoming clogged (Gosling 2003). Furthermore, finely suspended matter such as clay, sand, and other organic and inorganic particulate materials at the culture site is usually undesirable as it causes ill effects on the bivalves being cultured and often resulting in high mortalities (Lovatelli 1988). The collector harness of the deployed longline construction has enough clearance from the sea bottom to avoid sand uptake by the mussels and no further mussel cleaning from incorporated sand is necessary. Additionally, Secci-Depth readings showed a low turbidity load within the test area (Buck, unpublished data) with values ranging from 3-8 m in summer time. Tiensongrusmee et al. (1986) have shown that water containing a high suspended particle load of more than 400 $mg \cdot l^{-1}$ have a lethal effect on the grow-out of mussels, thus sites having a disc reading less than 15 cm are usually considered unsuitable for bivalve culture.

However, moderate currents are needed to provide adequate transport of water masses carrying the food supply in form of phytoplankton. Slow water movement usually results in slow growth of the bivalves due to the poor replenishment of the food (Wildish and Kristmanson 1984, 1985; Jenkins 1985; Hickman 1989), however, mussels cultured within a high energy environment are not food-limited particularly in waters of high primary productivity (Klepper and van de Kamer, 1988). Slow currents also promote the settling of organic and inorganic particulate materials on the cultured organisms (Lovatelli 1988). Indeed, clearance rates also decrease when current velocity exceeds a certain value due to the pressure differential between the inhalant and exhalent siphon (Gosling 2003). Potential sites for longline culture should have a current speed within the range of 0.02–1.5 $m \cdot s^{-1}$ (Rosenberg and Loo 1983, Hickman et al. 1991). At "Nordergründe", measurements of current velocities at a depth of 4, 6 and 8 m depth were 0.53 ± 0.25, 0.49 ± 0.23 and 0.44 ± 0.21 $m \cdot s^{-1}$, respectively, (WSA 2002) to insure a minimum particle flow.

Exposure to high wave action normally disqualifies a potential cultivation site due to the loss of mussels through passive detachment (Scarratt 1993). Although, waves of up to 6.4 m in height were determined, the choice of floatation and the depth of the suspended collector harness may offset the effect of extreme wave forces as it is the case for the dense living mussel spat at the deployed submerged longline system at "Nordergründe". Mortalities of mussels may occur if they are exposed to extreme wave action while at the same time food limited (Gosling 2003). The suspended cultivation method and the determined chlorophyll concentration as well as the POC/PON values eliminate these effects.

Pollution: Pollution of inshore areas and estuaries has been one of the most delicate subject for coastal countries in the past few years and has been a problem for decades in areas where mussel or oyster farming has been traditionally practiced (e.g. The Netherlands, Spain and France). The location of and the distances to the pollution sources relative to the selected offshore farm site should be carefully considered, particularly with regard to ongoing urban sewage release or diffuse coastal inputs from intensive agricultural activities. The coastal current patterns responsible for long-distance transport of potential pollutants should be carefully considered. Fortunately, the River Weser estuary and the adjacent offshore location at "Nordergründe" are monitored by the *Bund Länder Messprogramm* and various other local authorities, providing sufficient safeguard. Furthermore, mussels originating from wild habitats and culture plots are monitored routinely and are screened for toxins by local authorities (Zander, pers. comm.). There seems to be no need for further expansion of such costly monitoring activities for this location.

Conclusion

Site selection for an offshore aquaculture system is a process by which a number of factors need to be carefully analysed prior to the planning and technical installation thereby minimizing the risk of inappropriate investment. Despite the technical difficulties mentioned above, there seems to be suitable settlement densities and sufficiently fast growth at the test sites to employ a culture strategy for a complete growth cycle (from settlement to market size). It also seems to be fair to say that the data indicate a potential for mussel production in the offshore waters of the German Bight limited mainly by available space. The resulting knowledge of the project for design engineering and understanding operational logistics and management requirements is considered to be vital for the potential commercial development of a viable mussel offshore aquaculture industry.

The submersed deployment of a longline as harness for suspended mussel culturing eliminates the worst effects of surface waves and makes the system components robust and sustainable for a long time use. It is anticipated that material failures can be minimized by using polypropylene-based systems instead of stiff and inflexible wire-based systems or submerged elongated fender type installations. However, several serious scientific questions (e.g. long term health status, fitness, spat fall), technological problems (e.g. connection to offshore constructions such as wind generators), and economic (e.g. economic returns, investment costs) as well as policy issues remain to be clarified or resolved before the potential of this form of aquaculture can be realized.

Outlook

The excellent growth rates of mussels during the present study led to the suggestion to build and install a number of longlines parallel to each other to prove the principal. This is considered to be an opportunity to conduct offshore mussel culture for a commercial enterprise by various ways: (1) to collect mussel spat to supply the on-bottom culturists in the tidal flats within the backwaters of the Frisian Island because of seed mussel shortages frequently occurring in subsequent years, (2) to collect the mussel spat and grow it to market size offshore, or (3) to use spat from inshore areas and use the offshore site as a grow-out location. For these purposes it is necessary to ascertain the consistency of seed settlement rates at a potential farm location. Also, while allowing settled seed to grow to market size on collector lines and therefore eliminating stripping and re-seeding to growing ropes, sizes could be inconsistent and yield of market mussels could be reduced and need to be verified.

Offshore cultivation of marine organisms is at the brink of becoming a new aquaculture production sector. Therefore, the development of a commercially viable offshore aquaculture operation on a pilot-scale basis seems to be a feasible undertaking once the testing is completed to reduce risks in all relevant technical and biological areas under concern. More specifically, future project activities should include R&D elements targeted at reducing operational risks through a coordinated, interdisciplinary effort involving engineering research on offshore structures, analysis of scientific criteria concerning biological productivity, and studies on project economics. Finally, tests to assess the suitability (or comparability) of the resulting product at existing or new markets, while there is still a need to clarify the regulatory and licensing issues associated with offshore activities.

Although not harmful to the mussels themselves, growing areas may occasionally suffer from outbreaks of harmful toxic algae which the mussels consume, rendering them unsuitable for human consumption. An algae-early-warning system, which already exists for overall monitoring purposes but too wide-spread to serve the small-scale requirements of such a localized offshore industry should be expanded to areas used for offshore mussel culture.

In the past, because of the limited extent of areas used for aquaculture, such natural environmental events (e.g. algal blooms) have been dismissed as inconsequential. However, the proposed massive increase in areas to be used for mussel cultivation changes the scale of any impact and prompts concern. In particular, the construction of large (2000–4000 ha) mussel farms up to 7 km offshore will extend mussel cultivation into areas used by offshore species (petrels, shearwaters, seals and whales) that have not previously encountered mussel farms. The potential interactions with these species (e.g. disease transfer) will have to be tested.

Finally, once an offshore wind-farm is installed mussel culture constructions should be tested in a connected manner with the pylon of a wind farm. In this special case, it is of great importance that expensive offshore techniques, such as offshore windmills and offshore culture systems, do not develop independently.

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Appendix VIII

Publication VIII

Response of offshore cultivated* Laminaria saccharina *to hydrodynamic forcing in the North Sea

Buck BH, Buchholz CM (2005). Aquaculture 250: 674-691

1 2 3 4 5 6 7 **8** 9 10 11 12

Abstract

The aim of the presented investigation was to test the sensibility of macroalgal aquaculture in offshore wind farms in the North Sea and to find arguments for the choice of appropriate sites among the planned wind farms. Based on experience with an offshore aquaculture of *Laminaria saccharina* conducted in 2002, we assessed the maximum hydrodynamic forces affecting farmed algae by applying the model software "WaveLoad". Drag measured in a towing tank was considerably higher on algae with a more ruffled margin and wider blade collected from sheltered environments than on flat and narrow farmed *Laminaria* despite comparable blade areas. Drag varied according to frond size, current velocity and acceleration reaction. Dislodgement of laminarian holdfasts and the forces necessary to break the stipe depended on blade length and surface area. Neither did our measured nor our calculated values of drag exceed those forces provided the algae had been grown in a current >1 $m \cdot s^{-1}$. Even in storm conditions with maximum current velocities of 1.52 $m \cdot s^{-1}$ and wave heights of up to 6.4 m can cultivated *L. saccharina* withstand the high energy environment.

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Response of offshore cultivated *Laminaria saccharina* to hydrodynamic forcing in the North Sea

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Abstract

The aim of the presented investigation was to test the sensibility of macroalgal aquaculture in offshore wind farms in the North Sea and to find arguments for the choice of appropriate sites among the planned wind farms. Based on experience with an offshore aquaculture farm of *Laminaria saccharina* conducted in 2002, we assessed the maximum hydrodynamic forces affecting farmed algae by applying the model software "WaveLoad". Drag measured in a towing tank was considerably higher on algae with a more ruffled margin and wider blade collected from sheltered environments than on flat and narrow farmed *Laminaria* despite comparable blade areas. Drag varied according to frond size, current velocity and acceleration reaction. Dislodgement of laminarian holdfasts and the forces necessary to break the stipe depended on blade length and surface area. Neither did our measured nor our calculated values of drag exceed those forces, provided the algae had been grown in a current >1 m s^{-1}. Even in storm conditions with maximum current velocities of 1.52 m s^{-1} and wave heights of up to 6.4 m can cultivated *L. saccharina* withstand the high energy environment.

Keywords: *Laminaria saccharina*; Kelp; Offshore aquaculture; Mariculture; Drag; Drag coefficient; Attachment strength; Dislodgement; Breaking force; Resistance

1. Introduction

Along the German North Sea coast the occurrence of kelp of the genus *Laminaria* is restricted to the surroundings of the rocky island of Helgoland, the only hard substratum area in the wider German Bight. Due to the nature reserve status of Helgoland, harvesting of wild growing *Laminaria saccharina* is prohibited while aquaculture of this endemic species would be acceptable. Mariculture in offshore areas might help to meet the future demand for single species and clean macroalgae grown under well-controlled conditions for pharma-

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ceutical or cosmetic use (Buck and Buchholz, 2004).

Various efforts to find suitable locations for the establishment of aquaculture facilities for macroalgae in the German Bight were unsatisfactory, due to the lack of appropriate natural substrate and adverse hydrographic and weather conditions (Lüning and Buchholz, 1996; Buck, 2002). They cause a generally very rough wind wave climate in combination with strong tidal currents in the North Sea (e.g., Ducrotoy et al., 2000). Moreover, the bottom topography of the German Bight, which becomes rather shallow in the southern part, contributes to the wave impact. Current velocities at the surface can reach 2–2.5 m s^{-1} or even 3.4 m s^{-1} in some nearshore areas (Mittelstaedt et al., 1983; Dick et al., 1992). Wave heights of 5–6 m are common during storms (BSH, 2003).

Generally, the National Park "Wadden Sea" (NPG, 2001) in the south of the German Bight with its sheltered tidal mud flats as well as the seaward sandy beaches of the belt of Frisian islands does not offer suitable locations for mariculture endeavours. An exception is the highly regulated bottom culture of blue mussels (*Mytilus edulis*) and oysters (*Crassostrea gigas*). Cultivation of other marine organisms is not permitted (Boysen, 1991) and would most likely raise stakeholder conflicts in nearshore areas (Buck, 2002; Buck et al., 2004).

An alternative for the development of marine aquaculture is the utilisation of existing or projected offshore constructions (Krause et al., 2003; Buck et al., 2004). The attachment of culture units to rigid platforms could prevent damage or even loss of whole culture modules. Presently, the obvious aims of such aquaculture considerations are the planned offshore wind farms in Europe. These wind farms will probably cover larger areas of the North Sea and hold potential for multifunctional uses.

Moving to the offshore area of a wind farm to cultivate macroalgae would be a way to overcome the conflicts of space allotment and utilisation. Laminarians characteristically grow in tidal habitats with continuous but varying water motion. In offshore areas these plants must cope with violent currents and high waves causing acceleration reactions. In contrast to other seaweeds with a relatively rigid and upright stipe (e.g., *Eisenia arborea*, *Pterygophora californica* or *Laminaria hyperborea*) *L. saccharina* has a flexible stipe, which is capable of quickly reorienting and thus becoming aligned with the direction of the current. However, the response of cultured algae to this high energy environment of the North Sea is still unknown. If cultured kelp can be expected to stay in place while growing in the rough offshore environment, this would facilitate a commercially successful mariculture, provided culture techniques concerning seeding strategies and the design of culture constructions will be improved (Buck and Buchholz, 2004). The multifunctional use of offshore habitats could moreover combine the needs of stakeholders, such as wind farmers and fishermen, who would probably run the maricultures.

While Kawamata (2001) has been the only one so far to use culture derived *Laminaria* seedlings (*L. japonica*) for his biomechanical investigations, Gerard (1987) conducted her experiments on *L. saccharina* collected from the sea. The present study describes the resistance of maricultured and wild grown *L. saccharina* to the impacts of tidal currents and wave action. Morphological parameters of laminarian blades were taken into account, drag coefficients were determined, dislodgement and breaking forces, and hydrodynamic field conditions were measured and evaluated.

2. Material and methods

2.1. Origin of experimental plants

The experiments were conducted with wild and cultured *L. saccharina* from the German North Sea (Fig. 1). Wild specimens were collected by divers from habitats around the island of Helgoland (Hgl; 54°11′N, 7°54′E) (right inset in Fig. 1) from a water depth of 1–4 m. Cultured *L. saccharina* were taken from a new ring construction designed for cultivation of algae (Buck and Buchholz, 2004). The ring was located at an experimental offshore aquaculture farm adjacent to the lighthouse "Roter Sand" (53°49.9′N, 8°8.7′E), at a distance of 17 nautical miles from the city of Bremerhaven. At this location water depth and the sandy bottom do not normally allow settlement and growth of benthic algae, and the hydrodynamic conditions are rougher than in

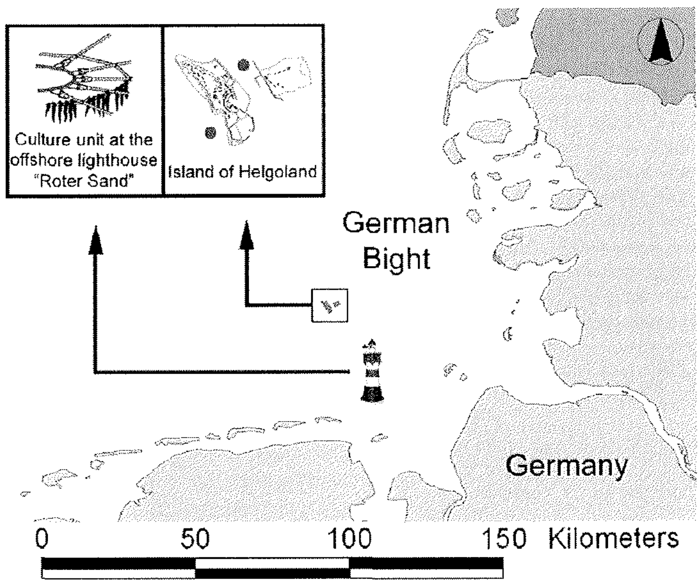

Fig. 1. Map of the German North Sea region. Right inset: Enlarged island of Helgoland, where specimens of *L. saccharina* were collected (black spots). Left inset: Culture unit for *L. saccharina* located at the aquaculture farm near the offshore lighthouse "Roter Sand".

natural *L. saccharina* beds. The cultured algae were grown on 6 mm ropes attached to a culture unit at a depth of 1 m below the water surface (left inset in Fig. 1).

2.2. Determining site-specific, environmental conditions

In order to describe the local hydrodynamic conditions at the experimental farm, current velocities and directions were measured by the Water and Shipping Agency (WSA) Bremerhaven with an acoustic Doppler current meter (RCM 9, Aanderaa). The sensor was placed in the vicinity of the offshore aquaculture farm for 1 month. Data on significant wave height, direction of waves with the absolute energy maximum, wave length, periods of wind waves and swell were obtained by a wave following buoy (Waverider, Datawell). The buoy was deployed by the Federal Maritime and Hydrographic Agency (BSH) 4 nautical miles NE of the aquaculture farm "Roter Sand" in early 2002 and recorded data for 300 days.

2.3. Morphometric analysis of L. saccharina fronds

Morphological data of *L. saccharina* thalli were acquired to assess growth patterns (length, width, surface area, volume) and test their possible correlations with drag, dislodgement and breaking forces, and effects on acceleration reactions.

For measurements, sporophytes were individually collected at sea from culture lines or from the natural habitat. Blade length was measured from the transition zone between stipe and blade to the blade tip. Blade width was recorded well beyond the meristematic zone or for larger algae at 15 cm distance from the transition zone. To test the correlation between blade length and blade width 1300 algal fronds of different sizes from two seaweed culture constructions in the

German Bight (Buck and Buchholz, 2004) were measured. From these results standard algae were calculated for a length of 50 cm (Standard 50 = S50) and 100 cm (Standard 100 = S100) in order to additionally scrutinize the drag coefficient (C_D) relevant to all sizes of laminarians.

Blade area was assessed by two different methods in order to find an appropriate technique for further investigation. The tapering of the distal and proximal blade ends was neglected by simply multiplying length and width of the lamina. In addition, algae of different sizes were cut in pieces, pressed between two glass plates and photocopied ($n = 50$). A plate marked with a grid (one square = 1 cm^2) was superimposed and the "real" blade area (single-sided) measured to the nearest cm^2 (Koehl and Alberte, 1988; Koehl, 2000).

For calculation of the blade volume the fronds were sectioned at 15 cm distance from the transition zone and the thickness of the blade's margin (T_{Mar}) and centre (T_{Cen}) measured using a micrometer screw (Fig. 2A). The shape of the blade's cross-section was copied on graph paper (one square = 1 mm^2) and the area measured to the nearest mm^2. Volume of fronds was calculated from cross-section area and length. To simplify this rather awkward procedure we tried a second method by multiplying length, width, and thickness. For this purpose we assumed that the lamina's cross-section has an extended double-trapezoid shape, the width of which can be divided into three equal parts (W_1–W_3). Two thirds, the left (W_1) and the right (W_3) margin of the lamina, had an identical isosceles trapezoid profile. The inner section of the lamina (W_2) had a rectangular shape (Fig. 2A). Section volumes of the lamina (V_{Lam}) were calculated using the equation:

$$V_{Lam} = \underbrace{[(W_1 \cdot T_{Res}) + (W_1 \cdot T_{Mar})]}_{\text{left trapezoid}} + \underbrace{(W_2 \cdot T_{Cen})}_{\text{inner section}} + \underbrace{[(W_3 \cdot T_{Res}) + (W_3 \cdot T_{Mar})]}_{\text{right trapezoid}} \quad (1)$$

In this equation W is the lamina's width with the thirds W_1–W_3, T_{Mar} is the thickness of the blade's margin, T_{Cen} the thickness in the blade's centre and T_{Res} the result of $T_{Cen} - T_{Mar}/2$. If the right and the left margins of *L. saccharina* blades have an identical thickness, a simplified version of the Eq. (1) can be used:

$$V_{Lam} = \underbrace{\left(T_{Cen} \cdot \frac{W}{3}\right)}_{\text{inner section}} + 2 \cdot \underbrace{\left[\left(\frac{T_{Cen} + T_{Mar}}{2}\right) \cdot \frac{W}{3}\right]}_{\text{left and right trapezoid}} \quad (2)$$

2.4. Device for measurements of dislodgement forces and drag

For measurement of dislodgement (F_{Dis}), breaking (F_{Brk}) and drag forces (F_{Drg}) a digital force gauge, "Centor Dual" (Andilog Technologies, France), was employed. The gauge had two sensors, an external sensor with a force range of 0 to 50 N (Sensor I), and an internal sensor with a force range of 0 to 250 N (Sensor II). It was possible to read both sensors

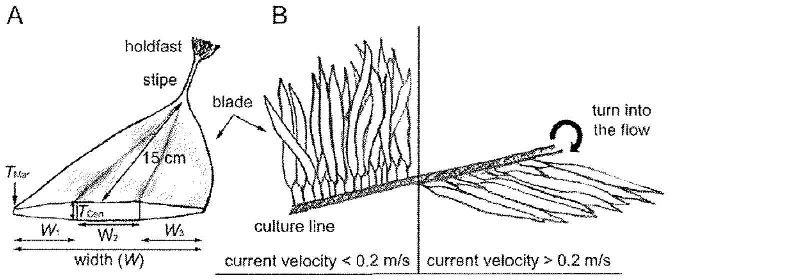

Fig. 2. (A) Drawing of a cultured *L. saccharina* blade in cross-section. The blade thickness was measured in the centre (T_{Cen}) and at the margins (T_{Mar}) at 15 cm distance from the transition zone. W = blade's width. (B) Drawing of *L. saccharina* growing on the culture line. In steady flow the sporophytes are oriented downstream rotating the culture line into the same direction.

simultaneously. On the graphic screen display of the gauge a simultaneous readout of the actual and the maximum values and the complete force curve (force $=F_{(t)}$) provided a comprehensive overview as the test was progressing. An interface (RS232, Andilog Technologies, France) connected to the gauge allowed the data transfer to a PC via a serial output port. The software "R-SIC" (Andilog Technologies, France) facilitated the transfer to Microsoft Excel spreadsheets.

2.5. Measurement of dislodgement forces of L. saccharina from culture lines

L. saccharina grown on 6 mm culture lines in the North Sea (Buck and Buchholz, 2004) were divided into a group of densely growing algae ($n=94$) with holdfasts growing on top of each other and one of individual algae with single holdfasts attached to the culture line ($n=37$). The third group of seaweeds, which grew on ropes but were adapted to sheltered low current conditions (≤ 0.2 m s^{-1}), were taken from a holding tank kept in the laboratory facilities of the AWI ($n=60$).

A string, thick enough to avoid damage of the tissue, was knotted to the holdfast in a manner that every extension of the holdfast was wrapped (excluding some very small haptera). In this way the dislodgement force affected the complete holdfast, and no part of the stipe was involved. The string was then connected to the digital gauge, which was fixed to a rigid bar. In contrast to Carrington (1990) and Kawamata (2001), who pulled the string parallel to the substratum, it was necessary to remove the holdfast in the direction of the stipe, because under culture conditions the laminarians including their holdfasts and the culture rope, which is a supple substratum, turn into the direction of the flow (Fig. 2B). Therefore, the holdfast was torn-off by rapidly pulling down the string into the direction of the stipe, which was in a right angle to the culture rope. Only one single attempt to tear off the holdfast was allowed in order to avoid eventual weakening of the attachment strength by repeated pulling (c.f. "post-storm sampling" Milligan and DeWreede, 2000). It was helpful to watch the display of the digital gauge to ascertain the characteristics of the complete graph. Acquired data were only accepted if the curve of the dislodgement force showed a rapid decrease. Both sensors (I, II) of the digital gauge were used for this purpose.

An additional experiment was conducted testing whether holdfast or stipe were the predetermined dislodgement or breaking points. The stipe, disconnected from the lamina, was wrapped with a string on both sides and torn apart pulling longitudinally at one side. The breaking force was measured by the same digital gauge.

2.6. Measurement of drag on L. saccharina

A towing tank (length 80 m, width 3.8 m, depth 3 m) of the Hamburg Ship Model Basin (HSVA, Hamburg) was used to determine the drag coefficient (C_D) for *L. saccharina* (Fig. 3A). The length of the tank allowed sufficiently long measuring times.

Clean specimens of wild ($n=4$; W1–W4) and cultured ($n=4$; C1–C4) *L. saccharina* were prepared for measurements of drag by removal of the holdfast (Table 1). A thin thread was knotted around the proximal end of the stipe (Fig. 3B). This thread was directed over a guide reel fixed to the bottom of a beam (Fig. 3C). A cavity within the beam allowed the thread to be hooked onto the digital gauge, which was placed on the control panel of the carriage. The beam had a drop-like shape to minimize friction and was fastened to the base frame of the towing tank's carriage. It was lowered 1 m deep into the tank filled with fresh water (Fig. 3D). Blades tied to the thread of the gauge were towed through the tank by the carriage at velocities of 0.5, 1.0, 1.5, 2.0, and 2.5 m s^{-1}. *L. saccharina* of different sizes, originating from the wild and from the farm, as well as "Standard 50" and "Standard 100" algae were used. To assess drag of a group of blades, a bunch of laminarians ($n=13$) was measured as well. Force data were recorded when the carriage had reached the designated velocity. Sensor-I was employed for these entire experiments.

The drag measurements of each *L. saccharina* thallus were used to calculate the dimensionless coefficient of drag (C_D) by applying the equation:

$$C_D = \frac{2F_{Drg}}{\rho A v^2} \quad (3)$$

In Eq. (3) F_{Drg} denotes the measured drag, ρ the density of water, A is the blade area exposed to the

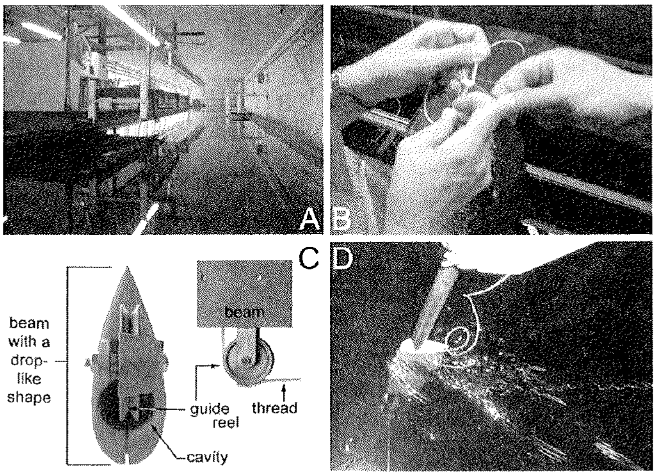

Fig. 3. (A) Towing tank of the HSVA used for drag measurements on *L. saccharina* blades in steady flows. (B) A thin thread, connected to the digital gauge, was knotted around the proximal end of the stipe. (C) Lateral view on the beam and the guide reel used to tow the laminarian blades in the towing tank. (D) Beam with its drop-like profile to minimize friction during towing.

current of velocity v. While for relatively rigid or bluff organisms the projected area of the organism across the flow is generally used (e.g., Vogel, 1984; Denny, 1988), we decided on the maximum plan area (single-sided) of the thallus as it is recommended, e.g., by Koehl (1986), Vogel (1984) and Gaylord et al. (1994) for flexible organisms like macroalgae.

Table 1
Cultivated and wild *Laminaria saccharina* used for the drag force experiment

Origin of algae	Seaweed denotation	Phylloid length (cm)
Cultivated algae from offshore farm "Roter Sand"	C1	161
	C2	101.4
	C3	64.8
	C4	49
	S50	50
	S100	100
	Bunch ($n=13$)	34.95 ± 8.97 (mean ± S.D.)
Wild algae from Helgoland	W1	137.6
	W2	123
	W3	80
	W4	45

2.7. Estimations of drag for natural conditions

For solid objects being accelerated in fluid in addition to drag a force occurs which is commonly described as *acceleration reaction* (e.g., Daniel, 1984; Denny et al., 1985; Denny, 1988). In order to take orbital motions into account the drag F_{Drg} from Eq. (3) has to be written in vector notation, and an acceleration term is added (Morison et al., 1950):

$$\vec{F}_{Drg} = C_D \cdot A \cdot \frac{1}{2} \cdot \rho \cdot |\vec{v}| \cdot \vec{v} + C_M \cdot \rho \cdot Q \cdot \frac{d\vec{v}}{dt} \qquad (4)$$

where C_M is the dynamic drag coefficient and Q the volume of water displaced by the object. In order to initially avoid uncertainties with C_D and the area A for flexible organisms it is useful to write the first term in Eq. (4) in terms of dynamic pressure ($\vec{F}*$), which can be exactly computed from current measurements:

$$\vec{F}* = \frac{\vec{F}_{Drg}}{C_D \cdot A} \qquad (5)$$

i.e.

$$\vec{F}* = \frac{1}{2} \cdot \rho \cdot |\vec{v}| \cdot \vec{v} \qquad (6)$$

For a detailed demonstration of the time history of drag forces occurring under the action of tidal currents, wind wave and swell model calculations were carried out using the software "WaveLoads" developed by Mittendorf et al. (2001), which solves Eq. (4) for offshore structures. The forces were computed for a hypothetical test body (cylinder) of 2 m in length and such a diameter that the area exposed to the current corresponded with that of the plan area of the algae as determined before. The drag coefficients measured in the towing tank experiments were used instead of the ones determined for cylinders. The cylinder was exposed perpendicular to the flow direction. The results render information on the distribution of horizontal and vertical forces which act on the alga.

2.8. Statistical analysis of data

The data on blade lengths and widths were split into four obvious groups and the regression calculated separately for each growth phase. To determine if regressions of two groups within a class were significantly different (coefficient of determination/stability index) z-tests with an initial Fisher z-transformation were used (blade surface area, growth periods at length to width ratio) (Steel et al., 1997; Birkicht, 2004).

F-tests (one dimensional, $f=n-1$) were conducted to prove homogeneity of variance as a prerequisite for applying the average-t-test (blade length, blade surface area). Difference-t-tests with pre-assigned F-test were used to show differences between two sample groups and data pairs (dislodgement and breaking force; blade surface area) (Birkicht, 2004).

The limit for acceptable correlations was set at $R^2 \geq 0.5$. Diagrams, plotting algal size against forces were fitted with logarithmic trend lines, because growth processes often follow a logarithmic pattern.

Standard deviations (S.D.) were calculated and applied in graphs as appropriate using Excel 2000 software; these are shown in bars.

3. Results

3.1. Hydrodynamic conditions

The wave and current conditions varied tremendously during the period of measurements even at a single location. Thus, *L. saccharina* within our offshore aquaculture farm "Roter Sand" experienced a wide range of sea states (Fig. 4A–D). The algae encountered rapid tidal currents flowing in one direc-

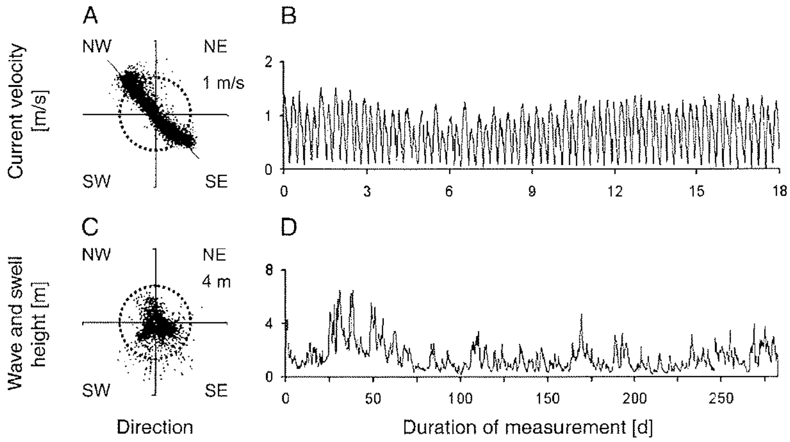

Fig. 4. Wave climate and current velocities near the offshore farm "Roter Sand". (A) shows the directions of currents at all velocities and (B) shows the current velocity over an 18-day period ($n=5188$). (C) demonstrates the direction of waves of all heights and (D) shows the wave heights over a 293-day period ($n=2259$). Dotted circles: (A) 1 m s^{-1}, (B) 4m.

tion for some hours, slowing and stopping at slack tide, and then flowing rapidly in the opposite direction. NW and SE are the main tidal current directions in the semi-diurnal tidal regime at the experimental farm. Maximum current velocity measured at the aquaculture farm in the 2002 measuring campaign was 1.52 m s^{-1}.

The mean significant wave height during the 300 days of measurements was recorded at 1.49 m ± 1.01 (mean ± S.D., n = 2259). Maximum wave height including swell came to 6.46 m with the waves of the absolute energy maximum being predominantly directed southward towards the coast. Wave lengths of wind waves and swell ranged from 7.8 to 334 m (67.02 ± 43.49, n = 2259) and wind wave periods varied from 2.6 to 9.8 s (4.95 ± 1.25, n = 2259).

3.2. Morphometric analysis of *L. saccharina* fronds

While plants harvested from the less exposed natural habitat had relatively wide blades with a ruffled margin (Fig. 5A) algae from the mariculture under offshore conditions had an elongated shape with a narrow and flat phylloid (Fig. 5B,D). Cultivated algae from the offshore farm had holdfasts densely growing on top of each other (Fig. 5C). One typical bunch or aggregation from the culture rope is displayed in Fig. 5D.

In cultivated algae of known age we found a significant positive correlation between blade length and blade width (R^2=0.98) during the first year of plant growth. However, the data shown in Fig. 6A reveal that the entire growth phase can be subdivided into four consecutive periods (p < 0.001). Up to a blade length of 5 cm width development is relatively fast with a slope of 0.24x (R^2=0.88). In the next group up to a blade length of 60 cm development of blade width declines to a slope of 0.06x (R^2=0.94). The third group between 60 and approximately 150 cm blade length shows more variation in its growth pattern and an even slower increase in blade width (slope 0.05x, R^2=0.75). Longer *L. saccharina* were

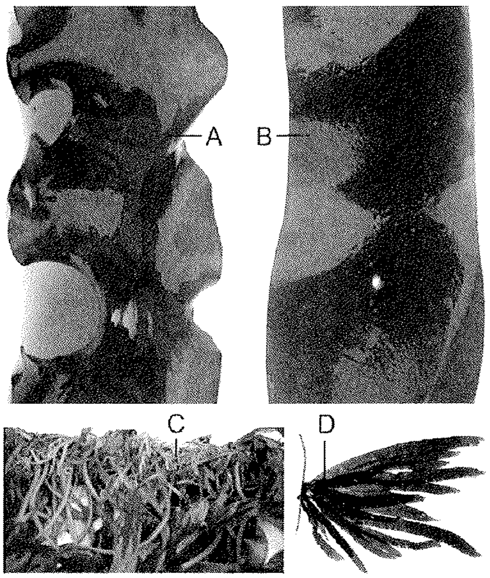

Fig. 5. Plants used for towing tank experiments. (A) *L. saccharina* from a sheltered site with a wider blade and ruffled margins and (B) cultivated *L. saccharina* from the offshore site with a streamlined shape. (C) depicts a culture line with holdfasts growing densely on top of each other. (D) represents the laminarian bunch used for drag experiments in the towing tank.

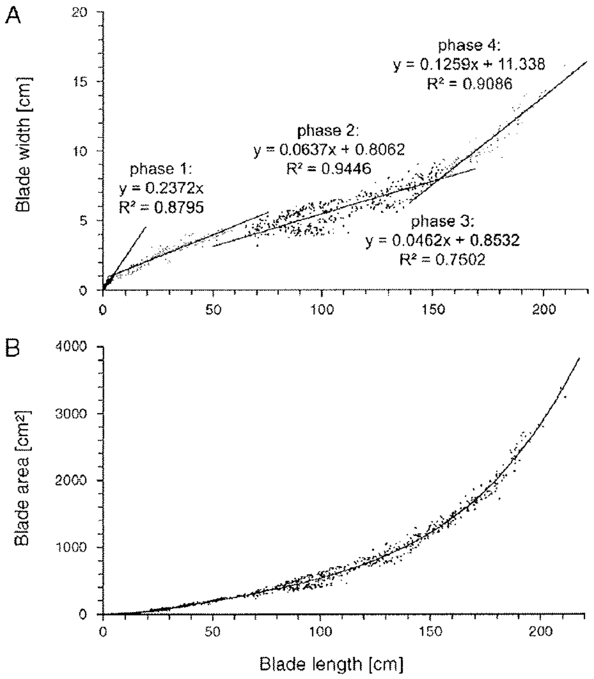

Fig. 6. Morphometric data of *L. saccharina* cultured at an offshore site ($n=1300$). (A) shows the blade length to width ratio revealing four consecutive periods ($p<0.001$) of plant growth. (B) shows the blade surface area to blade length ratio with roughly the same consecutive growth periods.

increasing their blade area by an again intensified transversal growth at a slope of 0.13x ($R^2=0.91$). Results of the determination of blade surface area show, that there is no significant difference whether grid measurement or simple multiplication of length and width are used ($p<0.5$). Thus, a significant positive correlation ($R^2=0.99$) can be described for the ratio of blade length to blade surface area using the multiplication method (Fig. 6B). The four previously described morphometric stages from the length–width measurements (Fig. 6A) can be found to a lesser extent.

From the large data set of blade length/width relations standard algae were defined as Standard 50, 50 cm long 4.3 cm wide and Standard 100, 100 cm long and 5.8 cm wide.

Volume data of both, field algae and cultivated algae, followed a positive correlation to blade length as well as blade surface area. At a given length field algae always had a greater volume than cultivated algae.

3.3. *Drag on L. saccharina in steady flows*

The plot of measured drag against various flow velocities (Fig. 7A) shows the increase of drag with increasing velocity of flow. Three of four plants from wild habitats show by far the highest drag exposure. Only the smallest of the wild plants blends in with the group of cultured specimens. The "standard" algae, 50 and 100 cm long, which were chosen from cultured *L. saccharina* belong into this group of algae encounter-

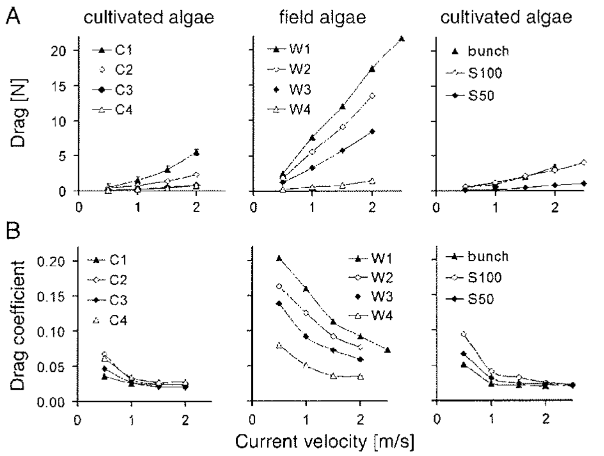

Fig. 7. Results from the towing tank experiments ($n=50$) with cultivated (C1–C4, S50, S100, bunch) and field (W_1–W_4) *L. saccharina*. (A) Drag as a function of current velocity. (B) Drag coefficient C_D as a function of current velocity.

ing less drag at the chosen flow velocities. At a comparable blade area of about 200 cm^2 the wild grown *L. saccharina* W4 is exposed to almost twice as much drag as the cultured C3. W4 being the shortest of the wild algae towed (blade length 45 cm) is the only one to group with the cultured specimens. Cultured C1, the longest (blade length 161 cm) of all the measured algae, is nearest to specimens from the field, but even though its blade area exceeds that of the longest field specimen W1 by 170 cm^2, only a fifth to a third of the drag was recorded for the cultured specimen. The differences in drag became more pronounced with increasing current velocities. The left diagrams represent conditions for *L. saccharina* growing individually on the culture line. Growing in an aggregation, as it is usually the case, reduces the drag on the individual (Fig. 7A, far right). At a similar cumulative blade area of a bunch of *L. saccharina* (1136 cm^2) compared to the cultured *Laminaria* C1 (1115 cm^2), measured drag of the aggregation of algae was smaller at higher current velocities than that of the individual alga.

Considering the drag coefficient C_D as a function of velocity (Fig. 7B), the grouping of the cultured versus the field algae becomes even more evident. The drag coefficient C_D of cultured *L. saccharina* of "Helgolandian morphology" without bullae and hardly any undulation was calculated at velocities of >0.5 m s^{-1} to range between 0.024 and 0.034 independent of the size of the algae. The graphs for cultivated algae (C1–C4, S50, S100, bunch) show a pronounced bend at a velocity of 1 m s^{-1}. This appears to approximately mark the minimum speed required for orientation of the plants into downstream direction. When comparing the bunch with a single cultivated alga of similar surface area (C1) the drag coefficient of the bunch was about 30% higher at the lowest current velocity (bunch 0.052 versus C1 0.036 at 0.5 m/s), but became very similar to that of C1 at faster velocities. At higher velocities $\geq$1.5 m s^{-1}, C_D is almost a constant for individual algae as well as for the bunch and is independent of current velocity. The progress of reconfiguration into lower drag-shaped blade morphology seems to be accomplished. Contrastingly, laminarian fronds from less exposed sites (broader and with more undulated margins) appear distinctly different in the diagrams. Their reconfiguration, at least of larger plants, was not yet completed at 2 m s^{-1}, while the small plant W4 had already acquired its final shape of minimized exposure to the current.

Based on our empirical data the drag expected for various current velocities and possible blade areas of *L. saccharina* is depicted in Fig. 8. At a maximum current velocity of 1.5 m s^{-1}, like that measured near "Roter Sand" in 2002, large algae would be exposed to forces of ≥16 N.

While the empirical determination of C_D of solid bodies is a well-established procedure it is complicated for flexible plants, because they are changing their shape in the flow. To describe the relative reduction in drag for flexible bodies as they reconfigure with increasing flow velocity, Vogel (1984) proposed the determination of the proportionality between speed and drag and several authors followed his suggestion (e.g., Armstrong, 1989; Carrington, 1990; Gaylord et al., 1994; Koehl, 2000). In order to compare the performance of *L. saccharina* in currents to that of other algae, we also determined the "figure of merit", *B* (Vogel, 1984; Koehl et al., 2003): The log transformed "specific drag" F_{Drg}/v^2 was plotted against log transformed current velocity and the slopes (*B*) of the graphs determined. They are called "figure of merit" (Vogel, 1984) and are listed in Table 2.

The values are typically negative. The higher absolute values of field algae demonstrate that they could experience more relative drag reduction by morphological reconfiguration than our cultured laminarians (Vogel, 1984; Koehl, 2000; Gaylord et al., 1994; Koehl et al., 2003).

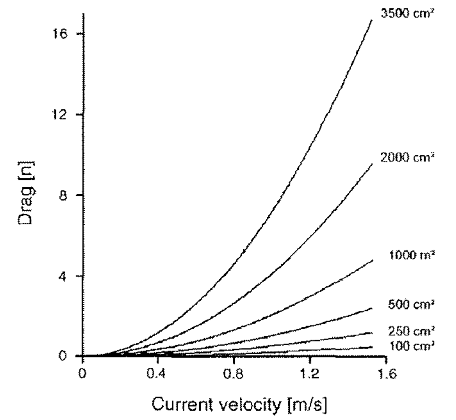

Fig. 8. Drag at various current velocities for different plant sizes (blade surface area) based on measurements in the towing tank experiment and morphometric data of *L. saccharina* from the offshore site.

Table 2
"Figure of merit" *B* of cultivated and field *Laminaria saccharina*

Origin of algae	Seaweed denotation	Current velocity (m/s)	*B*	R^2
Cultivated algae from offshore farm "Roter Sand"	C1	1–2	−0.10	0.79
	C2	1–2	−0.39	0.94
	C3	1–2	−0.39	0.92
	C4	1–2	−0.30	0.87
	Bunch	1–2	−0.25	0.98
	S50	1–2.5	−0.49	0.99
	S100	1–2.5	−0.69	0.99
Field algae from Helgoland	W1	1–2.5	−0.84	0.99
	W2	1–2	−0.72	0.99
	W3	1–2	−0.62	0.99
	W4	1–2	−0.52	0.84

B = slope; R^2 = goodness of fit for $y = \log F_{Drg}/v^2$; $x = \log v$.

3.4. Estimation of drag for natural conditions

The observations at "Roter Sand" are dominated by a combination of tidal currents, wind waves, and swell, which is characteristic for the shallow areas of the German Bight.

To better assess the highest forces probably impacting *L. saccharina* at an offshore location we employed the numerical model "WaveLoads" (Mittendorf et al., 2001). Typical oceanographic parameters to supply the model were chosen from the field measurements at "Roter Sand", and the necessary structural parameters were taken from the morphometric data gained on the algae in the towing tank experiments. The parameters chosen for selected runs of the model are summarised in Table 3 together with the computed maximal drag.

Three comments on the relationships between drag and water movements for the environmental conditions prevailing in this study shall precede the presentation of the results of the model calculations.

Firstly, a rough estimation shows that the second term in Eq. (4) is very small compared to the first one and can be neglected: The volume of the algae was determined in the order of $Q = 200$ cm^3. Multiplication by the density of seawater $\rho = 1025$ kg m^{-3} and

Table 3
Drag forces under natural conditions

	Period (s)	Wave height (m)	Tidal velocities (m/s)	C1 (N)	C2 (N)	C4 (N)
Wind waves	5	2	2	11.7	4.9	–
Swell	10	2	2	12.4	5.5	–
Storm waves	6	6	2	34.3	14.6	4.4
Storm swell	10	4	2	23.0	10.9	–

assuming the worst case $C_M = 1$ for the dynamic drag coefficient results in $C_M \cdot \rho \cdot Q = 0.205$ kg for the mass of water displaced by the algae. Thus, a large orbital acceleration of 3 m s^{-2} (about a third of the acceleration of gravity) provides a dynamic force of 0.31 N while the first term reaches 35 N. The "WaveLoads" model takes the acceleration term into account, but uncertainties with C_M will not have a noticeable effect.

Secondly, because of the non-linear relationship between drag and velocity the combined action of orbital wave motion and tidal currents enhances the total forces considerably. For example, if a tidal current has the same velocity as the amplitude of the horizontal orbital velocity, the total force increases by a factor of 4.

Thirdly, due to the shallow depth of 12 m at the experimental farm the orbital velocities of long swell waves are increased, because they make the transition to shallow water waves.

The above mentioned phenomena were confirmed by the numerical model "WaveLoads". One has to bear in mind that the forces are calculated for a symmetrical test body which represents the real alga with respect to its two fluid mechanical properties, drag coefficient and constant area exposed to the currents. Three examples for the distribution of horizontal and vertical drag on the test body are presented in Table 3. Fig. 9A visualizes calculations for the cultivated alga C1 with wind waves at normal conditions (height: 2 m) at various current velocities (0, 1, 2 m s^{-1}) and Fig. 9B shows worst cases (height: 6.4 m; current velocity: 2 m s^{-1}) for cultivated *L. saccharina* of different lengths and blade areas (C1, C2, C4). The selected waves propagate in the direction in which the tidal current flows. The starting point of each curve, indicated by a small marker circle in the diagram, corresponds to the moment, when a wave crest passes the site. Without tidal currents the results of the model for horizontal and vertical forces show a symmetrical

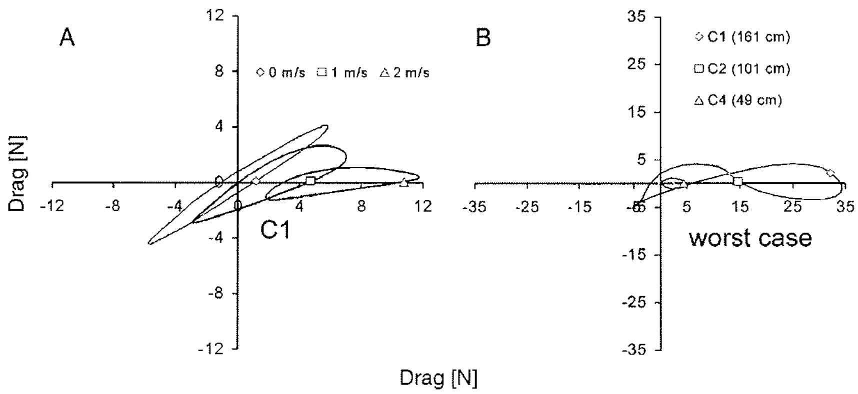

Fig. 9. Drag on cultivated algae under natural conditions derived from the model "WaveLoads" (Mittendorf et al., 2001). (A) shows the increasing drag as a function of current velocity (0, 1, 2 m s^{-1}) experienced by the algae C1 at wind waves of 2 m height and 5 s period. (B) shows the drag on the algae C1, C2 and C4 under worst case conditions (height of wind wave 6 m, period 6 s, current velocity 2 m s^{-1}).

ellipse which is elongated and shifted into downstream direction with increasing tidal velocity. Fig. 9B shows a worst case scenario, when storm conditions boost the drag experienced by cultivated algae. The largest alga (C1) has to withstand the highest drag of approximately 35 N.

3.5. Dislodgement of holdfasts and stipe breaking forces

After the assessment of wave generated forces affecting *L. saccharina* cultured offshore the second step was to determine what it takes to detach our cultured algae from their substrate. It can be expected that either the holdfast is torn from its substrate or the stipe breaks. The results of our experiments are shown in Fig. 10 with dislodgement force of the holdfast on the abscissa and breaking force of the stipe on the ordinate. If both forces were equal all values would be found on the bisector of the angle. The first two diagrams show that in individually growing *L. saccharina* as well as in those growing in aggregations, greater force had to be employed to break the stipe than to detach the holdfast. Algae that were retrieved from a tank with water movement only from air bubbles had a very weak resistance to any of the applied stresses and were dislodged or broke at less than a fifth of the force needed for laminarians exposed to a 2 m s^{-1} current.

L. saccharina displays a significant positive correlation of blade length to blade surface area (Fig. 6B, $p<0.01$, $R^2=0.99$). To assess dislodgement and breaking stresses on *L. saccharina* stipes the respective forces (F_{Dis} and F_{Brk}) were normalized by blade area and plotted against the length of the blades (Fig. 11). The basic trend is towards a decreasing resistance to adverse forces with increasing size. *L. saccharina* cultured "singly grown" and in currents up to 1.52 m s^{-1} require the highest forces to be broken off at their stipes ($p<0.001$). Dislodgement forces (F_{Dis}) between singly grown algae (current velocity > 1 m s^{-1}) and those in aggregations (densely growing and current velocity > 1 m s^{-1}) are statistically indifferent, even though growing singly and therefore directly attached by their holdfasts to the culture line seems to give them an advantage at least when they are still small. For densely grown laminarians the force per cm^2 needed to either dislodge them from the culture line or break their stipes can likewise not be statistically differentiated.

L. saccharina grown in an almost current-free environment were far more susceptible to dislodgement and breaking stresses than algae adapted to currents.

4. Discussion

The question we posed in our present investigation was, whether it seemed sensible to try the aquaculture of macroalgae in the projected North Sea offshore wind farms. A second problem to be tackled would be the selection of appropriate sites among those locations. A closer look at the conditions in an offshore algal farm that existed in 2002 should help to find answers. The seaweeds cultured on the ring

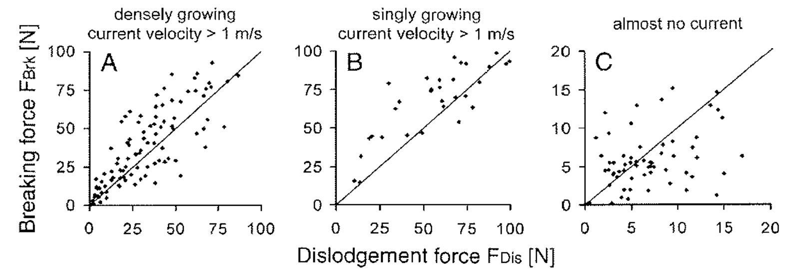

Fig. 10. Forces necessary to break the stipe (ordinate) or to dislodge the holdfast (abscissa) of *L. saccharina* grown in exposed conditions (singly grown, $n=37$; densely grown, $n=94$) and in sheltered conditions (almost no current, $n=60$). The bisector of the angle indicates where both forces would be equal (breaking force = dislodgement force).

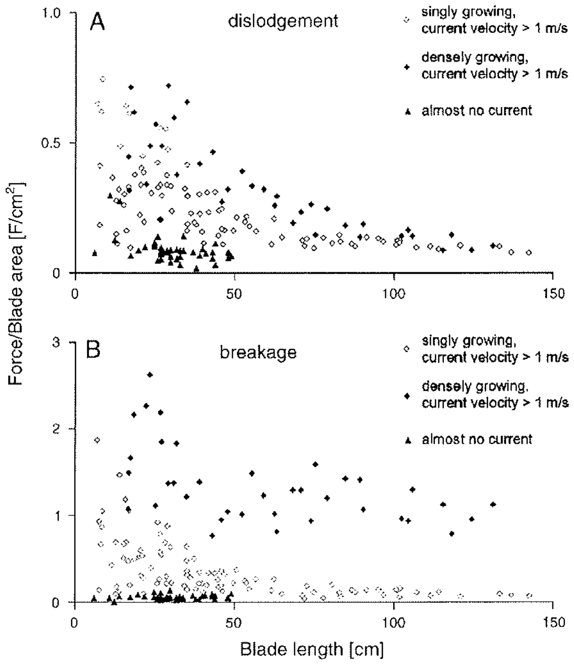

Fig. 11. Susceptibility to dislodgement (F_{Dis}) (A) and breaking (F_{Brk}) (B) forces per area of individual *L. saccharina* as a function of blade length. Single plants versus plants grown in aggregations both in water currents and plants grown in almost no current.

system (Buck and Buchholz, 2004) at the farm near the lighthouse "Roter Sand" were subject to various stress factors in the wave-swept environment. Current velocities of 1.52 m s^{-1} and wave heights of up to 6.4 m at wave periods of 2.6 to 9.8 s caused complex impacts on *L. saccharina*. These impinging forces stress the phylloid, the stipe and the holdfast exerting "tension, friction, shear forces, bending, and twisting" (Koehl, 1982, 1986). The behaviour of cultured *L. saccharina* as well as some field specimens towards hydrodynamic forces resulting in dislodgement of the holdfast, breaking of the stipe, and general drag was examined in detail.

The highest drag in steady flows expected from the extrapolation of our drag measurements in the towing tank related to current velocity amounts to 16 N for cultured Helgolandian type *L. saccharina*. It holds true for algae possessing a blade area of about 0.3 m^2 in a realistic one season culture period (Fig. 8). The results of the model calculations of drag on *L. saccharina* under natural conditions including current velocity in combination with wind waves or swell affect the algae at normal sea states with up to 12 N. This is the same order of magnitude and only in the worst cases of storm conditions can drag of up to 35 N be expected (Table 3, Fig. 9). These figures were computed under the assumption of rigid test bodies representing blade area and drag coefficient of the algae. In contrast to solid bodies algae change their area exposed to currents by adjusting their shape until minimum drag is reached (e.g., Daniel, 1984; Denny et al., 1985; Denny, 1988). To account for the complex interactions between algae and currents, elaborate physical–mathematical models have been developed (Gaylord and Denny, 1997; Gaylord, 2000; Gaylord et al., 2003). Within the scope of our investigation we restricted ourselves to estimations of worst cases and used the solid body formula. The use of the solid body approach is supported by the finding that for velocities >1 m s^{-1} the drag coefficients of cultivated algae were found to be almost independent of velocity (Fig. 7). Deviations in favour of drag avoidance by the flexible plants are probable, judged from observations on, e.g., *Chondracanthus exasperatus* (Koehl, 2000) and on *Hedophyllum sessile* (Armstrong, 1989). Nevertheless, the order of magnitude in our "worst case" calculations is thought to be realistic.

Drag on the bunch of *Laminaria* blades was smaller than the total drag of all solitary blades. Johnson (2001) explored this topic in some detail for *Chondrus crispus* and found similar results, where forces decreased with increasing canopy density. While Carrington (1990) determined that the ratio of the drag from a clump of blades to the sum of the individual drag forces of *Mastocarpus papillatus* never dropped below 0.8 the ratio was 0.35–0.38 in the laminarian case (bunch consisted of 13 blades). This difference can be explained by the fact that a bunch of streamlined laminarian blades experiences a lower drag increase with increasing current velocity than thalli with a bushy shape. In contrast to *L. saccharina* occurring at the Isle of Man with deep bullations on the blade *L. saccharina* originating from the island of Helgoland were described to have a smooth shape (Lüning, 1975). Such regional differences may be the adaptive result of the local wave and current climate of these two islands.

Morphological characteristics of *L. saccharina* like blade area and volume were needed to determine the drag coefficient C_D and to parameterise the model. To get an idea of how these parameters develop over time and to assess their interrelation to impinging forces in the field, lengths and widths of 1300 blades were measured on cultured *L. saccharina* from "Roter Sand" in 2002. We observed four consecutive growth phases in the development of blade length and blade width (Fig. 6A). All phases seem to mirror the environmental conditions in which the laminarians grew at the time. Phase (1) took mainly place under laboratory conditions. Sporophytes were very small and grew in all dimensions, while moderate currents interacted with the phylloids. During phase (1) plants were transferred to the sea to meet the wind induced turbulent water conditions of winter and early spring. The morphological plasticity of *L. saccharina* allowed them to react with an intensified length growth in phase (2) and to reach a more streamlined shape. It is well-known that laminarians exposed to wave action or high current velocities have narrower blades than plants from calm and sheltered areas and also differ in length and thickness (e.g., Parke, 1948; Svendsen and Kain, 1971; Gerard, 1987). During summer corresponding to algal sizes of stage (3), weather conditions were calmer resulting in a variety of length to width ratios. The variance of lengths and widths may moreover be attributed to shading effects among the plants. In size phase (4) of samples collected in late summer, sea conditions seemed to allow a higher increase in blade width. If this growth pattern were the rule, which future annual cultures will have to show, *L. saccharina* would ecologically sensible have gained blade area for the onset of sorus in autumn. For site selection in mariculture strategies the information displayed in Fig. 6 together with the expected drag impinging on algae of different sizes will help to identify the adequate marine environment for a given plant size.

While Fig. 10 shows the quality of haptera attachment to the substrate versus the resistance against breakage of the respective stipe independent of algal size, Fig. 11 depicts the individual vulnerability to drag of each *Laminaria* plant in relation to its blade area, the target for drag. In relation to blade area, the strength of the individual algae relative to dislodgement as well as breaking forces becomes smaller with increasing blade length and area before levelling off (Fig. 11). Nevertheless, we found that the absolute forces (not shown) that can be applied prior to dislocation are smaller (≤35 N of the "worst case") in small size classes (Fig. 6, phase 1 and phase 2). This might be expected and may be partly counterbalanced by the lower individual vulnerability of small algae, but does not explain, how larger algae cope with the higher drag they experience at comparable current velocities (Fig. 7A). The material properties of laminarians of different sizes that in addition to morphological characteristics determine their sturdiness towards adverse forces are yet to be examined more closely in a quantitative biochemical study.

Algal resistance to hydrodynamic forces depends on several ecological conditions. Firstly, a relatively strong current at an early age of the sporophyte is an absolutely necessary prerequisite for any mentionable attachment strength of the holdfast as well as tensile strength of the stipe resisting breakage (Fig. 10) (Buchholz and Buck, unpublished data). A further important factor is, whether they had a chance to anchor their holdfasts in the culture line (Tovey and Moss, 1978), growing singly, or whether they grew in aggregations with their holdfasts on top of those of their neighbours (Fig. 5C). Individually growing specimens developed a distinctly higher resistance towards breakage of the stipe and a clearly visible, if slight, better resistance towards dislodgement. This has long been promoted in Asian aquacultures, where algae are singled out after some grow out time, which in addition enhances individual growth (Ohno and Critchley, 1997; Scoggan et al., 1989). We found the forces needed to remove *L. saccharina* growing in aggregates generally smaller, but could detect a drag coefficient comparable to that of cultured individuals particularly at higher current velocities, when a bunch of laminarians reconfigured into a better hydrodynamic shape. The "figure of merit" of the bunch, characterising the relative drag reduction dependent on increasing current velocity, is also well within the range of individual algae (Table 2). A third influence on algal resistance to adverse forces is determined by its morphology. Our cultured algae looked like typical *L. saccharina* from high current locations around Helgoland, having grown in a likewise exposed environment. Comparing them with specimens of the same species with a more undulating (ruffled) border from less exposed field sites showed that the narrow and flat blades of the cultured algae experienced distinctly smaller drag than the field algae (Fig. 7). Gerard (1987) postulated that strong currents enhance hydrodynamic streamlining of the Laminarian frond, while at the same time such morphological adaptation reduces the mechanical stress on the thallus (Armstrong, 1989). Moreover, they were almost perfectly adjusted to the flow at much lower current velocities than the "ruffled" field algae and their drag coefficients were almost constant at ≥ 1 m s^{-1}. In our experiment with the ruffled laminarians they had not yet reached a perfect profile at a current velocity where the drag coefficient would not have decreased any more (Fig. 7; probable exception: W4). The "figure of merit" B (Table 2) for field algae, at current velocities ≥ 1 m s^{-1}, additionally indicates that a reduction of drag could be expected for current velocities beyond 2.5 m s^{-1}. More reliable values for B could probably be generated at these higher current velocities, but the carriage of the towing tank was limited to a velocity of 2.5 m s^{-1}. Fortunately, higher current velocities are uncommon for the German areas of the North Sea and it can be assumed that under such conditions stipes may break or holdfasts become dislodged.

B, frequently also named E, as the value of the "figure of merit" determined in the region of the graph "without inflection" (Vogel, 1984) shows a negative slope for cultured as well as field algae. The negative value of the slope results from the relative reduction of F_{Drg} experienced by *L. saccharina* as it reconfigures with increasing flow velocity. While for cultivated algae B (B_{C1-C4} and B_{bunch}) was determined at the value of -0.29 ± 0.12 (mean $\pm$ S.D.) field algae were found to have a greater B (B_{W1-W4}) of -0.68 ± 0.14 (mean $\pm$ S.D.) (Table 2). The greater the absolute value of B the greater the reduction of F_{Drg} and the greater the ability of the blades to get streamlined.

Our results on cultured laminarians and more ruffled wild ones correspond to those described by Armstrong (1989), who reported that ruffled individuals with bullations of the brown macroalga *Hedophyllum sessile* originating from protected sites had a steeper descending slope than those having a strap-like blade morphology occurring at more exposed sites. In addition, mean values of B for *L. saccharina* fit into the range of values collected in Carrington (1990) and Koehl (2000), where values of B for seaweeds with comparable blade-like morphology vary from -0.28 to -1.2.

In experimental offshore cultures of laminarians on floating ring systems (Buck and Buchholz, 2004) an artificial canopy was created that certainly further reduced flow and therefore the impact of drag at least on the more centrally placed algae. The lower resistance to dislodgement or breaking forces of *L. saccharina* algae growing in aggregations versus those growing singly (Fig. 11) is probably balanced by a neighbourhood protection against the full impact of currents. Reduction of drag by natural canopies has been reported, e.g., for large kelp canopies of *Nereocystis* or *Macrocystis* (Koehl and Alberte, 1988; Jackson, 1984) or the smaller red algae like *Mastocarpus* and *Chondrus* (Dudgeon and Johnson, 1992; Johnson,

2001) or *Chondracanthus* (Koehl, 2000). The latter might better compare to conditions in young *Laminaria* cultures.

5. Conclusion

Forces generated by local currents and waves at "Roter Sand" were not strong enough to dislodge *L. saccharina* holdfasts or to break their stipes. While drag increased with the square of velocity, the drag coefficient remained constant at velocities >1 m s^{-1} due to the reorientation of the laminarian fronds into a streamlined shape. This mechanism functions as an adaptation to offshore forces. A prerequisite for this adaptation is the early transfer of young cultured sporophytes into the sea, which requires a well-organised seeding and pre-cultivation strategy and needs familiarity with site-specific parameters of a certain area. Due to the fact that singly grown plants withstood stronger forces, offshore areas with current velocities >2 m s^{-1} and waves higher than 6 m require cultures with less densely seeded sporophytes. Provided the above mentioned prerequisites are met, extensive aquaculture of *L. saccharina* in the high energy environment of the German Bight appears to be feasible.

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Appendix IX

Publication IX

Inshore-offshore comparison of parasite infestation in* Mytilus edulis*: Implications for open ocean aquaculture

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1 2 3 4 5 6 7 8 **9** 10 11 12

Summary

Offshore production offers a new perspective for mussel aquaculture in the German Bight (North Sea) as no expansion is possible in the intertidal and subtidal zone of the Wadden Sea because of restrictions on the number of licenses. The development of offshore wind farms offers a unique opportunity because of the associated infrastructure. Service platforms, as well as the pylons themselves, offer perfect structures for mooring longlines and other culture units. One of the advantages of offshore culture may be a lower parasite load in offshore mussels compared with mussels produced under traditional inshore bottom culture. By sampling mussel spat from offshore suspended buoys or collectors, we simulated an offshore culture situation and compared parasite infestation rates with those in mussel spat obtained from suspended inshore buoys or collectors, in mussels from inshore benthic subtidal beds and from inshore benthic intertidal mussel beds. Mussels from offshore sites were free of trematodes and shellboring polychaetes. Parasitic copepods only occurred at a single offshore site, on a 20-year-old research platform, but not on buoys or collectors exposed for shorter time periods. All three monitored parasite taxa were present at all other sites. The highest prevalence was found for trematodes in inshore benthic intertidal mussels (78.7 ± 6.4%) and locally reached 100%. Through a variety of detrimental effects, trematodes, parasitic copepods and shell-boring polychaetes are known to affect growth performance and product quality. We therefore propose that offshore mussel production could be a promising culture procedure because it seems to result in lower parasite burden than at traditional culture sites. Whether offshore production also results in better survival and growth, compared with inshore mussel culture on a commercial scale, needs to be investigated further.

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Inshore–offshore comparison of parasite infestation in *Mytilus edulis*: implications for open ocean aquaculture

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Summary

Offshore production offers a new perspective for mussel aquaculture in the German Bight (North Sea) as no expansion is possible in the intertidal and subtidal zone of the Wadden Sea because of restrictions on the number of licenses. The development of offshore wind farms offers a unique opportunity because of the associated infrastructure. Service platforms, as well as the pylons themselves, offer perfect structures for mooring longlines and other culture units. One of the advantages of offshore culture may be a lower parasite load in offshore mussels compared with mussels produced under traditional inshore bottom culture. By sampling mussel spat from offshore suspended buoys or collectors, we simulated an offshore culture situation and compared parasite infestation rates with those in mussel spat obtained from suspended inshore buoys or collectors, in mussels from inshore benthic subtidal beds and from inshore benthic intertidal mussel beds. Mussels from offshore sites were free of trematodes and shell-boring polychaetes. Parasitic copepods only occurred at a single offshore site, on a 20-year-old research platform, but not on buoys or collectors exposed for shorter time periods. All three monitored parasite taxa were present at all other sites. The highest prevalence was found for trematodes in inshore benthic intertidal mussels (78.7 ± 6.4%) and locally reached 100%. Through a variety of detrimental effects, trematodes, parasitic copepods and shell-boring polychaetes are known to affect growth performance and product quality. We therefore propose that offshore mussel production could be a promising culture procedure because it seems to result in lower parasite burden than at traditional culture sites. Whether offshore production also results in better survival and growth, compared with inshore mussel culture on a commercial scale, needs to be investigated further.

Introduction

Aquaculture of blue mussels (*Mytilus edulis*) and related species in Europe traditionally uses two types of farming procedures: (i) bottom cultures where mussel spat is collected by boat from natural seeding grounds and relayed on culture lots where growth is known to be better and more consistent (Seaman and Ruth, 1997); mussels remain there for a certain time and are then harvested at marketable size. Alternatively, (ii) suspended cultures, where spat is collected on specially designed structures (e.g. Walter and Liebezeit, 2003) where mussels either grow directly until they reach marketable size or are transferred to grow-out areas. Both culture methods are usually applied in shallow inshore waters with intertidal and subtital environments.

A new perspective for mussel aquaculture has been proposed in which either spat collection or grow-out culture are transferred from inshore to offshore systems (Buck, 2002; Buck et al., 2004a,b). The mussel spat is also hereby collected by longline collectors and harvested from these floating units by boats, but the lines are placed in the open sea and are not close to the mainland (e.g. Wadden Sea). A major difficulty with this farming method is the infrastructure costs for extensive moorings to cope with high seas and strong currents. However, by combining mussel culture with projected offshore wind farms, the opportunity for developing cost-effective infrastructure for servicing as well as for reliable moorings presents itself. A new mooring technique has been developed using windmill pylons (Buck et al., 2004c). This farming method is considered to be a promising modern approach for a variety of reasons. From a nature conservation perspective, such culture practices would lower the impact from mussel fisheries on highly sensitive and protected areas such as the Wadden Sea, where the development of fisheries is restricted by environmental laws. From an economic perspective, an expansion of the industry to commercial scale appears to be possible while at the same time growth of mussels in offshore waters is much faster than inshore, shortening the grow-out time. In addition, field trials indicate that recruitment of mussel spat may be relatively consistent between years. In inshore areas, strong natural fluctuations in the biomass of seed mussels occur, drastically influencing – from year to year – the productivity of the leased plots. Walter and Liebezeit (2001) found even in years with a low inshore spat fall and benthic settlement success that post-larvae of *M. edulis* settled in high densities on suspended collectors. This may be primarily linked to less siltation, less mobility of sediment, lower suspended solids concentrations and more consistent currents (Pulfrich, 1995); new methods to collect seed mussels for their cultures in an environmental friendly way should be of general interest to the fisheries.

Another potential advantage of offshore mussel culture may be a lower or negligible overall parasite burden in offshore mussels. There are three major groups of parasites known to negatively affect mussels: trematodes, parasitic copepods and shell-boring polychaetes (Cheng, 1967; Lauckner, 1983; Sindermann, 1990). Burdens of these types of parasites may be less in offshore mussels because trematodes have complex life cycles, most often with gastropods functioning as their first intermediate host, bivalves as second intermediate and birds as final hosts (Lauckner, 1980, 1983). As the most common first intermediate hosts (e.g. *Littorina littorea* and *Hydrobia ulvae*) are exclusively intertidal organisms, the life cycle for these parasites is incomplete in offshore waters and therefore should result in no or very low trematode burdens in offshore cultured mussels. Parasitic copepods like *Mytilicola intestinalis* and shell-boring polychaetes such as *Polydora ciliata* frequently occur in inshore areas and are dispersed as planktonic larvae (Hempel, 1960; Daro and Polk, 1973). The relatively short duration of these planktonic phases before settlement occurs limits the distance of larval drift; therefore the probability of viable larvae reaching offshore culture structures and encountering mussels is greatly reduced. The risk of infestation is further reduced by the enormous dilution effect occurring during the dispersal of larvae over the relatively large distances between inshore hosts and offshore mussels. Thus, the infestation potential by these parasite species to infest offshore mussels should be greatly impaired and the overall burden substantially reduced.

The objective of this study was to investigate the infestation of mussels with trematodes, parasitic copepods and boring polychaetes at offshore culture sites (> 6 nm from mainland Germany) compared with traditional inshore sites. Mussel spat was therefore collected from experimentally deployed offshore-suspended collectors or buoys, from inshore-suspended collectors, from inshore benthic subtidal mussel beds and from inshore benthic intertidal mussel beds. The three inshore culture types were chosen to reflect the different culture methods currently employed commercially to gather spat, while also comparing benthic vs suspended and subtidal vs intertidal collection methods. The present study focused on mussel spat only because the German, Dutch and Danish inshore mussel culture industry production relies entirely on inshore spat collection. Furthermore, the focus on spat/juvenile growth improved the comparability of the data by ensuring that the mussels investigated were of approximately the same age to avoid potentially confounding age/size–parasite burden relationships.

Material and methods

Origin and collection of mussel spat

Spat of *M. edulis* (n = 30–50 per sample) was collected from various locations within the German Bight in September and October 2003 (Fig. 1). The sample locations were chosen in the following habitats: inshore benthic intertidal (16 sites), inshore benthic subtidal (four sites), inshore-suspended (four sites) and offshore-suspended (seven sites) positions (Table 1). Mussel spat from intertidal sites were sampled at low tide; spat from all other sites were harvested using boats and SCUBA gear. At benthic subtidal sites, *M. edulis* spat was gathered from the seabed. At inshore- and offshore-suspended sites, samples were taken from spat collectors with polypropylene tufts (Tortell, 1976) or buoys. The collectors were fastened into a steel frame, which itself was fixed to a research mooring 3–4 m below the water surface (Fig. 2). These moorings were also used in a research project to investigate the feasibility of mussel offshore aquaculture at offshore wind farms (Buck et al., 2004a,b). Buoys were official navigation marks.

To ensure that all mussels were of approximately the same age (2003 year-class), mussels were selected according to a shell length ranging from 15 to 45 mm. These represented immature specimens of similar physiology, also used in standardized bioassays (Ernst et al., 1991). Mussels from suspended offshore sites were known to be from the 2003 year-class because the spat collector devices were deployed during that year (Buck et al., 2004b).

Mussel samples were in general checked and analysed immediately, except for those samples collected at offshore locations (3-day cruises) and at eight intertidal locations, and were stored deep frozen.

Parasite analysis

The length and width of each of the selected mussels were measured using a vernier calliper [maximum anterior–posterior dimension according to Seed (1968)] to the nearest 0.1 mm. The mussel shells were opened with a scalpel by cutting the adductor muscle. The soft tissue was removed, placed on a thick glass slide and carefully cut in pieces. Tissue residues were dispersed on a compressorium (in order to avoid piling up thick tissue) and then squeezed. Crushed preparations were examined by stereomicroscope at a magnification of 25–50 under transmitted light for the presence of trematodes and parasitic copepods.

Parasite species were identified from relevant literature descriptions (e.g. Dethlefsen, 1970, 1972; Lauckner, 1983; Watermann et al., 1998). As freezing does not affect the size of metacercariae (Lepitzki et al., 1994), identification of trematodes was also reliable in frozen specimens. In addition, mussel shells from five inshore benthic intertidal and from all localities at other sites were inspected for the presence of shell-boring polychaetes.

Statistical analysis of data

In this study, the prevalence of parasites is defined as the percentage of infected mussels within the total sample, which is assumed to be representative of the sampled population. Intensity in this study is defined as the mean number of parasites in all infested mussels in a sample. Prevalence and intensity of the three parasite taxa (Fig. 3) were compared between the four sampling habitats by one-way ANOVA. Data were arcsine-transformed for prevalence and log-transformed for intensity data (Underwood, 1997) prior to analysis resulting in homogenous variances and normality. *Post hoc* calculations were done with Tukey's HSD-test for unbalanced data sets (Spjotvoll/Stoline) (Day and Quinn, 1989). Arithmetic mean values and standard errors were calculated for each sample and for each of the determined parameters.

Results

The prevalence of trematodes and copepods was significantly different among the four sampling sites (one-way ANOVA: trematodes $F_{3,27} = 24.04$, $P < 0.001$; copepods $F_{3,27} = 6.09$, $P < 0.01$, respectively). The prevalence of boring polychaetes was not significantly different (one-way ANOVA: $F_{3,16} = 1.86$, $P = 0.18$). Only *Myt. intestinalis* was present at all sites (inshore benthic intertidal: 27.4 ± 5.3%; inshore benthic subtidal: 26.5 ± 11%; inshore suspended: 13.7 ± 2.7%; offshore suspended: 2.9 ± 2.9%). However, in offshore-suspended sites this parasite occurred at only a single locality (ODAS II). *Polydora ciliata* was not found at offshore-suspended sites and occurred at similar prevalence at the three other sites (Tukey HSD-test, Table 2) (inshore benthic intertidal: 2.7 ± 1.9%; inshore benthic subtidal: 2.5 ± 0.8%; inshore suspended: 1.7 ± 1.7%). Trematodes showed the highest

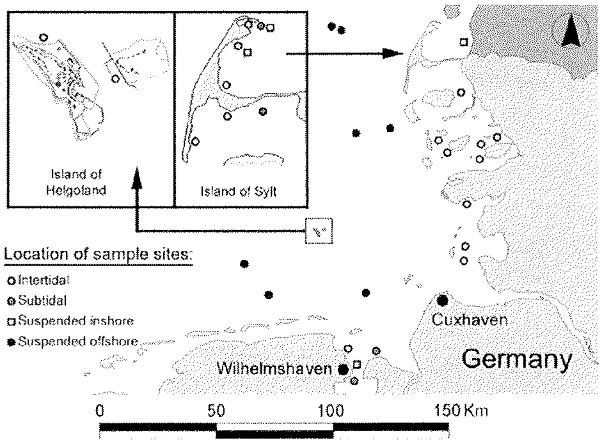

Fig. 1. Map of the German Bight including the enlarged island of Helgoland (upper left) and the enlarged island of Sylt (upper right). Figures indicate the test location of intertidal, subtidal, inshore-suspended and offshore-suspended sample locations

Table 1
Origin of experimental mussels from inshore and offshore habitats

Site number	Location	Habitat	Name of location	Depth (m)/distance from low water line (nautical miles)	n
1	Inshore	Inshore benthic intertidal	Helgoland I: Tetrapoden	0/0	30
2			Helgoland II: Lange Anna	0/0	30
3			Geniusstrand	0/0	30
4			Uthörn	0/0	50
5			Blidselbucht	0/0	39
6			Munkmarsch	0/0	50
7			Puan Klent	0/0	50
8			Archsum	0/0	34
9			Föhr	0/0	34
10			Holmer Fähre I	0/0	36
11			Holmer Fähre II	0/0	50
12			Holmer Siel	0/0	50
13			Rummelloch I	0/0	50
14			Rummelloch II	0/0	50
15			Neufahrwasser Trischen	0/0	50
16			Büsum	0/0	50
17		Inshore benthic subtidal	Fedderwardersiel	7/2	30
18			Jade estuary	6/2.4	30
19			DB	4–8/1	37
20			Nösse Süd	1/1	50
21		Inshore suspended	Niedersachsenbrücke	0–5/< 1	30
22			*Tonne Hoyer Dyb*	0–5/3	50
23			*Tonne Lister Ley 3*	0–5/2.3	50
24			*Tonne Lister Ley 19*	0–5/0.5	30
25	Offshore	Offshore suspended	TG 15 (EEZ)	4/15	30
26			TG 10 (EEZ)	4/8	30
27			Roter Sand	3/15	30
28			Amrumbank West	4/13	30
29			Vortrapptief	4/6	30
30			ODAS I	4/16	30
31			ODAS II (research platform)	4/16	30

For suspended habitats, italics indicate sampling from buoys; other samples were taken from collectors.

prevalence at inshore benthic intertidal sites (78.7 ± 6.4%) and lower prevalence at inshore benthic subtidal (21.7 ± 7.7%) and inshore-suspended sites (28.2 ± 14.1%) (Tukey HSD-test, Table 2). No trematodes were found at offshore sites. The dominating trematode species were *Renicola roscovita* followed by *Himasthla continua*, *H. elongata* and *Psilostomum brevicole* (Table 3). All trematodes occurred as encysted metacercariae; only a single mussel from an inshore benthic subtidal site showed sporocysts, which may refer to *Monorchis parvus* (Bartoli et al., 2000).

Mean intensity among sites differed for trematodes (one-way ANOVA: $F_{3,27} = 5.31$, $P < 0.01$) and for *Myt. intestinalis* (one-way ANOVA: $F_{3,27} = 9.75$, $P < 0.001$) (Fig. 4). Trematode intensity was highest at inshore benthic intertidal sites

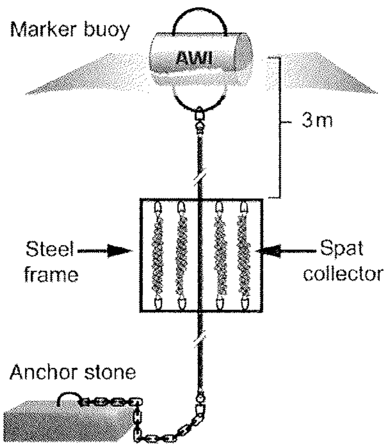

Fig. 2. Mooring device for the use of mussel spat collection in offshore locations. The metal frame, which was the holding unit for the spat collectors, was fixed to the anchor rope at a depth of 3–4 m to avoid the loss of mussel spat because of harsh weather conditions

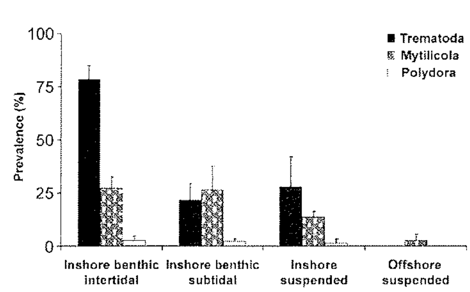

Fig. 3. Mean prevalence (%) (±SE) of trematodes, copepods (*Mytilicola intestinalis*) and shell-boring polychaetes (*Polydora ciliata*) at the four habitats: inshore benthic intertidal: n = 16; inshore benthic subtidal: n = 4; inshore suspended: n = 4; offshore suspended: n = 7

(98.9 ± 86.8 ind host^{-1}) and lower at inshore benthic subtidal (1.7 ± 0.2 ind host^{-1}) and inshore suspended (3.9 ± 1.9 ind host^{-1}) sites (Tukey HSD-test, Table 2). The intensity of trematodes at offshore sites was 0. The intensity of *Myt. intestinalis* was not different for inshore benthic intertidal (1.4 ± 0.1 ind host^{-1}), inshore benthic subtidal (1.7 ± 0.3 ind host^{-1}), inshore suspended (1.2 ± 0.1 ind host^{-1}) or offshore suspended (1.83 ± 1.17 ind host^{-1}).

Discussion

The design of the study includes a sufficiently large area with a representative sampling grid covering the four distinct habitats: inshore benthic intertidal, inshore benthic subtidal, inshore suspended and offshore suspended. Mussels cultured at offshore sites were generally free of parasites. In the case of trematodes, absence of typical first intermediate hosts (*Littorina* spp., *Hydrobia* spp.), which may be restricted to nearshore

Table 2
Results of *post hoc* tests (Tukey's HSD/Spjotvoll-Stoline test for unbalanced data sets) of one-way ANOVAs for trematode and copepod prevalence (a) and trematode and copepod intensity (b) in mussels (*Mytilus edulis*) at the four different sites

	Intertidal	Subtidal	Inshore suspended
Prevalence			
Trematodes			
Subtidal	**0.01**		
Inshore suspended	**0.03**	0.97	
Offshore suspended	**0.0002**	0.28	0.13
Mytilicola			
Subtidal	0.99		
Inshore suspended	0.81	0.94	
Offshore suspended	**0.007**	0.1	0.29
Intensity			
Trematodes			
Subtidal	0.39		
Inshore suspended	0.82	0.88	
offshore suspended	**0.02**	0.83	0.4
Mytilicola			
Subtidal	0.92		
Inshore suspended	0.96	0.99	
Offshore suspended	**0.0007**	**0.04**	**0.03**

Significant results are in bold.

waters, explains this observation. Additionally, a low infection pressure of trematode larvae (cercariae) at offshore sites can be predicted. A low density of larvae at a distance from the host populations in addition to a dilution effect is likely an explanation for the absence of shell-boring polychaetes and parasitic copepods. The probability that larvae will reach such outposts in the open ocean is low. However, the possibility of larvae eventually reaching and infesting offshore sites is indicated by the presence of a few *Myt. intestinalis* in mussels from a 20-year-old research platform (ODAS II) located 16 nm offshore. Given sufficient time, small numbers of *Myt. intestinalis* have become established at the platform and have founded a remote population of yet-unknown size. Despite the short distance to ODAS II (approximately 60 m), mussels from ODAS I were not infested. However, mussels at potential offshore culture sites would be harvested within 1–2 years and hence the risk of infestation with parasitic copepods should remain very low.

At inshore sites, mussels harboured trematodes, parasitic copepods and shell-boring polychaetes. *Mytilicola intestinalis* and *P. ciliata* showed similar prevalence and intensity at the different localities. This may result from a more or less homogenous distribution of larvae in inshore waters during their pelagic stages, leading to a relatively uniform infestation rate of mussels. Even if the distribution of mussels is patchy, the infestation should be similar within the plume of larval dispersal. In contrast, trematodes showed a markedly higher prevalence and intensity at inshore benthic intertidal sites than at the two other inshore areas. This reflects the distribution of typical first intermediate hosts (*Littorina* spp., *Hydrobia* spp.) that reach highest abundance in intertidal areas (Ziegelmeier, 1966). Our results are in agreement with studies from other inshore sites, including raft cultures that also show high local infestation rates and similar species compositions (Svärdh and Thulin, 1985; Villalba et al., 1997; Fuentes et al., 1998, 2002; Svärdh, 1999; Zens, 1999).

With no parasites present at short-lived offshore sites, mussels are free from a variety of negative effects described in mussels and other bivalves. Trematodes have been shown to

Table 3
Mean prevalence (%) and intensity (individual per infected host) of the trematode species found at the four habitats: inshore benthic intertidal: n = 16; inshore benthic subtidal: n = 4; inshore suspended: n = 4; offshore suspended: n = 7

	Intertidal		Subtidal		Inshore suspended		Offshore suspended	
	Prevalence	Intensity	Prevalence	Intensity	Prevalence	Intensity	Prevalence	Intensity
Himasthla continua	5.1 ± 3.9	2.1 ± 0.2	2.4 ± 2.8	2.5 ± 0	3.7 ± 2.7	2.5 ± 0	–	–
Himasthla elongata	27.8 ± 23	2.9 ± 0.9	3.0 ± 3.9	1.4 ± 0.1	3.7 ± 2.7	1.5 ± 0	–	–
Renicola roscovita	69.2 ± 29.9	97.5 ± 86.0	16.9 ± 15.4	1.5 ± 0.3	20.8 ± 41.6	9.7 ± 0	–	–
Psilostomum brevicole	1.8 ± 3.4	1.2 ± 0.1	–	–	–	–	–	–

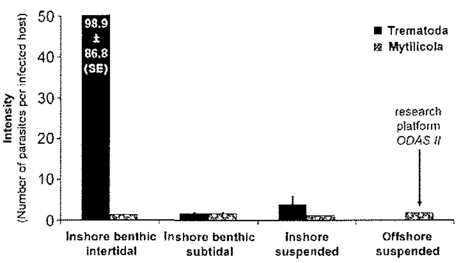

Fig. 4. Mean intensity (individual per infected host) (±SE) of trematodes and copepods (*Mytilicola intestinalis*) at the four habitats: inshore benthic intertidal: n = 16; inshore benthic subtidal: n = 4; inshore suspended: n = 4; offshore suspended: n = 7

reduce survival in mussels and cockles especially under environmental stress (Sannia and James, 1978; Goater, 1993; Wegeberg and Jensen, 1999; Desclaux et al., 2004) and to reduce bivalve growth and condition (Calvo-Ugarteburu and McQuaid, 1998; Taskinen, 1998; Wegeberg and Jensen, 2003). In a previous experiment (D. W. Thieltges, unpubl. data) mussels were artificially infected with *R. roscovita* and placed in intertidal and subtital cages. Results have shown significant differences in the growth rate, being lowest in infected mussels as well as in intertidal cages. In mussels, trematodes have been shown experimentally to reduce the production of byssus threads, presumably enhancing the risk of dislodgement of parasitized mussels (Lauckner, 1983). Furthermore, Seed (1976) and Cousteau et al. (1990) mentioned that trematode sporocyst infestation often led to sterilization, which does not primarily affect the cultured mussel itself but does limit the potential spat fall for the following season. The parasitic copepod, *Myt. intestinalis*, has been suggested to live as a commensal rather than a harmful parasite as observed in a 10-year study carried out in the Cornish estuary (Davey, 1989). However, *Myt. intestinalis* has been suspected to be involved in mass mortalities of mussels (Korringa, 1951), but its actual pathogenicity has been questioned (Davey et al., 1978; Gee and Davey, 1986). However, *Myt. intestinalis* also seems to be involved in a reduction of the condition of infected mussels (Theisen, 1987; Camacho et al., 1997). *Mytilicola intestinalis* has negative effects on the oocytes of mussels, which affects both fecundity and condition (e.g. Theisen, 1987; Tiews, 1988). Dethlefsen (1974, 1975) demonstrated that *Myt. intestinalis* infestation affected meat content of market-size mussels. Excavations of the shell-boring polychaete, *P. ciliata*, reduce shell strength, thus making mussels more susceptible to predators (Kent, 1981). They also negatively affect the condition of the mussels (Kent, 1979; Ambariyanto and Seed, 1991). As *P. ciliata* produces shell deformations on the inner surface of the shell, infested mussels may be less attractive to consumers.

A number of studies have described the parasite load of *M. edulis* in the German Wadden Sea. The general pattern indicates, particularly for *Myt. intestinalis*, a relatively high prevalence during the early years after introduction of this non-indigenous parasite into the German Wadden Sea. Later, a generally lower level persisted, with some year-to-year variability (e.g. Dethlefsen, 1992). Our data indicate prevalence and intensity similar to those observed historically. It is unfortunate that no studies of parasite loads have been undertaken in the German Wadden Sea since the mid-1970s. We are, therefore, unable to conclude that the snapshot findings of our one-season survey are representative in the long term. The implication of this critical point is obvious: if our observations were made during a year of exceptionally low overall infestation, then the likelihood of some higher prevalence in offshore sites cannot be excluded for years with much higher overall prevalence inshore. In other words, high levels of infestation inshore will result in the release of planktonic reproductive stages which may disperse greater numbers offshore, thereby increasing the probability of encounters and infestation at offshore locations. This may have strategic management implications for mussel farming. Nevertheless, our findings indicate that overall infestation rates in offshore mussels will always be somewhat lower than in mussels from inshore locations.

As described above, the absence of metacercaria in offshore mussels is probably due to the absence of one of the obligatory intermediate hosts (e.g. the snail). On the contrary, this does not mean that trematode infestations do not occur in offshore habitats (away from the Wadden Sea). For example, our samples from the northern tip of the island of Helgoland showed the highest infestation rate in this study (max. 5053 metacercaria in a single mussel). The coast of Helgoland contains a variety of hard (rocky) substrates at tidal, intertidal and subtidal levels, thereby supporting a large variety of taxa. Several snail species (all intermediate hosts) exist in these habitats (Ziegelmeier, 1966; Janke, 1989). Additionally, these rocky shores are protected areas and accommodate large breeding populations of migratory birds. In conclusion, high seasonal populations of birds and high biodiversity of intermediate hosts at the same rocky shores result in high diversity and prevalence of mussel parasites.

The overall findings and the comparisons among different sites allow some firm suggestions for management options of offshore mussel farms to keep parasite loads as low as possible. Structures used for attachment (e.g. longlines, all parts of buoyancy, mooring chains, service platforms) should be limited to a lifetime of a few years or cleaned and disinfected at regular intervals (2–3 years). This should avoid the development of large fouling communities that include the intermediate hosts, particularly on permanent structures (e.g. wind farm pylons and service platforms). The most appropriate frequency for cleaning should be determined through a long-term monitoring programme of the fouling communities with special emphasis on target species (e.g. snails).

Conclusions

In conclusion, we may safely state that mussels from offshore sites are largely free of parasites. Offshore mussels should survive better and grow faster than their inshore counterparts. Our results indicate that mussels raised at offshore sites offer a promising perspective for mussel aquaculture as they carry low parasite burdens. Other advantages include reduced fishery pressure on inshore seed mussels, higher yield and more reliable recruitment. However, our investigation was not undertaken at established commercial offshore farming sites, but at an experimental unit which is believed to simulate offshore culture situations realistically. How the parasite infestations will actually develop offshore will require investigation once commercial offshore farming has started. Another knowledge gap is the potential infestation of offshore mussels with microparasites such as human pathogens (viruses and bacteria). Similar to the macroparasites investigated, dilution effects and limited dispersal might lead to a favourable situation in offshore waters. Further, it is not known whether highly infested mussels from intertidal mussel beds, which are collected by fishermen and relayed for on-bottom mussel culture at suitable subtidal licensed plots, may transfer parasites to less-infested habitats.

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Appendix X

Publication X

Larval occurrence and settlement in the German Bight – a trial to estimate potentials for **Mytilus edulis** *culture in offshore areas*

Walter U, Buck BH, Liebezeit G (accepted), Aquaculture International

1 2 3 4 5 6 7 8 9 10 11 12

Abstract

To obtain information on the occurrence of blue mussel larvae (*Mytilus edulis*) in the German Bight (North Sea), plankton sampling was carried out at nine test locations in offshore areas 10-40 nautical miles offshore. Furthermore, the settlement of *Mytilus* spat was estimated on test moorings equipped with suspended artificial collectors. Larvae were distributed heterogeneously in time and space, with the highest numbers recorded in May (80-25,000 larvae m^{-3}). Lower larval numbers were observed in the offshore areas (>20 nm (nautical miles) off the coast) compared to the inshore locations (<20 nm). Numbers of settled *Mytilus* spat ranging from 0-1,100 mussels·m^{-1} collector were low offshore compared to inshore data of several tens of thousands settlers m^{-1} collector. Water samples were also obtained to get insight into nutrient concentrations, chlorophyll contents and the POC/TPN ratios (particulate organic carbon to total particulate nitrogen) as potential indicators for the availability and quality of food for blue mussels. Water samples showed good food availability for mussel growth in the offshore areas. However, further detailed studies on larval distribution and settling are needed to fully assess the utility of seed mussel recourses in offshore areas.

Larval Occurrence and Settlement in the German Bight - a Trial to Estimate Potentials for *Mytilus edulis* Culture in Offshore Areas

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Abstract

To obtain information on the occurrence of blue mussel larvae (*Mytilus edulis*) in the German Bight (North Sea), plankton sampling was carried out at nine test locations in offshore areas 10-40 nautical miles offshore. Furthermore, the settlement of *Mytilus* spat was estimated on test moorings equipped with suspended artificial collectors. Larvae were distributed heterogeneously in time and space, with the highest numbers recorded in May (80-25,000 larvae m^{-3}). Lower larval numbers were observed in the offshore areas (>20 nm (nautical miles) off the coast) compared to the inshore locations (<20 nm). Numbers of settled *Mytilus* spat ranging from 0-1,100 mussels·m^{-1} collector were low offshore compared to inshore data of several tens of thousands settlers m^{-1} collector. Water samples were also obtained to get insight into nutrient concentrations, chlorophyll contents and the POC/TPN ratios (particulate organic carbon to total particulate nitrogen) as potential indicators for the availability and quality of food for blue mussels. Water samples showed good food availability for mussel growth in the offshore areas. However, further detailed studies on larval distribution and settling are needed to fully assess the utility of seed mussel recourses in offshore areas.

Keywords: mussel farming, offshore aquaculture, larval distribution, settlement, POC/ TPN ratio, North Sea

Introduction

Most coastal European countries are engaged in mussel culture. Mussel farming along the German North Sea coast has a long tradition (Kleinsteuber and Will 1988). Although the exploitation of natural mussel beds (*Mytilus edulis*) in the German Wadden Sea has taken place for centuries, an extensive, combined fishery-culture system has developed only since the 1950's (Korringa 1976), using the techniques described by Seaman and Ruth (1993). In this system seed mussels are collected from dense, wild beds in subtidal or intertidal parts of the Wadden Sea area. They are re-laid at densities of 30-40 t ha^{-1} at a shell size of 5-20 mm on specific, permanently water-covered culture plots resulting in an increase of growth rate and a doubling in size within about one year (Hickman 1992) thus allowing a harvest of up to 100 t ha^{-1} (half-grown size: 20-40 mm) (Seaman and Ruth 1993). However, negative aspects of bottom culture are that the mussels are subject to higher predation pressure from eider ducks, starfish and/or crabs and that this technique depends on the availability of seed mussels from the wild.

Initiated as a result of poor recruitment over several years, research commenced in 2000 to investigate whether or not suspended culture techniques could be used to obtain seed mussels in an inshore area of the Jade estuary (Walter and Liebezeit 2001, 2003). The technique employed was a longline, commonly described as off-bottom culture, which was suspended into the water column. Attached to the longline, different types of collectors were deployed to act as settling substrates for the mussel spat. Thus, the number of larvae in the water column is a main factor affecting the production output. However, the potential of a direct expansion of the industry in the Wadden Sea is limited due to the nature reserve status along the German North Sea coast and its harsh and highly dynamic environmental conditions (NPLSH 1999; NPLLS 2001). Because of the relatively short coastline in relation to its inland area the only option for further development of mussel cultivation within German national marine waters seems to be to move to more exposed, i.e. offshore farming sites (Buck 2002). With this in mind, a multiple-use concept for the areas where offshore wind farms are planned has been developed (Buck et al. 2004). This encompasses various aquaculture species including macroalgae, blue mussels and oysters.

The present study aimed at identifying the occurrence and distribution of mussel larvae in the coastal area 10-40 nautical miles off the

German North Sea coast, where offshore wind farms are planned. While inshore (Wadden Sea) distribution and settlement is known, no data are as yet available for offshore areas. The present study provides first data on spat settlement on suspended collectors while also offering insight into the time scale and density of spat settling. Furthermore, the contents of chlorophyll and the C/N ratios (particulate organic carbon to total particulate nitrogen) was determined to indicate whether one could in principle expect sufficient food for blue mussels at the offshore test sites in the German North Sea territory and the Exclusive Economic Zone. If the limited data set would indicate that the minimum required for a reasonable nutrition of mussel larvae cannot be met this would be considered as a negative sign in the list of site selection criteria.

Material and Methods

Offshore wind farm sites and test moorings

In order to find suitable offshore locations where the biological background conditions were suitable for both wind and aquaculture farms, a number of offshore wind farm sites within the German Bight were surveyed in 2002. Subsequently nine locations 10-40 nautical miles off the German North Sea coast were selected for further investigation (Fig. 1). Site criteria for this survey were the vicinity to a planned wind farm, the distance from the coast, the water depth, the water quality, and the substratum.

In January 2003, the selected offshore locations were equipped with test moorings on a

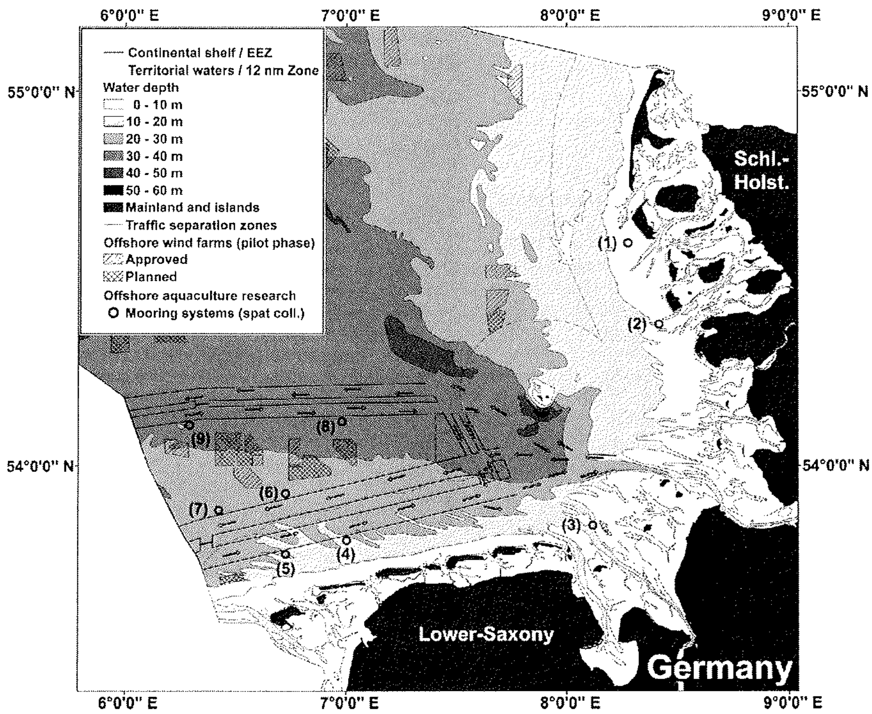

Figure 1. Map of the German Bight including the positions of the nine test locations, 10-40 nautical miles off the German North Sea coast.

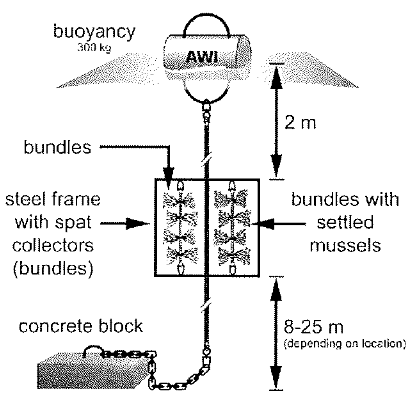

Figure 2. Special designed offshore spat collector. The frame holding the bundles is attached 3 m below the surface.

cruise with the research vessel RV *Heincke*. The moorings were deployed adjacent to proposed wind farms. For safety reasons they were placed at least 1 nm from the wind farm areas.

The mooring's marker buoy had a buoyancy of 300 kg and was connected to a 2 ton concrete block with a 22 mm steel wire and a heavy buoy chain (Fig. 2). At 3 m below the surface a 1*1 m metal frame was fixed to the wire, providing a holding unit for two spat collectors clamped into the frame. The depth was chosen because of multi-annual data (Walter and Liebezeit 2001, Joschko et al. 2006) indicating little settlement in depths <4 m. Each collector consisted of a polypropylene carrier rope (10 mm) with four inserted transverse elements to enlarge the surface area. The elements were made of 15 cm long pieces of the same polypropylene rope, which were frayed manually in 1,100 single fibres to produce a bow-tie-like bundle. This type of collector is equivalent to the type used by Tortell (1976) and Dare et al. (1983) and has proven successful in its ability to attract mussel spat in tens of thousands of individuals per meter (Walter and Liebezeit 2003).

Once a month if possible (February, March, April, May, July, September), samples were collected on a 5-day cruise using the research vessels RV Heincke, RV *Uthörn*, and RB *Remzy*.

Determination of larvae numbers and settlement of post-larvae

To determine the number of mussel larvae in the water column, 50 l samples of seawater (3 replicates) were taken from a depth of 5 m using a submersible pump (Cáceres-Martinez and Figueras 1998; Roegner 2000). The seawater samples were filtered through a plankton net (mesh size: 125 µm), fixed in buffered formaldehyde (4 %) and stored at 4 °C. In the laboratory, mussel larvae were quantified on a counting grid using a binocular microscope (magnification 20-50). Due to the poorly developed morphological diagnostic features, especially at the early larval stages, mussel species were not discriminated routinely (Cáceres-Martinez and Figueras 1998).

Bundles placed at the study site were sampled monthly to follow the settlement of post-larvae during the study period. The remaining ropes were not collected until the end of the eight month experimental period to provide information on long term settlement. Removed bundles were preserved in buffered formaldehyde (4 %). All bundles were later rinsed with water and settled mussel spat were removed. When larvae remained on the filaments, the whole bundle was bathed in sodium hypochlorite solution to ease the detachment of the byssus threads. Mussel spat were separated from other fouling organisms and counted. Small mussels (<4 mm) were measured in length using a binocular microscope and a micrometer. Individuals with a size >4 mm in length were measured using vernier calipers.

Water samples

Water samples for the determination of chlorophyll as well as particulate organic carbon (POC) and total particulate nitrogen (TPN) were collected at a depth of 3-5 m (depending on tidal level and current velocity on the time of sampling) with the same electric pump used for the larvae sampling.

All water samples were screened through 300 µm plankton gauze to remove larger particles.

To measure chlorophyll (chl *a*, *b*, c_1, c_2) and phaeophytin contents, 800 ml of seawater were filtered through Whatman GF/C® filters (n = 2). The filters were cut into small pieces and stored at -20 °C in 1.5 ml Eppendorf cups. These were transferred into test tubes with 10 ml aqueous acetone (90 %) and treated ultrasonically (Ultra Sonifier W 250 Branson) for 20 seconds while cooled on crushed ice. Samples were then incubated at 4 °C in the dark for two hours followed by centrifugation for 10 minutes at 4000 rpm. The extinction of the supernatant was measured (optical path length 5 cm) at 750, 630, 647, 663, 664, 665 nm (Parsons and Strickland,

1963) using a spectrophotometer (Milton Roy Genesis). The reference was aqueous acetone (90 %). Thereafter, 0.1 ml HCl was added and the measurement at 665 nm was repeated. After correction of the extinction for all wavelengths by the extinction at 750 nm the chlorophyll contents were calculated employing the equations given by Jeffrey and Humphrey (1975). The total chlorophyll (TCHL) is therefore the sum of *a*, *b*, c_1, c_2-chlorophyll and the phaeophytin.

Samples for the determination POC and TPN were filtered over pre-combusted (450 °C, overnight) glass fibre filters (Whatman GF/C®), washed with 2 ml doubly distilled waters and dried at 65 °C. After weight determination the samples were acidified with 1M HCl to remove inorganic carbonates and redried. POC/TPN was then determined by high temperature combustion (Nitrogen Analyser 1500, Carlo Erba Strumentazione). Acetanilide was used as calibration standard.

To determine the seasonal availability of inorganic nutrients as an indicator for phytoplankton growth conditions ammonium, nitrate, phosphate and silicate were analysed in the seawater according to Grasshoff et al. (1999) on replicate samples. Reproducibilities were ± 3.0 % (reactive dissolved phosphate, n = 94), ± 5.2 % (nitrite, N = 95), ± 3.3 % (nitrate, n = 93), ± 4.5 % (ammonium, n = 95) and ± 2.5 % (silicate, n = 94).

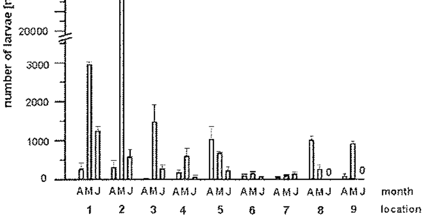

Figure 3. Number of mussel larvae (mean ± SD, means = columns, SD = bars) within the water column in a depth of 3-5 m in April, May and July 2003; test locations are given in Fig. 1.

Statistical analysis of data

The statistical analysis was performed using the Statistical Package for Social Sciences (SPSS 12.0). The normal distribution of the variables was checked using the Kolmogorov-Smirnov test. To assess differences in mussel larvae and spat numbers in relation to distance from the shore (group 1 <20, group 2 >20 nautical miles offshore) the non-parametric Mann-Whitney test was applied. Significance was accepted at $P < 0.05$ (Sachs 1972).

Results

Sample acquisition

Due to very stormy weather on two cruises, some of the test moorings could not be retrieved to collect data. Every opportunity was used during calm weather to collect water and mussel spat samples and to supply the metal frame with new collector bundles. Additionally, due to the harsh environmental conditions two of the moorings were lost. In April the buoy at location 2 disappeared, and the buoy at location 1 was lost after the sampling in May.

Determination of larvae numbers and settlement of post-larvae

The abundance of planktonic mussel larvae showed an inhomogeneous distribution among the nine test locations in the offshore area of the German Bight (Fig. 3). In April numbers of 25 - 1,030 mussel larvae/m^3 were recorded, with numbers >1,000 at both near-shore and further offshore stations. Increasing abundance of larvae in May was closely related with the spawning periods usually occurring in April to May (Pulfrich 1995, Pulfrich 1997, Walter & Liebezeit 2001). Both test locations off the Schleswig-Holstein coast (locations 1 + 2) showed the highest larval contents (3,000 - 25,000 larvae/m^3), whereas numbers at locations off the Lower Saxonian coast were low by comparison (80 - 1,500 larvae/m^3). In July, the numbers of larvae decreased after the peak in May, again with higher larval densities at locations 1 and 2 and lower numbers off the coast of Lower Saxony. In general, significantly lower larval numbers could be observed in the offshore areas (>20 nm off the coast) compared the inshore locations (< 20 nm).

The first settlement of post-larvae on suspended bundles was recorded in April 2003 at test locations 1 and 4 - 6 with mean values of

4 - 29 ind.·m^{-1} (Fig. 4). Due to harsh weather conditions the settlement record in May is incomplete. Numbers were low (4 - 56 ind.·m^{-1}) with the exception of the Weser estuary where higher numbers were observed (800 ± 400 ind.·m^{-1}). After the larval peak from May-July a maximum of 300 ind.·m^{-1} was recorded. Long-time records from bundles deployed for the full experimental period (January to August) showed a further increase in the number of mussels settling at most of the locations, ranging from 11 to 1,100 ind.·m^{-1}. Results from all locations showed no significant relationship between distance from the shore and density of settlement of mussel spat.

Nutrients and chlorophyll

Inorganic nutrient concentrations were high in winter and decreased towards March remaining at a relatively low level until September (Fig. 5). Reactive phosphate showed an increase in July at the Lower Saxonian stations. Chlorophyll contents showed a peak of around 16 µg·l^{-1} in April and summer values around 7 µg·l^{-1} (Fig. 4). POC/TPN ratios, on the other hand, display little variation over time. A slight decrease was, however, noticeable for the April samples. Marked changes occurred in the POC/TCHL ratio with a decrease from 380 in January to 30 in April and a slight increase to 50 in May and July. The chlorophyll data indicate a pronounced early phytoplankton spring bloom followed by lower summer values (Fig. 6). None of the inorganic nutrients became limiting. Reactive dissolved phosphate had its lowest concentrations in May (0.07 µMol·l^{-1}), dissolved inorganic nitrogen (DIN -sum of ammonium, nitrite and nitrate) showed a minimum concentration of 3.0 µMol·l^{-1} also in July while the minimum concentration of silicate (0.9 µMol·l^{-1}) was observed in April. This indicates that, as expected for the North Sea, the spring bloom was dominated by diatoms.

Discussion

Larvae numbers and settlement of post-larvae

Favoured by a preceding spring phytoplankton peak (Niesel and Günther 1998), spawning of *Mytilus edulis* along the North Sea coast of Germany generally occurs in May to June (Pulfrich 1995, Pulfrich 1997, Walter and Liebezeit 2001). Although subsequently larvae are also present larval numbers in the water column are considerably smaller than at the main peak (Fig. 3). The fate of the *Mytilus* larvae in the plankton over the course of development is at present not well known.

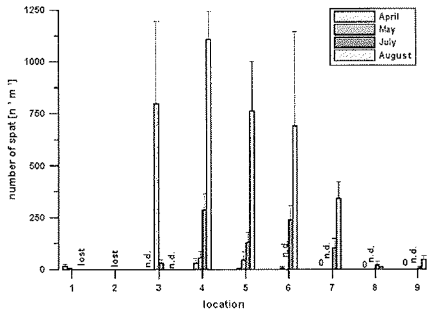

Figure 4. Number of mussel spat (mean ± SD, means = columns, SD = bars) on tufts in April, May, July and August 2003; test locations are indicated in Fig. 1; n.d. = no data; lost indicates the loss of moorings due to storm conditions or accidents.

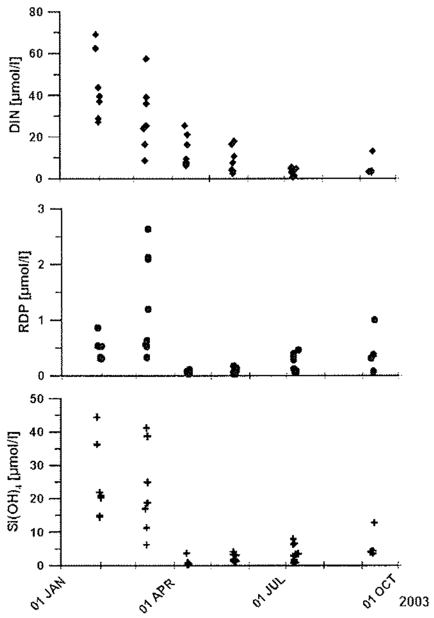

Figure 5. Nutrient concentrations at the test locations between January and September 2003 (mean plus standard deviation).

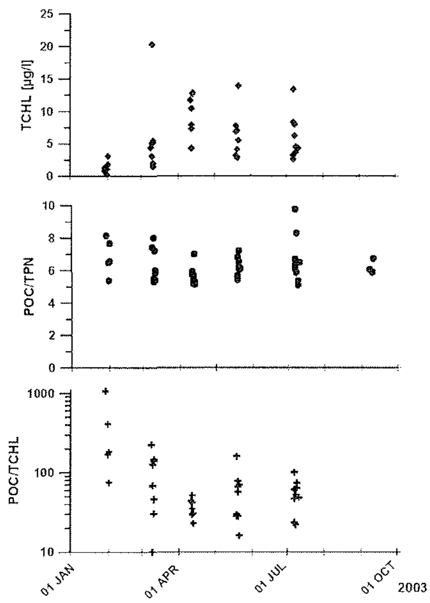

Figure 6. Chlorophyll concentration, POC/TCHL and POC/TPN ratios respectively at the test locations (mean plus standard deviation).

Mussel beds are predominantly located in the tidal waters of the Frisian Islands (Wadden Sea) where hard substrates suitable for settlement are absent. There are indications that mussel beds are also present in front of the East Frisian Islands although exact locations are presently not known. Successful settlement of larvae, which derive from these areas, is dependent on timing of larval release with wind forces and currents (Young et al. 1998; Metaxas 2001). If the colonisation of hard substrate in the vicinity of the origin is impossible *Mytilus edulis* larvae potentially delay metamorphosis for a number of weeks (Bayne 1965, 1976). This allows the colonisation of substrates in great distances off the coast (McQuaid and Phillips 2000), however, large scale mortality of mussel spat settling in unsuitable areas offshore could occur (Chicharo and Chicharo 2000; Roegner 2000). During the extended dispersal time in the water column *Mytilus* larvae are able to survive periods of exposure to physical stresses such as water turbulence and unfavourable currents (Belgaro et al. 1995, Morgan 1995, Richards et al. 1995) as well as to biological constraints such as predation (Young & Chia 1987, Rumrill 1990) and starvation. Predation by fish and invertebrates and starvation exceeds mortality of these larvae (Thorson 1966, Mileikovsky 1971, Purchon 1977, Jørgensen 1981). Furthermore, due to a dilution effect long drift times to offshore settlement sites result in declining densities of mussel larvae in the water column (Young et al. 1998, Metaxas 2001, Buck 2004). Therefore, it can be assumed that the larval abundance in offshore areas is *a priori* lower than in inshore locations. For a coast-dependent population, an excessive export to the open North Sea would represent a loss from the parental stock. The gradient in larvae numbers from the inshore to offshore areas in the German Bight confirms this assumption. Typical inshore larval densities range from 9,000 to 190,000 individuals·m^{-3} (Heiber 1988; Pulfrich 1995; Boysen-Ennen 1997; de Vooys 1999; Nehls 2001; Walter and Liebezeit 2001). The concentration of larvae was very low off the Lower Saxonian coast, even at the location closest to the inshore spawning areas in the Wadden Sea despite a sufficient nutritional quality of the phytoplankton. However, 10 nautical miles off the Schleswig-Holstein coast comparatively high larval numbers were recorded. This result indicates that in the Schleswig-Holstein region the mussels were of local origin, whereas off the coast of Lower Saxony mussel larvae drifting with the counter-clockwise directed coastal current (Becker 1990) may have originated from a more westerly origin. Thus, the coupling of these events (phytoplankton density and density of larval drift) is decisive for offshore settlement.

Mytilus pediveliger larvae preferably settle on threadlike structures, e.g. hydroids, algae or the byssus of adult mussels (Cooper 1981; Eyster and Pechenik 1987; Satuito 1995). This behaviour could be used in the collection of young mussel spat on artificial collectors for the suspended culture of mussels and for monitoring the number of plantigrades in the water column (King et al. 1990). For this study a robust collector type which could easily replaced was used. Previous studies had shown that the tufted polypropylene collector was successful in attracting spat in densities numbering tens of thousands of individuals per metre (Tortell 1976, Dare et al. 1983; Walter and Liebezeit 2003).

The highest settlement densities in the German Bight were 30 to several hundred times lower than in the inshore areas of the North Sea. In the Wash (UK) 100,000 to 400,000 ind.·m^{-1} of *Mytilus* spat settled on this collector type (Dare et al. 1983). At the Lower Saxonian Wadden Sea coast (Germany) mean numbers of monthly settled blue mussel spat of 33,000 to 72,000 ind.·m^{-1} were recorded (Walter and Fehrs 2004). Even long-term collectors subject to several settlements, although they also experienced losses caused through predation or wave action, showed higher densities in inshore compared with offshore areas by at least one order of magnitude (28,000 ind.$\cdot$m^{-1} in March to August 2000; Walter and Liebezeit 2001).

It can be assumed that the low larval concentrations in the water column resulted in the poor settlement. Unfortunately, there were no data available from the literature concerning the settlement at offshore sites. Ardisson and Bourget (1991) reported spat abundances on buoys in St. Lawrence Gulf in Canada. On these suspended substrata they observed a gradient in spat number from the inner sheltered regions to the outer more exposed waters of the Gulf. It was however not possible to directly compare densities owing to different settlement substrates. Many studies have investigated the appearance of *Mytilus* spp. in offshore habitats, mostly attached to the rigs of oil and gas platforms. These investigations primarily deal with fouling organisms (Ralph & Troake 1980), community structure (e.g. Wolfson et al. 1979, Forteath et al. 1982, Stachowitsch et al. 2002), biomass to size ratios (e.g. Richardson & Seed 1990; Richardson et al. 1990, Qvarfordt et al. 2006), depth zonation (Rule and Smith 2005), regional differences (Garcia 1991) and growth in relation to food availability and temperature (Page & Hubbard 1987).

There are only two publications describing a natural spat collection in an offshore area. One is a mussel farm established off the Santa Barbara coastline attached to an oil structure (Conte 1990). Unfortunately there was no information on the settlement of this farm. The other offshore related study is describing the settlement on the research platform FINO, 45 km off the Island of Borkum in the German Bight (Orejas et al. 2005). The percent coverage of the platform piles and the colonisation of various depths were investigated. However, there are no data available on the density of settlement and the numbers of larvae. Nearshore spat settlement, about 2 nm off the coast of New Zealand (Alfaro and Jeffs 2003), ranged from 844-2.562 ind. 1 m^{-1} and was attributed to the adjacency to the mussel farms one nautical mile away.

Food concentration and quality

As part of the site-selection criteria, i.e. to see whether offshore sufficient food will be available of for newly settled mussels, water samples were analysed for phytoplankton content in terms of chlorophyll as well as for C/N-ratios and nutrient concentrations. The data are, although at present not comprehensive, sufficiently indicative to be used for correlations between phytoplankton density and composition and growth of mussels. The data at hand suggest that beginning with the start of the spring bloom food of high quality is available for the settling of mussel larvae until at least July and probably through the summer to the autumn phytoplankton bloom. The precise extent and potential of this food resource needs to be investigated further. POC/TPN ratios were around 7 even in winter. This suggests that the particulate material had a relatively high nitrogen content possibly indicating a high bacterial colonisation. High terrestrial contributions to the particulate pool should have ratios in excess of 10. Sarà et al. (1998) observed low POC/TPN ratios only in connection with high phytoplankton cell counts and noted that higher ratios were connected to high detritus contents. If contributions from a bacterial biomass are indeed present then the available food for filter feeders will be of a reasonable quality even under non-bloom conditions. Similarly, the POC/TCHL ratios of 30 to 50 in spring and summer are indications of a high contribution of non-detrital carbon to the particulate pool while the high January values clearly suggest a pronounced detrital component (e.g. Steele and Baird 1965). Hence growth of mussel larvae will not be restricted by the availability and nutritional quality of particulate matter from late spring to autumn.

Conclusions

Although the settlement of *Mytilus edulis* larvae was low in 2003, the results described above are restricted to one season. Incomplete data acquisition due to bad weather conditions impeding the sampling and the loss of moorings influenced the quality of the results. On the other hand, these problems have highlighted the issues of concern in establishing aquaculture constructions offshore in the North Sea, and provide an insight into type of structures required to survive the harsh environment.

If the recruitment is consistently as low as in the study period, gathering seed mussels far offshore would not be economically viable. However, results from this study have shown that there is a sufficient, year round supply of food for filter feeders which could be harnessed in extensive farming of mussels with minimal handling in the offshore environment. Further studies on distribution and settling of mussel larvae will contribute to a better understanding of the aquaculture potentials in offshore areas.

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Appendix XI

Patent I

Trägervorrichtung zur Kultur von Makroorganismen in marinen Gewässern

Buck BH, Buchholz CM (2004), Patent No: DE 10 2004 010 652

1 2 3 4 5 6 7 8 9 10 **11** 12

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Bezeichnung
Trägervorrichtung zur Kultur von Makroorganismen in marinen Gewässern

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Innerhalb von drei Monaten nach Veröffentlichung der Patenterteilung kann nach § 59 Patentgesetz gegen das Patent Einspruch erhoben werden. Der Einspruch ist schriftlich zu erklären und zu begründen. Innerhalb der Einspruchsfrist ist eine Einspruchsgebühr in Höhe von 200 Euro zu entrichten(§ 6 Patentkostengesetz in Verbindung mit der Anlage zu § 2 Abs. 2 Patentkostengesetz).

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ung 412/2002. Alfred-Wegener-Institut für Polar- und Meeresforschung, 27568 Bremerhaven. Kap. 6,
S. 74-85;
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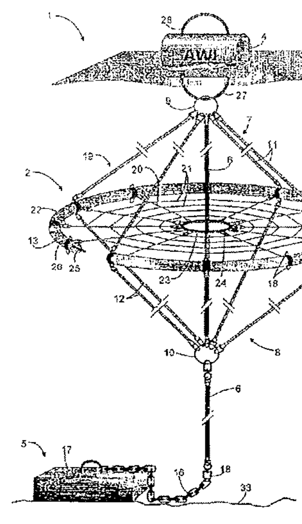
bei Helgoland zur Gewinnung von Phykokolloiden und zur Verwendung als Biosorptionsmittel". IN: Abschlussbericht zum Vorhaben O3F0096A des BMBF,
1996, Teil 1;

(54) Bezeichnung: Trägervorrichtung zur Kultur von Makroorganismen in marinen Gewässern

(57) Hauptanspruch: Trägervorrichtung (1) zur Kultur von Makroorganismen (31) in marinen Gewässern mit zumindest einer Ringkonstruktion (2), die unterhalb der Wasseroberfläche (3) zwischen zumindest einem Auftriebsmittel (4) und einer Verankerung (5) angeordnet ist und in einem geschlossenen Außenring (13) eine spinnennetzartige Kultureinheit (19) aus radialen Tragleinen (20) und azimutalen Kulturleinen (21) aufweist, dadurch gekennzeichnet, dass der Außenring (13) über eine obere Hahnepot (7) mit einem zentralen Auftriebsmittel (4) und über eine untere Hahnepot (8) mit der Verankerung (5) verbunden ist, wobei jede Hahnepot (7, 8) aus einem zentralen Hahnepotring (9, 10) und mehreren gleichmäßig am Umfang des Außenrings (4) befestigten und nach oben und unten jeweils von gemeinsamen Anschlagpunkten (14) aus verlaufenden Hahnepotseilen (11, 12) aufgebaut ist, dass die radialen Tragleinen (20) unter Spannung an einem zentralen Innenring (23) befestigt sind und dass das zentrale Auftriebsmittel (4) direkt mit der Verankerung (5) über zumindest ein durch den zentralen Innenring (23) verlaufendes und...



Beschreibung

[0001] Die Erfindung bezieht sich auf eine Trägervorrichtung zur Kultur von Makroorganismen in marinen Gewässern mit zumindest einer Ringkonstruktion, die unterhalb der Wasseroberfläche zwischen zumindest einem Auftriebsmittel und einer Verankerung angeordnet ist und in einem geschlossenen Außenring eine spinnennetzartige Kultureinheit aus radialen Tragleinen und azimutalen Kulturleinen aufweist.

Stand der Technik

[0002] Zu den in marinen Gewässern, wie den Meeren und Ozeanen, kulturfähigen Makroorganismen zählen in erster Linie Algen (Makroalgen wie Braun-, Grün- und Rotalgen) und Muscheln (wie Miesmuschel und Austern). In Ostasien werden traditionell Algen gezüchtet, wobei die dazu nötigen Erfahrungen bereits einige Jahrhunderte alt sind. Dort werden jedoch nur Meeresgebiete genutzt, die weitgehend und sehr gut gegen unwirsche Wetter- und Seebedingungen geschützt sind, wie beispielsweise Buchten oder Ästuare. Langleinen-, Floß- oder Pfahlsysteme sind die hauptsächlichen Trägervorrichtungen für Algenkulturen. Diese sind am Boden verankert und gegen raue See sehr anfällig. Meeresareale, in denen harsche Wetterbedingungen vorherrschen, wurden bisher für die Aquakultur aller potenziell züchtbaren Meeresorganismen kaum genutzt. Erst seit einigen Jahren erstreckt sich die marine Aquakultur aufgrund von Nutzerkonflikten im Küstenmeer und den damit verbundenen komplizierten Rechtslagen, den urbanen Abwässern, sowie besseren Sauerstoffbedingungen auch in den Offshorebereich der Meere. Es wurden die ersten absenkbaren Tauchkäfige für die Kultur von Meeresfischen im Offshorebereich bereits in den 1970er Jahren in Deutschland entwickelt und weitere Entwicklungen später in Kanada und in den USA eingesetzt, wobei solche Systeme noch Pilotcharakter haben. Makroalgen wurden jedoch in Gebieten mit ungünstigen Wetterbedingungen weltweit hauptsächlich zu Forschungszwecken gezüchtet. Zu erwähnen ist hier ein Projekt von der Isle of Man, wo verschiedene Konstruktionen, insbesondere die Langleinentechnik, eingesetzt wurden. Weiterhin ist aus der japanischen Zusammenfassung zu der JP 2001054330 A eine Käfigkonstruktion zur Algenkultur in 10 m bis 25 m Seetiefe bekannt, bei der als Kultureinheit zwischen flutbaren Eckbehältern eine Vielzahl von Streben und Seilen gespannt ist. Fieren und Hieven der Konstruktion erfolgt durch Belüften und Fluten der Eckbehälter und durch Angreifen an der instabilen Kultureinheit selbst. Aus der japanischen Zusammenfassung JP 11196696 A ist eine pfahlartige Steckkonstruktion mit in einem Auge eingebetteten Algenkulturen bekannt, die in den Meeresboden eingesteckt wird. Aus der WO 86/02395 A1 ist es weiterhin bekannt, laminare Algenkulturen an ihrem unteren Ende über eine mehrarmige Seilanordnung an einem Pflock im Meeresboden zu befestigen. Diese Konstruktionen sind jedoch nur in Küstennähe einsetzbar und für starken Seegang ungeeignet.

[0003] Auch in Deutschland gab es in den Jahren 1994 bis 1996 vor Helgoland Versuche, unter Nordseebedingungen Makroalgen zu züchten. Es handelt sich hierbei um ein vom BMBF geförderten Projekt: „Massenkultur mariner Makroalgen bei Helgoland zur Gewinnung von Phykokolloiden und zur Verwendung als Biosorptionsmittel" von Lüning und Buchholz (vergleiche Abschlussbericht zum Vorhaben 03F0096A, 1996, Teil 1). Es wurden versuchsweise unterschiedliche Trägervorrichtungen mit einer Langleinen-, einer Leiter- und einer Gitterkonstruktion entwickelt, um die Makroalgen Laminaria saccharina und Laminaria digitata zu züchten. Keine dieser Konstruktionen konnte jedoch den ozeanographischen Verhältnissen vor Helgoland standhalten. Zum ersten Mal wurde hier versucht, eine Ringkonstruktion für die Kultur von Laminaria-Arten zu bauen und an verschiedenen Standorten einzusetzen. Jedoch sind ein Großteil dieser Ringe unter dem Druck der starken und permanenten Strömung zerstört worden. Andere Ringe, die den Einflüssen standhielten, zeigten jedoch teilweise einen verkümmerten Bewuchs. Beim Versuch, eine Trägervorrichtung mit einer Ringkonstruktion im geschützteren Vorhafen aufzubauen, um den Kräften der Wellen und Strömung aus dem Wege zu gehen, zeigte sich ein anfangs erfolgreiches Längenwachstum der Algen, jedoch verkümmerten diese schnell, da sich aufgrund der geringen Strömung diverse Parasiten, Tiere und andere Algen auf den Blättern der Laminarien niederließen, wodurch diese abbrachen und dadurch sogar negative Wachstumsraten zu verzeichnen waren. Es wurde offensichtlich, dass die Algen, die in der Natur nur an exponierten Standorten zu finden sind, eine gewisse Umströmung brauchten.

[0004] Bei den aus dem Abschlussbericht (ebenda Seiten 6 bis 9 und **Abb.** 12 bis 16 und 18) bekannten Trägervorrichtungen handelt es sich um solche mit unterschiedlichen Ringkonstruktionen. Unter anderem wurde eine unter der Wasseroberfläche angeordnete Ringkonstruktion aus einem einzelnen PE-Kunststoffrohr als Außenring mit einem Durchmesser von 5 m erprobt. Der Außenring war mit 80 m Kulturleine in spinnenetzförmiger Anordnung versehen. Die Kulturleine dient dem Abwachsen der Makroorganismen, die zum einen aus dem Meer eingefangen (beispielsweise Muschellarven) oder als Zuchtsaat zuvor in die Kulturleine eingebracht (beispielsweise Algensaat) werden können. Der Auftrieb wurde durch acht Fender (zu je 23kg) als Auftriebsmittel gewährleistet, die am Außenring gleichmäßig verteilt angeordnet waren und außerdem als Markierungskörper dienten. Als Nachteil hat sich gezeigt, dass die radial angeordneten Fender entgegen der Vermutung, die Ringkonstruktion auch bei starken

Strömungen in der Waagerechten zu halten, als falsch erwies. Einzelne Fender konnten die Ringkonstruktion in der starken Strömung nicht tragen und wurden unter die Wasseroberfläche gedrückt. Dadurch wurden die Fender zunehmend komprimiert und wieder entlastet und teilweise zerstört. Das Verankerungssystem war so konzipiert, dass die gesamte Ringkonstruktion abgebaut werden musste, wenn die Ernte erfolgte. Dazu musste von einem Schiff aus die Ringkonstruktion an einem seiner acht Fender angepickt und hochgehoben werden. Dadurch wurde der Außenring senkrecht zur Wasseroberfläche gedreht, was oftmals durch das Touchieren des Außenrings mit dem Schiffsrumpf den Verlust von Algen zur Folge hatte.

[0005] Auch das Bergen der Ringkonstruktion über mehrere am Umfang befestigte Seile erwies sich als nachteilig, da eine starke Verformung der algenbewachsenen Ringkonstruktion auftrat. Meistens musste die Ringkonstruktion abgeschäkelt werden, um diese für die Ernte in den geschützten Hafen zu ziehen. Die Fender konnten sich außerdem miteinander verhaken und sorgten so zu einem Schamfielen der freien Leinen.

[0006] Eine erste mögliche, wenn auch theoretische Weiterentwicklung der beschriebenen Trägervorrichtung mit Ringkonstruktion ist der AWI-Veröffentlichung „Beispiele aus unserer Forschung 2002", Seiten 33 bis 39 unter dem Titel „Kombinierte Windpark- und Marikulturnutzung in der Nordsee" von B.H. Buck als Ergebnis einer zuvor angefertigten Machbarkeitsstudie (Berichte zur Polar- und Meeresforschung 412/2002, Kapitel 6, Seiten 74 bis 85) zu entnehmen. Die in der AWI-Veröffentlichung dargestellten Ringe und Langleinen sind Zuchtmöglichkeiten und bisher nur Theorie. Windparks gibt es noch nicht. Der schematischen Darstellung gemäß **Fig.** 9b ist die Anordnung einer Trägervorrichtung mit einer Ringkonstruktion in einem Offshoregebiet zu sehen, bei der die Trägervorrichtung zwischen dem Pylon einer Windenergieanlage und einer Verankerung aus Ankerkette und Ankerstein 1,5 m bis 5 m unter der Wasseroberfläche stationär gehalten wird. Die beiden Haltepunkte sind dabei an den äußersten Punkten am Außenring der Ringkonstruktion befestigt. Die Anordnung von zwei Verankerungen mit Befestigungen am Außenring (**Fig.** 9b) ist ebenso möglich wie die Zusammenschaltung mehrerer Ringkonstruktionen um den Pylon herum (**Fig.** 9a). Der geschlossene Außenring weist wiederum eine spinnennetzartige Kultureinheit aus radialen Tragleinen und azimutalen Kulturleinen auf, wobei die Netznabe von einem gemeinsamen Knoten gebildet wird.

[0007] Mit den zuletzt beschriebenen Trägervorrichtungen mit Ringkonstruktionen aus einem oder mehreren Außenringen, von denen die vorliegende Erfindung als nächstliegendem Stand der Technik ausgeht, soll insbesondere in Offshoregebieten die Möglichkeit geschaffen werden, marine Makroorganismen in geschützten und ungeschützten Meeresgebieten zu kultivieren, in denen ein mittleres bis starkes Strömungsregime sowie Perioden mit hohen Wellen vorherrschen oder zeitweise auftreten können. Geschützte und weitgehend ungeschützte Gebiete befinden sich in Europa in allen Bereichen der Ausschließlichen Wirtschaftszone (AWZ) und an fast allen Orten im Küstenmeer. Da das Küstenmeer aufgrund von Nutzerkonflikten und aus Naturschutzgründen kaum genutzt werden kann, zeichnet es sich in der marinen Aquakultur ab, graduell immer mehr exponierte, weitgehend offene (ungeschützte) Meeresgebiete zu nutzen.

Aufgabenstellung

[0008] Die Aufgabe für die Erfindung ist daher darin zu sehen, eine Trägervorrichtung der eingangs beschriebenen Art so weiterzubilden, dass ein Einsatz sowohl in geschützten als auch in den ungeschützten Offshorebereichen unter erschwerten Bedingungen erfolgen kann. Dabei sollen eine einfache Handhabung der auf unterschiedliche Größen auslegbaren Trägervorrichtung, eine nutzerfreundliche und kostengünstige Bauweise sowie die Möglichkeit, mit möglichst wenig Aufwand die Trägervorrichtung aus- und einzubringen, zu warten, zu beproben und die gezüchteten Makroorganismen zum frei bestimmbaren Zeitpunkt ihrer Marktreife zu ernten, Berücksichtigung finden. Beschädigungen der Trägervorrichtung sollen zu jedem Betriebszeitpunkt weitgehend vermieden werden.

[0009] Als Lösung für diese Aufgabe ist bei einer gattungsgemäßen Trägervorrichtung deshalb erfindungsgemäß vorgesehen, dass der Außenring über eine obere Hahnepot mit einem zentralen Auftriebsmittel und über eine untere Hahnepot mit der Verankerung verbunden ist, wobei jede Hahnepot aus einem zentralen Hahnepotring und mehreren gleichmäßig am Umfang des Außenrings befestigten und nach oben und unten jeweils von gemeinsamen Anschlagpunkten aus verlaufenden Hahnepotseilen aufgebaut ist, dass die radialen Tragleinen unter Spannung an einem zentralen Innenring befestigt sind und dass das zentrale Auftriebsmittel direkt mit der Verankerung über zumindest ein durch den zentralen Innenring verlaufendes und an den beiden Hahnepotringen angeschlagenes zentrales Tragseil verbunden ist.

[0010] Die Vorteile der erfindungsgemäßen Trägervorrichtung liegen in der besonderen Ausgestaltung einzelner Teilkomponenten und deren Funktionsprinzip. Dazu gehören die Ausführung und Umsetzung der Verankerung, der Ringkonstruktion und des Auftriebs. Durch diese Ausgestaltungen ist das Ausbringen und auch die Ernte von Makroorganismen, beispielsweise Algen, auf See sicher gewährleistet. Weitere Wartungs- oder Bergungsarbeiten sind sehr leicht durchzuführen, eine Beschädigung, Zerstörung oder sogar Verlust der gesamten Trägervorrichtung oder Teilen davon wird sicher vermieden. Zuvor nicht nutzbare Flächen im offenen Meer können nun mit Hilfe der Trägervorrichtung nach der Erfindung in marinen Gewässern für die effektive Kultivierung von Makroorganismen genutzt werden. Die erfindungsgemäße Trägervorrichtung ist durch ihre speziellen Konstruktionseinheiten im Inshore- und Offshorebereich einsetzbar. Sie bleibt durch ihre Einpunkt-Verankerung in der Wassersäule beweglich. Durch den Schojkreis und bei einer in der Strömungsrichtung ausgerichteten diagonalen Stellung werden für alle Makroorganismen in der Ringkonstruktion ein ausreichend frischer Nährstoff- und Planktoneintrag gewährleistet. Die besondere Konstruktion behält beim Hieven eine waagerechte Stellung und vereinfacht so bedeutsam die Ernte und Wartung.

[0011] Die erfindungsgemäße Trägervorrichtung ist dafür so aufgebaut, dass vom Auftriebsmittel eine direkte Verbindung über zumindest ein zentrales Tragseil zur Verankerung besteht. Wird nun das zentrale Auftriebsmittel gehievt, beispielsweise zum Schleppen der gesamten Trägervorrichtung bei geplanter Ortsveränderung oder bei der Algenernte, so werden keine Zugkräfte in die Ringkonstruktion eingeleitet. Kräfte, die durch Strömungen und Wellengang auf das Auftriebsmittel und/oder die Ringkonstruktion einwirken sowie durch das Eigengewicht der Ringkonstruktion entstehen, werden direkt über das oder die zentralen Tragseile in die Verankerung übertragen. Die Ringkonstruktion mit der Kultureinheit aus radialen Tragleinen und azimutalen Kulturleinen hängt an der vertikalen Verankerung mittels einer doppelten Hahnepot, wobei die obere Hahnepot mit mehreren Hahnepotseilen an dem zentralen Auftriebsmittel und dem Außenring angebracht ist und eine weitere untere Hahnepot ebenfalls den Außenring mit einem unteren Verbindungspunkt im zentralen Tragseil verknüpft. Die obere Hahnepot hält das Eigengewicht von Ringkonstruktion und Algenkulturen, die untere Hahnepot verhindert, dass die Ringkonstruktion über das zentrale Auftriebsmittel weggezogen wird, wenn sie bei starker Strömung mitgerissen wird und diagonal in der Wassersäule hängt. Bemerkt sein an dieser Stelle, dass zwar immer von einer „Ringkonstruktion" und einem „Außenring" gesprochen wird, dass dadurch aber nicht automatisch dessen kreisrunde Form impliziert sein soll. Beliebige Vielecke, beispielsweise in gut ankoppelbarer Wabenform, sollen ebenfalls von dem Begriff „Ringkonstruktion" erfasst sein. Wichtig bei der Wahl dieses Ausdruckes war es, zum Ausdruck zu bringen, dass es sich um eine geschlossene Konstruktion handelt im Gegensatz zu den bekannten Leinen und Gitterkonstruktionen.

[0012] Zwar wirken Kräfte, die durch Strömung und Wellen entstehen, trotz des Hängesystems mit den beiden Hahnepoten auch auf die Ringkonstruktion ein, was sich im rauen Offshore-Bereich nicht vermeiden lässt. Damit die Ringkonstruktion durch solche Kräfte, die insbesondere durch kurze Wellenfrequenzen zunehmen, jedoch trotzdem nicht deformiert wird, kann gemäß einer Erfindungsausgestaltung vorteilhaft vorgesehen sein, dass jeder gemeinsame Anschlagpunkt am Außenring von einer biegesteifen Manschette gebildet wird, die jeweils für ein oberes und ein unteres Hahnepotseil sowie für eine radiale Tragleine eine Öse aufweist. Einander zugeordnete Hahnepotseile, die von oben und von unten kommen, sind immer paarweise an einer Manschette angebracht. Sollten also Kräfte von einem Hahnepotseil der oberen Hahnepot auf den Außenring einwirken, so werden diese Kräfte durch die Manschette auf das entsprechend zugeordnete Hahnepotseil der unteren Hahnepot übertragen. Durch die Wahl der Breite der Manschetten kann der Kraftübertragungsvorgang noch unterstützt werden. Gleiches gilt für das Material der biegesteifen Manschette, die insbesondere aus Stahl, aber auch aus einem hochfesten Kunststoff, z.B. PP, PE oder PFT hergestellt sein kann. Bei der Verwendung von Stahl kann insbesondere das Anbringen der verschiedenen Ösen durch Anschweißen problemlos erfolgen und ein Rosten im Seewasser vermieden werden.

[0013] Die nach innen verspannten Tragleinen, an denen die im Außenring geschlossen umlaufenden Kulturleinen befestigt sind, sind zur Mitte hin an einem zentralen Innenring befestigt. Dadurch wird unabhängig von der Belastung auf die Verankerung einem Kollabieren der gesamten Kultureinheit entgegengewirkt, die Tragleinen samt Kulturleinen werden immer auf Spannung gehalten. Der zentrale Innenring dient außerdem als Führung für das zentrale Tragseil, wodurch ferner ein Schamfielen der Kulturleinen an dem zentralen Tragseil verhindert wird. Weiterhin kann vorteilhaft vorgesehen sein, dass der zentrale Innenring für jede radiale Tragleine eine Öse aufweist. Somit können die Tragleinen im Zentrum des Außenrings gut befestigt werden, ohne dass ein hinderlicher und schwer zu beherrschender Knoten entsteht. Zusätzlich können so leicht Leinen nach Bedarf ausgetauscht werden. Das Zentrum der Kultureinheit selbst bleibt für die Durchführung des zentralen Tragseils frei. Eine einfache Befestigungsmöglichkeit ergibt sich auch, wenn gemäß einer nächsten Erfindungsausgestaltung jede radiale Tragleine an einer Öse einer Manschette um den Außenring befestigt ist. Dabei kann die Manschette nur der Befestigung einer radialen Tragleine, aber auch gleichzeitig einem Paar von Hahnepotseilen dienen. Weiterhin kann vorteilhaft jede radiale Tragleine über ein Spannelement mit einer Öse des zentralen Innenrings verbunden sein. Dadurch kann eine einfache, dauerhafte Spannung in der gesamten Kultureinheit aufgebracht werden, die sich auch unter sich ändernden Lastverhältnissen, beispielsweise durch zunehmenden Algenbewuchs, durch sich ändernde Strömungsverhältnisse oder beim Ausbringen und Einholen der Trägervorrichtung, nicht betriebsstörend ändert.

[0014] Gemäß weiterer vorteilhafter Erfindungsausgestaltungen kann der zentrale Hahnepotring der oberen Hahnepot direkt an dem zentralen Auftriebsmittel oder unter Zwischenschaltung einer in ihrer Länge festlegbaren Absenkleine an dem zentralen Auftriebsmittel angreifen. Während die erste Variante eine sehr kompakte Trägervorrichtung konzipiert, die besonders leicht handhabbar ist, ermöglicht die zweite Variante eine höhenveränderbare Positionierung der Ringkonstruktion in der Wassersäule unterhalb der Wasseroberfläche. Dazu wird der Abstand zwischen dem Auftriebsmittel und dem oberen Hahnepotring durch Vorsehen einer entsprechend langen oder verlängerten oder verkürzten Absenkleine verlängert oder verkürzt. Eine tief hängende Ringkonstruktion ist günstig für die Kultur von jungen Algen, denn so wird das schädigende, starke UV-Licht durch die darüberliegende Wassersäule gefiltert. Außerdem sind in tieferen Wasserschichten die Orbitalbewegungen der Wasserteilchen geringer und verhindern so das Abreißen der jungen Algen bei starkem Wellengang. Sind die Algen dann größer, kann die Ringkonstruktion zur besseren Lichtausbeute dann weiter oben in der Verankerung eingehängt werden.

[0015] Als weiterer Vorteil wurde bereits die gute Nahrungszufuhr durch das freie Drehen der gesamten Trägervorrichtung in der Wasserströmung erwähnt. Dafür ist es gemäß einer nächsten Erfindungsausgestaltung vorteilhaft, wenn der zentrale Hahnepotring der unteren Hahnepot über eine frei drehbare Drehkupplung an einer mit einem Ankerstein verbundenen Ankerkette als Verankerung angreift. Somit wird eine freie Drehung der Ringkonstruktion über einer Einpunkt-Bodenverankerung ermöglicht, ohne dass es zu störenden Seilaufdrillungen und Rückstellkräften kommt. Gemäß einer anderen Erfindungsausgestaltung können alle oberen Hahnpotseile gleichlang sein. Dadurch kann eine waagerechte Ringkonstruktionsaufhängung beim Hebevorgang gewährleistet und Wartungsarbeiten sowie Erntevorgänge erleichtert werden. Weiterhin wurde bereits die gute Befestigungsmöglichkeit der Tragleinen und Hahnepotseilen an entsprechenden Ösen von Manschetten und zentralem Innenring erwähnt. Diese kann noch verbessert werden, wenn gemäß einer anderen Erfindungsfortführung alle Seil-, Leinen- und Kettenverbindungen über Ösen an den Seil-, Leinen und Kettenenden hergestellt sind. Schlecht herstell- und lösbare Knoten mit undefinierten Längenverhältnissen werden so vermieden. Eine problemlose Wiederverwendbarkeit der Seile, Leinen und Ketten ist ohne Längenverlust gewährleistet.

[0016] Eine besonders große Festigkeit des Außenrings ergibt sich zudem, wenn dieser vorteilhaft aus einer in einem Kunststoffrohr umlaufenden Stahltrosse besteht. Das Kunststoffrohr kann nach dem Einziehen und Schließen der Stahltrosse mit einer entsprechenden Muffe geschlossen werden. Eine Festlegung des Durchmessers des Außenrings ist einfach möglich, ohne dass die Festigkeit der Ringkonstruktion gefährdet wird. Ein besonders einfaches Ausbringen und Einholen der gesamten Trägervorrichtung kann erzielt werden, wenn gemäß einer nächsten Erfindungsfortführung das zentrale Auftriebsmittel eine Öse zum Hieven und Fieren der Trägervorrichtung aufweist. Ein zusätzliches Anschlagen von entsprechenden Seilen ist dann nicht erforderlich. Das Heben und Senken der gesamten Trägervorrichtung in der zentralen Achse zur Verankerung, das eine besonders geringe Belastung der Ringkonstruktion ermöglicht, wird einfach und zuverlässig ermöglicht. Schließlich kann noch eine Vergrößerung des Ertrags an gezüchteten Makroorganismen erzielt werden, wenn vorteilhaft mehrere gleichartige Ringkonstruktionen zusammengeschaltet sind. Dabei zeigt jede Ringkonstruktion denselben Aufbau mit einer zentralen vertikalen direkten Verbindung zwischen Auftriebsmittel und Verankerung. Eine Verschaltung kann zwischen den Außenringen über entsprechende lösbare Ösenverbindungen vorgenommen werden.

Ausführungsbeispiel

[0017] Ausbildungsformen der Erfindung werden beispielhaft nachfolgend zum weiteren Verständnis der Erfindung anhand der schematischen Figuren näher erläutert. Dabei zeigt

[0018] Fig. 1 eine perspektivische Gesamtansicht der Trägervorrichtung, Fig. 2 eine perspektivische Detailansicht einer Manschette,

[0019] Fig. 3 eine perspektivische Detailansicht des zentralen Innenrings und

[0020] Fig. 4 eine perspektivische Detailansicht der unteren Hahnepotverbindung zum zentralen Tragseil.

[0021] Die Fig. 1 zeigt eine mögliche Ausführungsform einer Trägervorrichtung **1** nach der Erfindung zur Kultur von Makroorganismen, beispielsweise Algen, in marinen Gewässern. Die Trägervorrichtung **1** weist eine Ringkonstruktion **2** auf, die unterhalb der Wasseroberfläche **3** mit veränderbarer Positionstiefe angeordnet ist. Dazu ist die Ringkonstruktion **2** zwischen einem Auftriebsmittel **4** an der Wasseroberfläche **3** und einer Verankerung **5** auf dem Gewässerboden **33** angeordnet. Damit möglichst geringe Kräfte, die sowohl durch das Gewässer als auch durch Transportvorgänge hervorgerufen werden, auf die

Ringkonstruktion 2 einwirken, ist diese aus der unmittelbaren Krafteinleitung entkoppelt. Dazu ist das Auftriebsmittel 4 direkt mit der Verankerung 5 über ein zentrales Tragseil 6, hierbei kann es sich beispielsweise um ein Stahlseil handeln, verbunden. Somit kann die Ringkonstruktion 2 ohne zusätzliche Kraftbeaufschlagung, beispielsweise durch die Verankerung 5, geborgen werden und muss nur die Erntelast der gezüchteten Makroorganismen tragen.

[0022] Die Ringkonstruktion 2 ist über eine obere Hahnepot 7 und eine untere Hahnepot 8 mit dem zentralen Tragseil 6 verbunden. Dazu weist jede Hahnepot 7, 8 einen zentralen Hahnepotring 9, 10 auf, von dem mehrere obere und untere Hahnepotseile 11, 12, im gewählten Ausführungsbeispiel jeweils vier, zum Außenring 13 der Ringkonstruktion 2 verlaufen. Die Länge der oberen und unteren Hahnepotseile 11, 12 und des zentralen Tragseils 6 ist wählbar (in der Fig. 1 durch Unterbrechungen angedeutet) und abhängig von der einsatz- und handhabungsbedingten Gesamtdimensionierung der Trägervorrichtung 1. Die Verteilung der Hahnepotseile 11, 12 auf dem Außenring 13 erfolgt gleichmäßig, damit insbesondere die Erntelast beim Hieven der Ringkonstruktion 2 keine einseitigen Ringverbiegungen hervorrufen kann und die Ringkonstruktion 2 gleichmäßig eingespannt ist. Für eine gute Kraftweiterleitung sorgt außerdem das Vorsehen von gemeinsamen Anschlagpunkten 14, in denen jeweils ein oberes Hahnepotseil 11 und ein unteres Hahnepotseil 12 gemeinsam befestigt sind. Zur guten und stabilen Befestigung dienen dabei biegesteife Manschetten 15 an den Anschlagpunkten 14, die für jedes Hahnepotseil 11, 12 eine Öse 18 aufweisen (vergleiche Fig. 2).

[0023] Im gewählten Ausführungsbeispiel ist an dem oberen Hahnpotring 9 direkt das Auftriebsmittel 4 befestigt, sodass die geringste Eintauchtiefe für die Ringkonstruktion 2 mit der höchsten UV-Einstrahlung eingestellt ist. Zur Vergrößerung der Eintauchtiefe wird zwischen dem Auftriebsmittel 4 und der oberen Hahnepot 7 ein in seiner Länge entsprechend bemessenes oder einstellbares Absenkseil zwischengekoppelt (in der Fig. 1 nicht weiter dargestellt). Am unteren Hahnepotring 10 ist ein weiteres Stück des zentralen Tragseils 6 befestigt, das an seinem anderen Ende mit einer Ankerkette 16 verbunden ist, die zu einem Ankerstein 17 führt. Im gewählten Ausführungsbeispiel bilden Ankerkette 16 und Ankerstein 17 die Verankerung 5. Weiterhin werden alle Seil-, Leinen- und Kettverbindungen über einfache Ösen 18 hergestellt, die eine gute Montage und Verbindungsstabilität garantieren.

[0024] Im Außenring 13 der Ringkonstruktion 2 befindet sich eine spinnennetzartige Kultureinheit 19 zur Aufzucht der Makroorganismen. Hierbei handelt es sich um radiale Tragleinen 20, zwischen denen azimutale Kulturleinen 21 in konzentrischen Ringen verlaufen. Die Leinen sind beispielsweise durch einfache Knoten oder mittels Kabelbindern miteinander verbunden. Die radialen Tragleinen 20 sind am Außenring 13 wiederum über Manschetten 15 an einer dritten Öse 22 befestigt (vergleiche Fig. 2). In der Fig. 1 ist erkennbar, dass nur jede dritte Manschette 15 auf dem Außenring 13 auch gleichzeitig der jeweiligen Befestigung eines oberen und eines unteren Hahnepotseils 11, 12 dient. Andere Belegungen und Ausführungen, beispielsweise mit Manschetten 15 mit unterschiedlichen Ösenanzahlen, sind ebenfalls möglich. Die gezeigte Ausführung ist jedoch besonders günstig, da sie nur eine Sorte von Manschetten 15 erfordert. An ihrem anderen Ende sind die Tragleinen 20 mit einem zentralen Innenring 23 verbunden, der als Führung und ungestörter Durchgang für das zentrale Tragseil 6 dient. Zur Straffung der Tragleinen 20 sind im gewählten Ausführungsbeispiel Spannelemente 24 zwischen geschaltet (vergleiche Fig. 3), sodass die gesamte Kultureinheit 19 immer straff gehalten werden kann. Die Tragleinen 20 können aber unter Straffziehung auch direkt durch die Ösen 29 gezogen und dann verspleißt werden.

[0025] Im gewählten Ausführungsbeispiel ist der Außenring 13 aus einer geschlossenen Stahltrosse 25 aufgebaut, die in einem geschlossenen Kunststoffrohr 26, beispielsweise aus PE, umläuft (in der Fig. 1 aufgebrochen dargestellt). Der Außenring 13 kann einen Durchmesser von ungefähr 5 m haben und weist in der beschrieben Ausführung eine gute Stabilität auf. Weiterhin ist das Auftriebsmittel 4 in Bojenform dargestellt, die eine untere Öse 27 zur Befestigung des zentralen Tragseils 6 und eine obere Öse 28 zum einfachen Hieven und Fieren der Trägervorrichtung aufweist.

[0026] Die Fig. 2 zeigt eine Detailansicht einer Manschette 15 mit drei Ösen 16, 22. Die beiden Ösen 16 dienen der Befestigung des oberen und unteren Hahnepotseils 11, 12, die Öse 22 dient der Befestigung der radialen Tragleine 20 jeweils am Außenring 13. Die gezeigte Manschette 15 ist geschlossen aus Stahl ausgeführt, die Ösen 16, 22 sind angeschweißt. Eine biegefeste Ausführung aus Kunststoff ist ebenfalls möglich.

[0027] In der Fig. 3 ist eine Detailansicht des zentralen Innenrings 23 mit den über Ösen 29, 30 befestigten radialen Tragleinen 20 der Kultureinheit 19 dargestellt. Der zentrale Innenring 23 ist wiederum aus rostfreiem Stahl und weist für jede radiale Tragleine 20 eine Öse 29 auf. Zwischen den Ösen 29, 30 sind Spannelemente 24, beispielsweise einfache Spann- oder Spiralfedern, angeordnet, die der Straffhaltung der radialen Tragleinen 20 und damit der gesamten Kultureinheit 19 dienen. Angedeutet ist in der Fig. 3 ein laminarer Algenbewuchs 31 an den Kulturleinen 21.

[0028] Die Fig. 4 schließlich zeigt eine Detailansicht der unteren Hahnepot 8. Über obere Ösen 18 sind die unteren Hahnepotseile 12 und das zentrale Tragseil 6 mit dem zentralen Hahnepotring 10 verbunden. Über eine untere Öse 18 und eine frei drehbare Drehkupplung 32 ist der zentrale Hahnepotring 10 mit dem unteren Abschnitt des zentralen Tragseils 6 verbunden. Eine solche Anordnung aus Öse 18 und Drehkupplung 32 kann auch zwischen dem Tragseil 6 und der Ankerkette 16 vorgesehen sein (vergleiche Fig. 1), sodass sich der gesamte Konstruktionsring 2 frei in der Strömung drehen kann.

[0029] Die vorbeschriebenen Ausführungsformen der Trägervorrichtung nach der Erfindung sind beispielhaft. Andere Ausführungsformen im Rahmen der Offenbarung sind ebenfalls möglich und von den Ausführungen eingeschlossen.

Patentansprüche

1. Trägervorrichtung (1) zur Kultur von Makroorganismen (31) in marinen Gewässern mit zumindest einer Ringkonstruktion (2), die unterhalb der Wasseroberfläche (3) zwischen zumindest einem Auftriebsmittel (4) und einer Verankerung (5) angeordnet ist und in einem geschlossenen Außenring (13) eine spinnennetzartige Kultureinheit (19) aus radialen Tragleinen (20) und azimutalen Kulturleinen (21) aufweist, **dadurch gekennzeichnet**, dass der Außenring (13) über eine obere Hahnepot (7) mit einem zentralen Auftriebsmittel (4) und über eine untere Hahnepot (8) mit der Verankerung (5) verbunden ist, wobei jede Hahnepot (7, 8) aus einem zentralen Hahnepotring (9, 10) und mehreren gleichmäßig am Umfang des Außenrings (4) befestigten und nach oben und unten jeweils von gemeinsamen Anschlagpunkten (14) aus verlaufenden Hahnepotseilen (11, 12) aufgebaut ist, dass die radialen Tragleinen (20) unter Spannung an einem zentralen Innenring (23) befestigt sind und dass das zentrale Auftriebsmittel (4) direkt mit der Verankerung (5) über zumindest ein durch den zentralen Innenring (23) verlaufendes und an den beiden Hahnepotringen (9, 10) angeschlagenes zentrales Tragseil (6) verbunden ist.

2. Trägervorrichtung (1) nach Anspruch 1, dadurch gekennzeichnet, dass jeder gemeinsame Anschlagpunkt (14) am Außenring (13) von einer biegesteifen Manschette (15) gebildet wird, die jeweils für ein oberes und ein unteres Hahnepotseil (11, 12) sowie für eine radiale Tragleine (20) eine Öse 18, 22) aufweist.

3. Trägervorrichtung (1) nach Anspruch 1 oder 2, dadurch gekennzeichnet, dass der zentrale Innenring (23) für jede radiale Tragleine (20) eine Öse (29) aufweist.

4. Trägervorrichtung (1) nach Anspruch 2 und 3, dadurch gekennzeichnet, dass jede radiale Tragleine (20) an einer Öse (22) einer Manschette (15) um den Außenring (13) befestigt ist.

5. Trägervorrichtung (1) nach Anspruch 2 und 3, dadurch gekennzeichnet, dass jede radiale Tragleine (20) über ein Spannelement (24) mit einer Öse (29) des zentralen Innenrings (23) verbunden ist.

6. Trägervorrichtung (1) nach einem der Ansprüche 1 bis 5, dadurch gekennzeichnet, dass der zentrale Hahnepotring (9) der oberen Hahnepot (7) direkt an dem zentralen Auftriebsmittel (4) angreift.

7. Trägervorrichtung (1) nach einem der Ansprüche 1 bis 5, dadurch gekennzeichnet, dass der zentrale Hahnepotring (9) der oberen Hahnepot (7) unter Zwischenschaltung einer in ihrer Länge festlegbaren Absenkleine an dem zentralen Auftriebsmittel (4) angreift.

8. Trägervorrichtung (1) nach einem der Ansprüche 1 bis 7, dadurch gekennzeichnet, dass der zentrale Hahnepotring (10) der unteren Hahnepot (8) über eine frei drehbare Drehkupplung (32) an einer mit einem Ankerstein (17) verbundenen Ankerkette (16) als Verankerung (5) angreift.

9. Trägervorrichtung (1) nach einem der Ansprüche 1 bis 8, dadurch gekennzeichnet, dass die oberen Hahnepotseile (11) alle gleichlang sind.

10. Trägervorrichtung (1) nach einem der Ansprüche 1 bis 9, dadurch gekennzeichnet, dass alle Seil-, Leinen- und Kettenverbindungen über Ösen (18) an den Seil-, Leinen und Kettenenden hergestellt sind.

11. Trägervorrichtung (1) nach einem der Ansprüche 1 bis 10, dadurch gekennzeichnet, dass der Außenring (13) aus einer in einem Kunststoffrohr (26) umlaufenden Stahltrosse (25) besteht.

12. Trägervorrichtung (1) nach einem der Ansprüche 1 bis 11, dadurch gekennzeichnet, dass das zentrale Auftriebsmittel (4) eine Öse (28) zum Hieven und Fieren der Trägervorrichtung (1) aufweist.

13. Trägervorrichtung (1) nach einem der Ansprüche 1 bis 12, dadurch gekennzeichnet, dass mehrere gleichartige Ringkonstruktionen (2) zusammengeschaltet sind.

Es folgen 2 Blatt Zeichnungen

DE 10 2004 010 652 B4 2006.07.27

Anhängende Zeichnungen

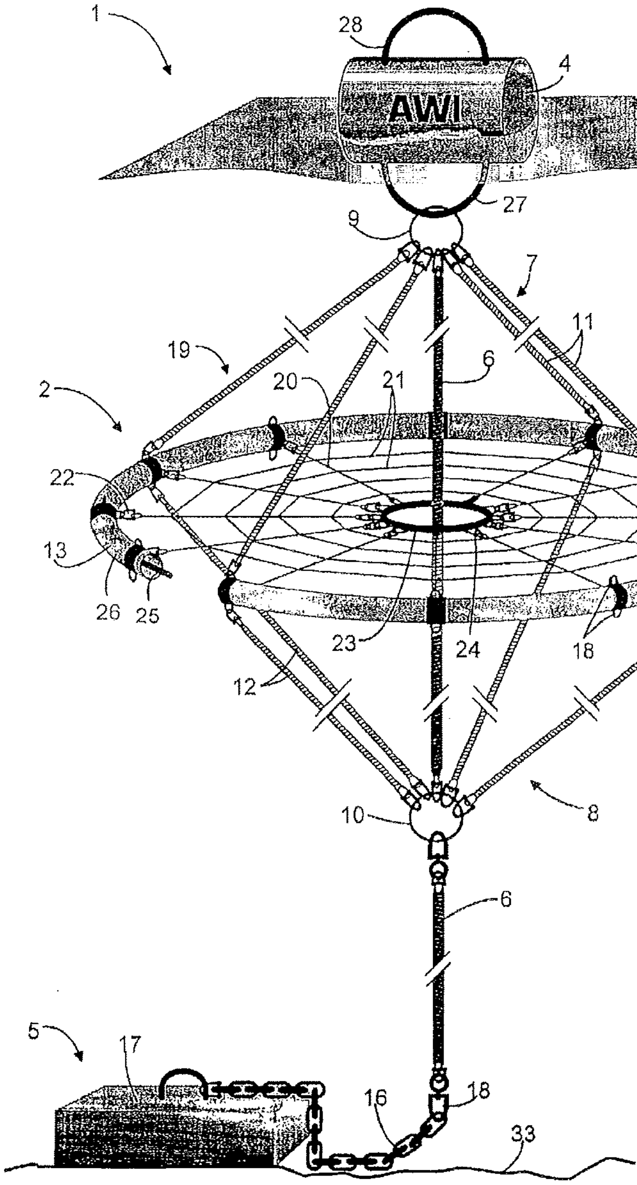


Fig.1

DE 10 2004 010 652 B4 2006.07.27

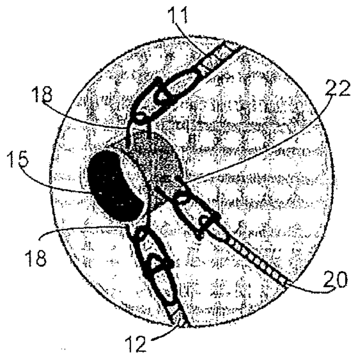


Fig.2

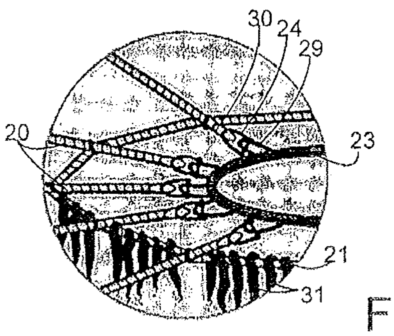


Fig.3

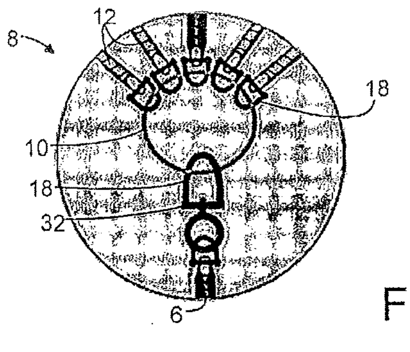


Fig.4

Appendix XII

Patent II

Inspektionseinrichtung für Unterwasserstrukturen mit einer Positionier-einrichtung

Buck BH, Wunsch M (2005), No: AWI 102005020070 DE

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URKUNDE

über die Erteilung des

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Bezeichnung
Inspektionseinrichtung für Unterwasserstrukturen mit einer Positioniervorrichtung

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Tag der Anmeldung
22.04.2005

München, den 14.09.2006

DEUTSCHES PATENT- UND MARKENAMT

Der Präsident des Deutschen Patent- und Markenamts

Dr. Schade

Dr. Schade

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Innerhalb von drei Monaten nach Veröffentlichung der Patenterteilung kann nach § 59 Patentgesetz gegen das Patent Einspruch erhoben werden. Der Einspruch ist schriftlich zu erklären und zu begründen. Innerhalb der Einspruchsfrist ist eine Einspruchsgebühr in Höhe von 200 Euro zu entrichten(§ 6 Patentkostengesetz in Verbindung mit der Anlage zu § 2 Abs. 2 Patentkostengesetz).

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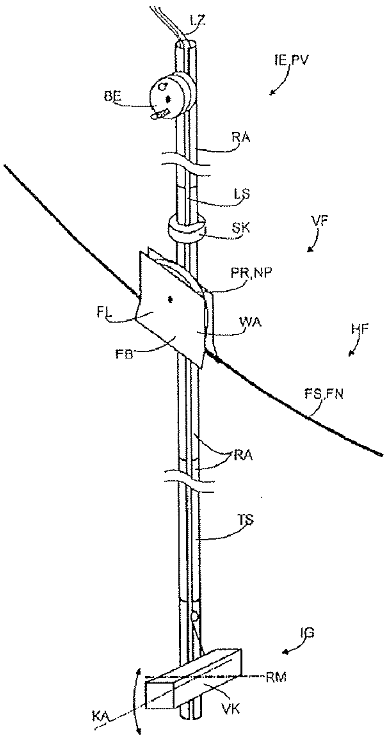
(56) Für die Beurteilung der Patentfähigkeit in Betracht gezogene Druckschriften:
US 29 45 428 A
WO 2004/0 08 077 A1
JP 61-0 82 146 A

(54) Bezeichnung: **Inspektionseinrichtung für Unterwasserstrukturen mit einer Positioniervorrichtung**

(57) Zusammenfassung: Derartige Inspektionseinrichtungen werden für die Beobachtung und Bedienung von Aquakulturen, Hafenanlagen oder anderen, unter Wasser befindlichen Oberflächen eingesetzt. Sie weisen eine stufenlos verstellbare Vertikalführung mit einer Teleskopstange und eine stufenlos verstellbare Horizontalführung mit einer einen Weg vorgebenden Führungsbahn und einem darauf auf Führungsrollen geführten Wagen zur Aufnahme der Vertikalführung und entsprechende Inspektionsgeräte auf. Bisher mussten dafür speziell ausgebildete Taucher, der zu inspizierende Gegenstand aus dem Wasser angehoben oder Inspektionseinrichtungen mit nur sehr begrenztem Aktionsraum eingesetzt werden. Mit der Erfindung wird eine kostengünstige und ohne Taucher bedienbare Inspektionseinrichtung (IE) vorgestellt, die über einen weitgehend unbegrenzten Beobachtungsraum verfügt. Dazu ist für die Vertikalführung (VF) die Teleskopstange (TS) mittels mehrerer Rohrabschnitte (RA) absatzfrei verlängerbar und für die Horizontalführung (HF) die Führungsbahn (FB) veränderlich in einer kontinuierlichen Kurve vorgebbar oder aus linearen Abschnitten zusammensetzbar. Vertikal- und Horizontalführung (VF, HF) spannen die Inspektionsebene für die diversen Inspektionsgeräte (IG) in den drei Raumachsen auf.



Beschreibung

[0001] Die Erfindung bezieht sich auf eine Inspektionseinrichtung für Unterwasserstrukturen mit einer Positioniervorrichtung, die eine stufenlos verstellbare Vertikalführung mit einer Teleskopstange und eine stufenlos verstellbare Horizontalführung mit einer einen Weg vorgebenden Führungsbahn und einem darauf auf Führungsrollen geführten Wagen zur Aufnahme der Vertikalführung aufweist, und mit einer Unterwasser-Videokamera als zumindest einem Inspektionsgerät, das an der Teleskopstange befestigt ist.

[0002] Derartige Inspektionseinrichtungen werden zum Beispiel zur Wartung groß angelegter Aquakulturanlagen benötigt, die weltweit zunehmend für die Produktion von Algen und Muscheln betrieben werden. Dabei wachsen die Kulturorganismen an oder in schwimmenden oder untergetauchten Systemen. Solche Systeme sind in der Regel Langleinen (Longline), Langröhren (Longtube), Ringsysteme, Flöße oder Pfahlbauten. Langleinen und Langröhren werden über einige 100 m Länge horizontal an der Wasseroberfläche oder in 1–10 m Tiefe unterhalb der Wasseroberfläche verspannt und dienen als Trägerleinen für die daran befestigten Kulturhalteleinen. An diesen Kulturhalteleinen werden schließlich die Algen oder Muscheln gezüchtet. Die Zucht solcher Kulturorganismen wird über mehrere Monate bis Jahre betrieben. Dabei wird neben Routinearbeiten (Kontrolle der Kulturen, Ausbringen von Organismen, Ernte) die technische Konstruktion auf ihren Zustand und ihre Sicherheit überprüft. Insbesondere die untergetauchten Strukturen müssen je nach Gewichtszunahme, die durch das Wachstum der Organismen entsteht, mit zusätzlichen Auftriebskörpern bestückt werden. Außerdem müssen die Kulturorganismen beobachtet werden, um den äußerlichen Zustand (Unversehrtheit, Ansiedlung), Wachstum, Prädation (Fressfeindschaft), Futteraufnahme und -konkurrenz bewerten zu können. Solche Aufgaben können von speziell ausgebildeten Tauchern durchgeführt werden. Eine weitere Möglichkeit besteht darin, die kompletten Strukturen mit Schiffskränen von Spezialschiffen anzuheben. Beide Möglichkeiten können nur bei geringem Seegang durchgeführt werden und sind sehr teuer. Außerdem können Unterwasserkamera-Systeme als Inspektionsgeräte zum Einsatz kommen. Andere Anwendungsgebiete für solche Inspektionseinrichtungen sind die Beobachtung und Wartung von technischen Einrichtungen unter Wasser wie Hafenanlagen usw.

Stand der Technik

[0003] Aus der GB 2 400 451 A ist eine einfache Teleskopstange mit einer Anbaumöglichkeit für eine Unterwasserkamera bekannt. Die Länge der Stange wird vor dem Einsatz mit Verlängerungsstücken eingestellt. Die Leitungszuführung geschieht äußerlich entlang der Teleskopstange. Überschüssige Leitung wird auf eine Spule gerollt. Diese Einrichtung wird von einem Kai oder von einem Boot oder Ponton aus zur Beobachtung von z.B. Hafenanlagen unter der Wasseroberfläche eingesetzt. Ein Einsatz auf offener See bei Wind und Wellengang wird durch die Bewegungen der Kamera vor dem Objekt sehr erschwert. Aus Gewichtsgründen ist der Einsatz der handgeführten Einrichtung auf geringe Tiefen beschränkt. Aus der US 6,119,630 ist eine ortsfeste Inspektionseinrichtung für Unterwassereinsatz bekannt, die ursprünglich zur ständigen Beobachtung der Wachstumsverhältnisse von Muscheln unter natürlichen Umgebungsbedingungen vorgesehen ist. Die Einrichtung ist nach der Einstellung der Tiefe und der Wahl eines Einsatzortes weder in horizontaler noch in vertikaler Richtung veränderbar. Aus der JP 10020382 A ist ein halbautonomes Beobachtungssystem mit einem fernsteuerbaren unbemannten Boot und einer kabelversorgten Videoeinrichtung bekannt. Das Boot wird über einen zu beobachtenden Ort gesteuert und das Videosystem über eine Winsch auf die gewünschte Tiefe abgelassen. Bild und Steuersignale werden über das Kabel geleitet. Das Beobachtungssystem ist aufwändig und der Einsatzort auf die mögliche Kabellänge beschränkt. Es ist nicht klar, wie die Kamera ihre Blickrichtung beibehält, wenn sie am Kabel hängt und Strömungen und Wellengang ausgesetzt ist. Ein ähnliches System wird in der DE 103 10 550 A1 offenbart. Eine stromlinienförmige Unterwassereinheit wird von einem fernsteuerbaren unbemannten Boot in durch ein Kabel veränderbarer Tiefe durch ein Gewässer geführt und nimmt Daten mit Hilfe daran befestigter Sensoren auf. Das Beobachtungssystem ist aufwendig und der Einsatzort auf die mögliche Sichtstrecke beschränkt.

[0004] Aus der US 2 945 428 A ist eine Kamerastabilisierung bekannt, bei der der Kameramann eine Horizontalführung auf seinen Schultern trägt. Diese besteht aus zwei parallelen, geradlinigen Führungsschienen, die den horizontalen Verfahrweg der Kamera festlegen. Zur horizontalen Verschiebung ist die Kamera auf einem Wagen gelagert, der mit jeweils zumindest einer rohrförmig geschlossenen Führungsmuffe jede Führungsschiene umfasst. Eine vertikale Verstellung der Kamera kann über einen Teleskopstab erreicht werden, die unterhalb der Kamera an dem Wagen befestigt ist und sich am Boden abstützt (vergleiche **Fig. 5** ebenda). Ein kurvenförmiges Verfahren der Kamera ist mit dieser bekannten Kamerastabilisierung nicht ohne weiteres möglich. Weiterhin ist für die Stabilisierung immer der Bodenbezug (für Kameramann und Teleskopstange) erforderlich.

[0005] Weiterhin ist aus der WO 2004/008077 A1 ein optischer Enkoder, beispielsweise ein Röntgengerät, mit zwei relativ zueinander bewegbaren Geräteteilen bekannt. An dem einen Geräteteil ist ein Positionsanzeiger, an dem anderen Geräteteil ein Bildaufnehmer befestigt. Der Positionsanzeiger ist mit einem sich bewegenden Objekt verbunden und wird von dem Bildaufnehmer in seiner Bewegung optisch erfasst. Der Enkoder umfasst einen verschiebbaren Wagen, der unterhalb einer Horizontalführung über vier Führungsrollen mit dieser verbunden ist (vergleiche **Fig.** 1 ebenda). Dabei bedingt die Anordnung der vier Rollen eine bauliche Sicherung. Weiterhin ist am Wagen eine teleskopartige Vertikalführung aus mehreren ineinander schiebbaren Vierkantrohren vorgesehen, die beim Ausfahren starke Absätze zueinander aufweisen..

[0006] Die JP 61082146 A, von der die vorliegende Erfindung als nächstliegendem Stand der Technik ausgeht, beschreibt ein über eine Winde betätigbares Teleskoprohr definierter Ausfahrlänge mit einer daran befestigten Unterwasser-Videokamera. Die Beobachtungstiefe wird mittels einer Handkurbel an der Winde eingestellt. Das Teleskoprohr kann mit einem Schlitten in horizontaler Richtung auf einem Ausleger von Hand verschoben werden. Der Ausleger kann an zwei Scharnieren um einen Tragmast ebenfalls von Hand gedreht werden. Die horizontale Bewegung ist also in zwei Raumrichtungen kontinuierlich, wobei in der einen Raumrichtung ausschließlich eine reine Kreisbewegung und in der anderen Raumrichtung eine lineare Bewegung durchgeführt werden kann. Die Bewegung des Schlittens kann nur linear entlang des Auslegers erfolgen. Der Einsatz der Kamera ist durch die Kombination dieser Bewegungen auf eine Kreisscheibe mit dem Radius des Auslegers und in der Tiefe auf die Ausfahrlänge des Teleskoprohrs beschränkt. Es wird also ein in Radius und Länge bestimmter, zylinderförmig begrenzter Beobachtungsraum zur Verfügung gestellt.

Aufgabenstellung

Aufgabenstellung

[0007] Die Aufgabe für die vorliegende Erfindung ist darin zu sehen, dass eine Inspektionseinrichtung für Unterwasserstrukturen mit einer Positioniervorrichtung der eingangs beschriebenen Art zur Verfügung gestellt wird, die einen weitgehend unbegrenzten Beobachtungsraum zur Verfügung stellt, preiswert herstellbar und ohne Spezialpersonal leicht handhabbar ist. Die erfindungsgemäße Lösung für diese Aufgabe ist dem Hauptanspruch zu entnehmen. Vorteilhafte Weiterbildungen der erfindungsgemäßen Inspektionseinrichtung sind in den Unteransprüchen aufgezeigt und werden im Folgenden im Zusammenhang mit der Erfindung näher erläutert.

[0008] Die erfindungsgemäße Inspektionseinrichtung besteht aus einer Horizontal- und einer Vertikalführung, die eine Ebene aufspannen, in der die Inspektionsgeräte kontinuierlich verfahren werden können. Die Vertikalführung weist eine rohrförmigen Teleskopstange auf und verläuft daher immer linear, die Horizontalführung kann eine Führungsbahn in der Ebene aufweisen, die senkrecht auf der Vertikalführung steht, Kurven beschreiben, bevorzugt aber aus linearen Abschnitten und besonders bevorzugt aus einem einzigen linearen Abschnitt bestehen kann. Die von der Horizontal- und der Vertikalführung aufgespannte Fläche kann also eben sein oder aus einer beliebigen Anzahl von in Winkeln zueinander stehenden Flächenabschnitten bestehen oder eine in der dritten Raumrichtung gekrümmte Fläche, zum Beispiel also ein Zylinder mit kreisförmigem Querschnitt sein. Zur Tiefeneinstellung des Inspektionsbereichs kann die Teleskopstange durch Hinzufügen oder Entfernen von Rohrabschnitten absatzfrei verlängert oder verkürzt werden. Die Teleskopstange wird von einer Leitvorrichtung an einem Wagen aufgenommen, der mittels einer Führungsrolle über die Führungsbahn der Horizontalführung greift und auf dieser abrollt. Dazu weist die Führungsrolle ein das Profil der Führungsbahn zumindest teilweise aufnehmendes Negativprofil auf. Die Inspektionsgeräte sind bevorzugt am unteren Ende der Teleskopstange angeordnet. Die Einstellung der jeweils gewählten Einsatztiefe der Inspektionsgeräte an der Teleskopstange, die kontinuierliche Führung des Wagens mit der Teleskopstange und den Inspektionsgeräten über die Horizontalführung sowie die gegebenenfalls möglichen Bedienungen der Inspektionsgeräte geschehen bevorzugt im Handbetrieb.

[0009] Die zur Versorgung und Bedienung der Inspektionsgeräte erforderlichen Leitungszüge zur Energiezufuhr, gegebenenfalls zur Bereitstellung von Signalen wie Bild- und Steuerdaten in beiden Richtungen und zur mechanischen Betätigung können zum Schutz vor mechanischer Beschädigung im Inneren der Teleskopstange untergebracht werden. Dazu ist diese bevorzugt als Rohr mit Längsschlitz ausgeführt, so dass auch eine Längenänderung der Teleskopstange durch Hinzufügen oder Entfernen von geschlitzten Rohrabschnitten sehr schnell vonstatten geht, ohne alle Leitungszüge entfernen und nach der Längenänderung wieder einfädeln zu müssen. Leitungszüge werden von einem Vorrat ab- oder auf ihn aufgewickelt und der geschlitzte Rohrabschnitt darüber geschoben oder davon abgezogen. Zur Längenänderung hat der Rohrabschnitt eine Rasteinrichtung, die dafür sorgt, dass er schnell und in Bezug auf den Längsschlitz passgenau mit dem vorhandenen Teleskoprohr verbunden, beziehungsweise auf einfache Weise davon entkoppelt und entfernt werden kann. Die Rohrabschnitte der Teleskopstange können an dem einen Ende bei konstantem Außendurchmesser auf einem Teilbereich der ungefähren Länge des Durchmessers des Teleskoprohres einen vergrößerten Innendurchmesser und auf dem anderen Ende auf einem gleichlangen Teilbereich bei konstantem Innendurchmesser einen derart verkleinerten Außendurchmesser aufweisen, dass die einen Enden der Rohrabschnitte gerade spielarm die anderen Enden weiterer Rohrabschnitte absatzfrei aufnehmen können. Die Rasteinrichtung kann bevorzugt aus zumindest einer federnden Zunge mit einer Rastnase bestehen, die im Inneren jedes Rohrabschnitts an dem anderen Ende mit verringertem Außendurchmesser angeordnet ist, wobei die Rastnase bei bezüglich des Längsschlitzes passgenauer Übereinanderstellung der ineinander greifenden Rohrabschnitte von innen nach außen genau durch dann ebenfalls übereinander stehende Bohrungen in den beiden, einen Verbindungsbereich bildenden Teilbereiche der ineinander greifenden Rohrabschnitte greift und diese fest miteinander verbindet. Durch Drücken auf die nicht weiter hervorstehende Rastnase der zumindest einen federnden Zunge und gleichzeitigem Auseinanderziehen der beiden angrenzenden Rohrabschnitte kann die Verbindung sehr einfach und ohne Werkzeug wieder gelöst werden.

[0010] Die den Weg vorgebende Führungsbahn der Horizontalführung kann ein gespanntes Führungsseil sein, das aus einem einzelnen linearen Seilabschnitt oder einer beliebigen Anzahl von unter kleinen Winkeln aneinander angrenzenden Seilabschnitten besteht. Die Variante aus mehreren Seilabschnitten kann damit eine quasikontinuierliche Kurve beschreiben, die von dem Wagen abgefahren werden kann. Der Wagen für eine Horizontalführung aus einem gespannten Führungsseil wird von einem Führungsbereich aus zwei dicht beieinander stehenden flächigen Führungslaschen gebildet, zwischen denen die Führungsrollen frei drehbar eingespannt sind. Die Führungsrollen sind an ihrem Umfang eingekerbt und am Grund der umlaufenden Kerbe derart profiliert, dass sie reibungsarm aber eng geführt über das gespannte Führungsseil laufen können. Für verschiedene Durchmesser des Führungsseils kann die Kerbe ein stufig angepasstes Profil aufweisen, wobei Breite und Höhe der Stufen von der Achse der Führungsrolle aus nach außen hin zunehmen. Die bei einem gewählten Durchmesser des Führungsseils jeweils nicht benutzten kleineren Stufen können durch eine am Grund der zu benutzenden Stufe umlaufende Manschette abgedeckt werden, wodurch ein Verklemmen des Führungsseils in der nächst kleineren Stufe vermieden wird.

[0011] Zum sichereren Abfahren des Führungsseils können die flächigen Führungslaschen des Wagens einen nach unten verlängerten und sich dabei ab der Unterkante der Führungsrolle leicht erweiternden Führungsbereich aufweisen, wodurch einerseits das Aufsetzen des Wagens auf das Führungsseil erleichtert und andererseits ein Abspringen des Wagens von dem Führungsseil bei heftigeren Bewegungen verhindert wird. Die den Weg vorgebende Führungsbahn der Horizontalführung kann auch ein in der horizontalen Ebene beliebig geformtes Führungsrohr, bevorzugt mit kreisförmigem Querschnitt sein. In diesem Fall wird der Wagen von zumindest zwei Paaren senkrecht links und rechts des Führungsrohrs und zumindest einem Paar waagerecht über dem Führungsrohr angeordneter, an den Durchmesser des Führungsrohrs zumindest teilweise angepasster konkav profilierter, walzenartig verbreiterter Führungsrollen, die gemeinsam an einer Deckplatte befestigt sind, gestützt und geführt. Das Profil insbesondere der oberen walzenartigen Führungsrollen ist dabei nur so stark ausgeprägt, dass sie gerade auf das Führungsrohr mit dem größten Durchmesser passt und dient im Wesentlichen der Lastverteilung des an dem Wagen hängenden Teleskoprohrs mit den Inspektionsgeräten. Es nimmt als Negativprofil zumindest teilweise das Profil des Führungsrohrs auf. Die seitlichen walzenartigen Führungsrollen müssen nicht konkav profiliert sein, da sie keine Last aufnehmen und nur die seitlichen Führungskräfte übertragen müssen. Zur Anpassung des Wagens an verschiedene Durchmesser des Führungsrohrs können die seitlichen walzenartigen Führungsrollen mit Schnellspannern in der Deckplatte verschiebbar angeordnet und fixierbar sein. Nicht profilierte seitliche Führungsrollen müssen dazu nicht in der Höhe verstellbar sein, da sie sich durch ihre gerade Berandung an jeden Durchmesser des Führungsrohrs anlegen. Die Achsen der seitlichen Führungsrollen können unterhalb der Deckplatte ein Gelenk mit einer Rückholfeder aufweisen, mit dem sie sich unterschiedlichen Rohrabmessungen und/oder Unebenheiten der Rohroberfläche anpassen können.

[0012] Das Teleskoprohr kann durch eine Leiteinrichtung mit dem auf der Horizontalführung bewegbaren Wagen verbunden sein. Diese kann aus einer Leitöffnung in der Deckplatte des Wagens bestehen, in die das Teleskoprohr durch Öffnen schnell seitlich eingesetzt und nach dem Wiederverschließen gegen Herausfallen gesichert werden kann. Durch das seitliche Einsetzen wird vermieden, das Teleskoprohr mit seinen Inspektionsgeräten und Leitungszügen von unten oder oben durch die Leitöffnung einfädeln zu müssen. Die geschlossene Leitöffnung umfasst die Teleskopstange derart, dass sie darin gleiten kann. Oberhalb der Leitöffnung kann ein Schnellspannring in beliebiger Höhe die Teleskopstange umfassen und damit die maximale Einsatztiefe der Inspektionsgeräte festlegen und die Teleskopstange am Herausrutschen nach unten sichern. Die Teleskopstange kann von Hand auf und ab bewegt und gedreht werden, wobei die Bewegung oben von dem Schnellspannring und unten von den Inspektionsgeräten begrenzt wird. Im Falle des Führungsrohrs, bei dem der Wagen mit einer Deckplatte mit walzenartigen Führungsrollen ausgeführt ist, kann die Leitöffnung ein einfacher Ausschnitt in der Deckplatte sein, die durch einen Sperrriegel geöffnet und verschlossen werden kann. Im Falle eines Führungsseils, bei dem der Wagen mit zwei seitlichen Führungslaschen mit den Führungsrollen dazwischen ausgeführt ist, kann die Leitöffnung aus einem das Teleskoprohr umfassenden geschlitzten Leitflansch bestehen, dessen Schenkel durch eine Schraube geöffnet und geschlossen werden. Der geschlitzte Leitflansch kann über ein einfaches Drehgelenk und einen starren Abstandhalter mit dem Wagen verbunden sein. Das Drehgelenk dient dem Ausgleich der gegenüber dem gerade in die Tiefe ragenden Teleskoprohr gegebenenfalls durch Unebenheiten in der Horizontalführung an einem Wagen mit mehr als einer Führungsrolle auftretenden kleinen Kippbewegungen. Da ein fest mit einem solchen Wagen verbundenes Teleskoprohr diesen Kippbewegungen aufgrund seiner Hebellänge und seines Gewichts nicht folgen könnte, würde bei Abwesenheit des Drehgelenks jeweils eine Führungsrolle mehr oder weniger weit von der Horizontalführung abheben und eine ungenaue Seitenführung bedingen. Der starre Abstandhalter verhindert die Reibung des drehbar gelagerten Teleskoprohrs an dem Wagen und sorgt für einen Mindestabstand zwischen der Teleskopstange mit den Inspektionsgeräten und der zu inspizierenden Oberfläche um beispielsweise einen zur Beobachtung ausreichenden Mindestabstand der Videokamera zu gewährleisten. Das Teleskoprohr sitzt in seiner Leitöffnung seitlich am Wagen wodurch sich ein Hebel zwischen dem Angriffspunkt des Gewichts der Teleskopstange und dem Auflage- und Drehpunkt des Wagens auf dem Führungsseil oder dem Führungsrohr ergibt. Um eine Schiefstellung des Teleskoprohrs im Wasser zu verhindern, kann zur Kompensation des Gewichts der Teleskopstange zumindest ein Auftriebskörper an einem längenveränderbaren Ausleger angeordnet sein, der mit dem Wagen in der gewählten Längeneinstellung fest verbunden ist. Auslegerlänge und Auftriebskraft werden dabei so hergestellt, dass das Gewicht der Teleskopstange gerade bis zu ihrer genau vertikalen Stellung kompensiert wird.

[0013] Als Inspektionsgerät ist zumindest eine Unterwasser-Videokamera vorgesehen. Diese kann in einem Gehäuse untergebracht sein, das von der Wasseroberfläche aus zumindest um die horizontale, einen rechten Winkel mit der optischen Kameraachse bildende Raumachse um zumindest ± 90° geschwenkt werden kann. Zusammen mit der seitlichen Verdrehmöglichkeit des gesamten Teleskoprohrs ist es möglich, einen Überblick über einen jeweils ganzen, relativ breiten vertikalen Abschnitt des Inspektionsobjekts zu erhalten, vor dem die Kamera gerade steht. Als weiteres Inspektionsgerät kann eine mit einem Saugschlauch versehene Ansaugvorrichtung für Wasserproben und kleine Organismen an der Teleskopstange in Höhe der Unterwasser-Videokamera montiert sein. Durch eine kleine Pumpe können Proben von Wasser und Schwebstoffen vom Beobachtungsort abgesaugt und bevorratet werden. Ein weiteres Inspektionsgerät kann eine Entnahmevorrichtung für Festkörperproben sein und einen Aufnahmekorb aufweisen, in den Festkörperproben vom Beobachtungsort untergebracht werden können. Dazu kann die Korbhalterung vorteilhaft mit scharfen Kanten versehen sein, so dass durch entsprechende Bewegungen der Teleskopstange Festkörperproben, z.B. Muscheln, vom beobachteten Untergrund abgekratzt werden und in den Aufnahmekorb fallen können. Eine andere Entnahmevorrichtung für Festkörperproben kann eine Trennvorrichtung für Festkörperproben aufweisen, die als mechanisch betätigbare Säge, Zange oder Messer ausgebildet ist. Eine weitere Ausführung einer Inspektionseinrichtung als Entnahmevorrichtung von Festkörperproben kann neben einem Aufnahmekorb einen mechanisch betätigbaren Greifer aufweisen, mit dem Festkörperproben vom beobachteten Untergrund aufgenommen und in den Aufnahmekorb befördert werden können. Darüber hinaus kann als weiteres Inspektionsgerät eine Vermessungsvorrichtung mit der Kamera an der Teleskopstange montiert sein, die vorteilhaft aus zwei in definiertem Abstand und exakt parallel zueinander angeordneten Lasern bestehen kann. Bei der Beobachtung der Unterwasserstrukturen kann durch Relation zwischen den Auftreffpunkten des Laserlichts und deren bekanntem Abstand auf die Größe der beobachteten Strukturen, z.B. Organismen, geschlossen werden.

[0014] Zur Bedienung der mechanisch betätigbaren Inspektionsgeräte können Bowdenzüge verwendet werden, mit deren Hilfe die notwendigen Bewegungen in der Tiefe von der Wasseroberfläche aus durchgeführt werden können. Die Bowdenzüge können mit Hebeln oder Drehelementen als Bedienungseinrichtungen in eine gewünschte Position gebracht und dort in Raststellungen fixiert werden. Beim Lösen der Rasten können die bewegbaren Inspektionsgeräte mittels Rückholfedern in eine Ausgangsstellung zurückbewegt werden. Die Drehelemente können gleichzeitig einen zur Verlängerung der Teleskopstange mittels geschlitzten Rohrabschnitten einen Drahtvorrat aufnehmen, der bei Bedarf einfach auf- oder abgewickelt werden kann.

Ausführungsbeispiel

[0015] Ausbildungsformen der Inspektionseinrichtung für Unterwasserstrukturen mit einer Positioniervorrichtung nach der Erfindung werden nachfolgend zum weiteren Verständnis der Erfindung anhand der schematischen Figuren näher erläutert. Dabei zeigt

[0016] Fig. 1 eine Inspektionseinrichtung mit Positioniervorrichtung und Inspektionsgeräten mit Führungsseil,

[0017] Fig. 2 einen Wagen mit profilierter Rolle und Leiteinrichtung,

[0018] Fig. 3 eine Inspektionseinrichtung mit Positioniervorrichtung und Inspektionsgeräten mit Führungsrohr,

[0019] Fig. 4 einen Wagen mit Deckplatte mit Leiteinrichtung,

[0020] Fig. 5 walzenartige Führungsrollen im Aufbau,

[0021] Fig. 6 Rohrabschnitte der Teleskopstange mit Rastnasen,

[0022] Fig. 7 ein Führungsrohr als Kreis,

[0023] Fig. 8 ein Führungsseil mit Abschnitten,

[0024] Fig. 9 eine Teleskopstange mit Inspektionsgeräten und

[0025] Fig. 10 eine Bedieneinheit für Bowdenzüge.

[0026] Fig. 1 zeigt eine Inspektionseinrichtung IE mit Positioniervorrichtung PV, Inspektionsgeräten IG und Horizontalführung HF mit Führungsseil FS. Die Vertikalführung VF mit Teleskopstange TS aus mehreren Rohrabschnitten RA wird in einer hier nicht sichtbaren Leiteinrichtung LE am Wagen WA auf- und abführbar sowie drehbar aufgenommen. Ein Schnellklemmring SK begrenzt dabei den möglichen Hub der Teleskopstange TS und legt die maximale Eintauchtiefe fest. Die Teleskopstange TS weist einen durchgängigen Längsschlitz LS zur Aufnahme von Leitungszügen LZ zur elektrischen Versorgung und zur mechanischen Bedienung der Inspektionsgeräte IG, in

[0027] Fig. 1 einer Videokamera VK, auf. Die Bedienungseinrichtung BE zur mechanischen Verstellung der Videokamera VK kann in hier nicht weiter dargestellten Raststellungen fixiert werden. Der Wagen WA in dieser Ausführung ist mit einer profilierten Führungsrolle PR ausgerüstet, die auf dem Führungsseil FS abrollt, ein das Profil des Führungsseils FS aufgreifendes Negativprofil NP und einen nach unten verlängerten und sich aufweitenden Führungsbereich FB aufweist. Die Videokamera VK kann zumindest um die horizontale, einen rechten Winkel mit der optischen Kameraachse KA bildende Raumachse RM schwenken.

[0028] Fig. 2 zeigt einen Wagen WA mit zwei profilierten Führungsrollen PR und Leiteinrichtung LE. Die profilierten Führungsrollen PR zeigen den an verschiedene Seildurchmesser in Stufen angepassten Profilbereich PB. Das bei der gewählten Darstellung in der Zeichnungsebene verlaufende Führungsseil FS ist zur Verdeutlichung im Querschnitt im oberen Profilbereich PB dargestellt. Die jeweils unbenutzten kleineren Stufen können durch Manschetten MA abgedeckt werden, um ein Verklemmen des Führungsseils FS zu verhindern. Die Manschette MA kann in die nächstkleinere Stufe füllend eingelegt und an ihren verjüngten Enden zum Ring verschraubt werden. Die profilierten Führungsrollen PR werden von dem Führungsbereich FB aus zwei ebenen Führungslaschen FL zusammengefasst und zwischen ihnen leicht drehbar auf Drehachsen DA gehalten und mit Sicherungsmuttern SM gesichert. Gleitscheiben GS zwischen den Führungslaschen FL und den profilierten Führungsrollen PR sorgen für den reibungsarmen Lauf. Die Drehachsen DA werden von einem gemeinsamen Abstandhalter AH getragen, der an seinem zentralen Punkt ZP die Leiteinrichtung LE für die Teleskopstange TS in einem Drehlager DL trägt. Die Leiteinrichtung LE besteht in diesem Ausführungsbeispiel aus einem über Scharniere SR aufklappbaren Leitflansch LF, der im durch eine Sicherungsschraube SS geschlossenen Zustand die Teleskopstange TS hält, ihr aber zur Drehung und Auf- und Abbewegung genügend Spielraum lässt.

[0029] Fig. 3 zeigt eine Inspektionseinrichtung IE mit Positioniervorrichtung PV, Inspektionsgeräten IG und Horizontalführung HF mit Führungsrohr FR als Führungsbahn FN. Die Vertikalführung VF mit Teleskopstange TS aus mehreren Rohrabschnitten RA wird in einer Leiteinrichtung LE am mit Deckplatte DP ausgerüsteten Wagen WA auf- und abführbar sowie drehbar aufgenommen. Die Leiteinrichtung LE besteht in diesem Ausführungsbeispiel aus einer Leitöffnung LO, die den Querschnitt der Teleskopstange TS mit Spiel aufnehmen kann, und einem als drehbarer, offener Ring ausgelegten Sperrriegel SP. Ein Schnellklemmring SK begrenzt dabei den möglichen Hub der Teleskopstange TS und legt die maximale Eintauchtiefe fest. Die Teleskopstange TS weist einen durchgängigen Längsschlitz LS zur Aufnahme von Leitungszügen LZ auf. Ein hier dargestelltes Inspektionsgerät IG ist eine Entnahmevorrichtung für Festkörperproben EF und besteht aus einem Aufnahmekorb AN mit Korbhalterung KH mit schneidenartig ausgebildeter Kante KK als Trennvorrichtung für Festkörperproben TF. Der mit Deckplatte DP ausgerüstete Wagen WA in diesem Ausführungsbeispiel ist mit zwei Paaren senkrecht links und rechts des Führungsrohrs FR und zumindest einem Paar waagerecht über dem Führungsrohr FR angeordneter, an den Durchmesser des Führungsrohrs FR zumindest teilweise angepasster konkav profilierter, walzenartig verbreiterter Führungsrollen PR ausgerüstet, die auf dem Führungsrohr FR abrollen. Die Führungsrollen PR können über Schnellspanner SN und Langlöcher LL auf dem jeweiligen Durchmesser des Führungsrohrs angepassten Positionen fixiert werden. Im Falle des mit Deckplatte DP ausgerüsteten Wagens WA wird das seitlich an dem Wagen WA angreifende Gewicht der Teleskopstange TS und der daran fixierten Inspektionsgeräte IG durch einen an einem Ausleger AL an der dem Führungsrohr FR abgewandten Seite des Wagens WA angeordneten Auftriebskörper AK kompensiert. Der Ausleger AL wird ebenfalls über Schnellspanner SN und Langlöcher LL an der Deckplatte DP einstellbar fixiert.

[0030] Fig. 4 zeigt einen mit Deckplatte DP ausgerüsteten Wagen WA und eine Leiteinrichtung LE in der Draufsicht. Die Teleskopstange TS wird darin auf- und abführbar sowie drehbar aufgenommen. Die Leiteinrichtung LE besteht in diesem Ausführungsbeispiel aus einer Leitöffnung LO, die den Querschnitt der Teleskopstange TS mit Spiel aufnehmen kann, und einem als Stange mit Griffknopf SG ausgebildeten und durch zwei Schellen SE gehaltenen Sperrriegel SP. Die unterhalb der Deckplatte DP angeordneten und in dieser Darstellung nicht sichtbaren Führungsrollen PR können über Schnellspanner SN und Langlöcher LL auf dem jeweiligen Durchmesser des Führungsrohrs angepassten Positionen fixiert werden. Der der Gewichtskompensation dienende Ausleger AL mit dem Auftriebskörper AK ist an der dem Führungsrohr FR als Führungsbahn FN abgewandten Seite des Wagens WA angeordnet. Der Ausleger AL wird über Schnellspanner SN und Langlöcher LL an der Deckplatte DP einstellbar fixiert.

[0031] Fig. 5 zeigt die walzenartige Führungsrollen PR in einem rahmenartigen Aufbau RB. Dabei werden die waagerecht angeordneten Führungsrollen PR mit einem an den größten möglichen Durchmesser des Führungsrohrs FR zumindest teilweise angepassten Profil AP als Negativprofil NP des Führungsrohrs FR versehen, mit dessen Hilfe sich der ganze Wagen WA auf dem Führungsrohr FR zentriert. Die vertikal angeordneten Führungsrollen PR erhalten kein Profil, sondern werden nur in ihrer Länge für den größten möglichen Durchmesser des Führungsrohrs FR ausgelegt. Dadurch besteht keine Notwendigkeit der Höhenanpassung der vertikal angeordneten Führungsrollen PR bei Änderung des Durchmessers des Führungsrohrs FR.

[0032] Die vertikal angeordneten Führungsrollen PR sind mit Achsen AS drehbar in je einer quaderförmigen Halterung QH angeordnet, von denen jeweils zwei über verschraubbare Streben VS miteinander verbunden sind. Die beiden dadurch entstehenden verbundenen Paare von vertikal angeordneten Führungsrollen PR sind über die beiden profilierten, horizontal angeordneten Führungsrollen PR verbunden, indem deren verlängerte Achsen VA in Querbohrungen QB je einer der beiden zugehörigen quaderförmigen Halterungen QH stecken. Die quaderförmigen Halterungen QH weisen zentrale vertikale Bohrungen ZB auf, über die der rahmenartige Aufbau RB insgesamt mittels der Schnellspanner SN und der Langlöcher LL an der Deckplatte DP fixiert wird. Die Achsen AS der vertikalen Führungsrollen PR können zur Unterstützung der Anpassung an den Durchmesser des Führungsrohrs FR oder zum Ausgleich von darauf befindlichen Unebenheiten Knickgelenke KG aufweisen. Zur Anpassung des Wagens WA an den Durchmessers des Führungsrohrs FR werden die Schnellspanner SN gelöst, der Wagen WA über das Führungsrohr FR gesetzt und die beiden verbundenen Paare von vertikal angeordneten Führungsrollen PR über die Langlöcher LL an das Führungsrohr FR herangeschoben. Die horizontalen Führungsrollen PR mit dem angepassten Profil AP können sich dabei durch die in den Querbohrungen QB der quaderförmigen Halterungen QH steckenden verlängerten Achsen VA solange verschieben, bis sie zentral auf dem Führungsrohr FR angeordnet sind. Anschließend werden die Schnellspanner SN wieder befestigt.

[0033] Fig. 6 zeigt zwei Rohrabschnitte RA der Teleskopstange TS, von denen der eine am oberen Ende OE bei konstantem Außendurchmesser dA auf einem Teilbereich TB der ungefähren Länge des Durchmessers der Teleskopstange TS einen vergrößerten Innendurchmesser gI und der andere am unteren Ende UE auf einem gleichlangen Teilbereich TB bei konstantem Innendurchmesser dI einen derart verkleinerten Außendurchmesser kA aufweist, dass die beiden Enden OE, UE der dargestellten Rohrabschnitte RA einander gerade spielarm absatzfrei aufnehmen können. Die Rasteinrichtung RE besteht aus zumindest einer federnden Zunge FZ mit einer Rastnase RN, die im Inneren des oberen Rohrabschnitts RA an dem unteren Ende UE mit verkleinertem Außendurchmesser kA angeordnet ist, wobei die Rastnase RN bei bezüglich des Längsschlitzes LS passgenauer Übereinanderstellung der ineinander greifenden Rohrabschnitte RA von innen nach außen genau durch dann ebenfalls übereinander stehende Bohrungen BN in den beiden, einen Verbindungsbereich VB bildenden Teilbereiche der ineinander greifenden Rohrabschnitte RA greift und diese fest miteinander verbindet. Durch Drücken auf die außen nicht weiter hervorstehende Rastnase RN der zumindest einen federnden Zunge FZ und gleichzeitiges Auseinanderziehen der beiden angrenzenden Rohrabschnitte RA kann die Verbindung sehr einfach und ohne Werkzeug wieder gelöst werden. Die Rasteinrichtung RE ist in der geöffneten Stellung zusätzlich gestrichelt dargestellt.

[0034] Fig. 7 zeigt ein Führungsrohr FR als Führungsbahn FN, das als Kreis KR ausgebildet ist. Der Wagen WA läuft auf dem Führungsrohr FR um und führt dabei die Teleskopstange TS mit sich. Mit diesem Aufbau können zylinderartige Unterwasserstrukturen inspiziert werden.

[0035] Fig. 8 zeigt ein Führungsseil FS als Führungsbahn FN, das unter Bildung kleiner Winkel in zusammenhängende Seilabschnitte SA eingeteilt ist. Der Wagen WA läuft auf dem Führungsseil FS und führt dabei die Teleskopstange TS mit sich. Mit diesem Aufbau können quasi kurvig geformte Unterwasserstrukturen inspiziert werden.

[0036] Fig. 9 zeigt eine Teleskopstange TS mit Inspektionsgeräten IG, hier insbesondere eine Ansaugvorrichtung für Wasserproben AW mit einem Hüllrohr HR und einem Saugschlauch SL, ein mechanischer, über Bowdenzug BZ (nicht sichtbar) und Rückholfeder RF betätigbarer Greifer MG als Entnahmevorrichtung für Festkörperproben EF mit dem zugehörigen Aufnahmekorb AN und eine Vermessungsvorrichtung W aus zwei in einem frei wählbaren Abstand wa und genau parallel zueinander ausgerichteten Lasern LR direkt an der Videokamera VK. Eine ebenfalls mögliche Trennvorrichtung für Festkörperproben TF als mechanisch betätigbare Säge, Zange oder Messer ist nicht weiter dargestellt. Die Inspektionsgeräte IG sind so angeordnet, dass die Videokamera alle Aktivitäten im Sichtbereich ihrer Optik und der Bedienende volle Kontrolle über die erforderlichen Tätigkeiten hat.

[0037] Fig. 10 zeigt eine Bedieneinheit für einen Bowdenzug eines Inspektionsgeräts. Am Teleskoprohr TS ist eine Rastscheibe RS mit Rastlöchern RL befestigt. Zentral dazu ist eine Drahtspule DS drehbar mittels einer Zentralschraube ZS angeordnet. Die Drahtspule DS, die mit der Handkurbel HK gedreht werden kann, weist eine umlaufende Vertiefung auf, in der ein Drahtvorrat DV für den Bowdenzug vorhanden ist. Ein Sicherungsstift ST verbindet die Drahtspule DS mit der Rastscheibe RS. Bei Längenänderungen des Teleskoprohrs TS muss Draht ab- oder aufgewickelt werden. Dazu wird der Sicherungsstift ST gegen eine Zugfeder ZF aus seinem Rastloch RL herausgezogen, um 90° gedreht und so in gelöster Stellung fixiert. Die Drahtspule DS kann nun mit der Handkurbel HK gedreht werden, bis der Draht entweder gelockert ist und ein Rohrabschnitt abgenommen oder die für den Bowdenzug erforderliche neue Länge aufweist und ein Rohrabschnitt an die Teleskopstange TS angesetzt werden kann. Anschließend wird der Sicherungsstift ST wieder in das nächstgelegene Rastloch RL eingeführt. Zum Bedienen des jeweiligen Inspektionsgeräts wird der Sicherungsstift ST wieder gelöst und die Handkurbel HK solange betätigt, bis das Inspektionsgerät die richtige Position aufweist. Beim Rückdrehen der Handkurbel HK wird das Inspektionsgerät durch eine Rückholfeder bis maximal in die Ausgangstellung zurückgeführt. Zur Beibehaltung einer bestimmten Stellung des Inspektionsgeräts kann die Drahtspule DS in jeder vorhandenen Raststellung mit dem Sicherungsstift ST fixiert werden.

Bezugszeichenliste

AH	Abstandhalter
AL	Ausleger
AK	Auftriebskörper
AN	Aufnahmekorb
AP	angepasstes Profil
AS	Achse
AW	Ansaugvorrichtung für Wasserproben
BE	Bedienungseinrichtung
BN	übereinander stehende Bohrung
BZ	Bowdenzug
DA	Drehachse
dA	konstanter Außendurchmesser
DL	Drehlager
dI	konstanter Innendurchmesser
DP	Deckplatte
DS	Drahtspule
EF	Entnahmevorrichtung für Festkörperproben
FB	Führungsbereich
FL	Führungslasche
FN	Führungsbahn
FS	Führungsseil
FR	Führungsrohr
FZ	federnde Zunge
gI	vergrößerter Innendurchmesser
GS	Gleitscheibe
HF	Horizontalführung
HK	Handkurbel
HR	Hüllrohr
IE	Inspektionseinrichtung
IG	Inspektionsgerät
KA	Kameraachse
kA	verkleinerter Außendurchmesser
KG	Knickgelenk
KH	Korbhalterung
KK	schneidenartige Kante
KR	Kreis
LE	Leiteinrichtung
LF	Leitflansch
LL	Langlöcher
LO	Leitöffnung
LR	Laser
LS	Längsschlitz
LZ	Leitungszug
MA	Manschette
MG	Greifer
NP	Negativprofil
OE	oberes Ende
PB	Profilbereich
PR	Führungsrolle
PV	Positioniervorrichtung
QB	Querbohrung
QH	quaderförmige Halterung
RA	Rohrabschnitt
RB	rahmenartiger Aufbau
RE	Rasteinrichtung
RF	Rückholfeder
RM	Raumachse
RL	Rastloch

RN	Rastnase
RS	Rastscheibe
SA	Seilabschnitt
SE	Schelle
SG	Stange mit Griffknopf
SK	Schnellklemmring
SL	Saugschlauch
SM	Sicherungsmutter
SN	Schnellspanner
SP	Sperrriegel
SR	Scharnier
SS	Sicherungsschraube
ST	Sicherungsstift
TB	Teilbereich
TF	Trennvorrichtung für Festkörperproben
TS	Teleskopstange
UE	unteres Ende
VA	verlängerte Achse
VB	Verbindungsbereich
VF	Vertikalführung
VK	Videokamera
VS	verschraubbare Strebe
W	Vermessungsvorrichtung
WA	Wagen
wa	wählbarer Abstand
ZB	zentrale Bohrung
ZF	Zugfeder
ZP	zentraler Punkt
ZS	Zentralschraube

Patentansprüche

1. Inspektionseinrichtung IE für Unterwasserstrukturen mit einer Positioniervorrichtung PV, die eine stufenlos verstellbare Vertikalführung VF mit einer Teleskopstange TS und eine stufenlos verstellbare Horizontalführung HF mit einer einen Weg vorgebenden Führungsbahn FN und einem darauf auf Führungsrollen PR geführten Wagen WA zur Aufnahme der Vertikalführung VF aufweist, und mit einer Unterwasser-Videokamera VK als zumindest einem Inspektionsgerät IG, das an der Teleskopstange TS befestigt ist, wobei die Teleskopstange TS mittels mehrerer Rohrabschnitte RA absatzfrei verlängerbar ist, die Führungsbahn FN einen veränderlich vorgebbaren Kurvenverlauf aufweist und die Führungsrollen PR ein das Profil der Führungsbahn FN aufnehmendes Negativprofil NP aufweisen.

2. Inspektionseinrichtung nach Anspruch 1, dadurch gekennzeichnet, dass die Teleskopstange TS einen in durchgehenden Längsschlitz LS zur geschützten Aufnahme von Leitungszügen LZ zur Versorgung und Bedienung des zumindest einen Inspektionsgerätes IG in ihrem Inneren aufweist.

3. Inspektionseinrichtung nach einem der Ansprüche 1 bis 2, dadurch gekennzeichnet, dass die Rohrabschnitte RA zur Verlängerung der Teleskopstange TS ineinander greifen und durch federnde Rastnasen RN miteinander verbunden sind.

4. Inspektionseinrichtung nach einem der Ansprüche 1 bis 3, dadurch gekennzeichnet, dass die den Weg des Wagens WA vorgebende Führungsbahn FN ein in der horizontalen Ebene verlaufendes, gespanntes Führungsseil FS ist.

5. Inspektionseinrichtung nach Anspruch 4, dadurch gekennzeichnet, dass die Führungsrollen PR ein an verschiedene Durchmesser des Führungsseils FS in Stufen angepasstes Profil AP aufweisen, wobei Breite und Höhe der Stufen von der Achse der Führungsrolle PR aus nach außen hin zunehmen und die bei einem gewählten Durchmesser des Führungsseils FS jeweils nicht benutzten kleineren Stufen abdeckbar sind.

6. Inspektionseinrichtung nach einem der Ansprüche 1 bis 5, dadurch gekennzeichnet, dass der Wagen WA beidseits der Führungsrollen PR Führungslaschen FL aufweist, die einen nach unten verlängerten und sich erweiternden Führungsbereich FB ausbilden.

7. Inspektionseinrichtung nach einem der Ansprüche 1 bis 3, dadurch gekennzeichnet, dass die den Weg vorgebende Führungsbahn FN ein in der horizontalen Ebene geformtes Führungsrohr FR ist.

8. Inspektionseinrichtung nach Anspruch 7, dadurch gekennzeichnet, dass der Wagen WA eine Deckplatte DP und daran angeordnet zumindest zwei Paare senkrecht links und rechts des Führungsrohrs FR und zumindest ein Paar waagerecht über dem Führungsrohr FR angeordnete, an den Durchmesser des Führungsrohrs FR zumindest teilweise konkav profiliert angepasste, walzenartig verbreiterte Führungsrollen PR aufweist.

9. Inspektionseinrichtung nach Anspruch 8, dadurch gekennzeichnet, dass die walzenartig verbreiterten Führungsrollen PR zur Anpassung des Wagen WA an verschiedene Durchmesser des Führungsrohrs FR mit Schnellspannern SN an der Deckplatte DP in Langlöchern LL verschiebbar und fixierbar sind.

10. Inspektionseinrichtung nach einem der Ansprüche 8 oder 9, dadurch gekennzeichnet, dass die walzenartig verbreiterten Führungsrollen PR in ihren Achsen unterhalb der Deckplatte DP ein Knickgelenk zur Anpassung des Wagen WA an verschiedene Durchmesser des Führungsrohrs FR aufweisen.

11. Inspektionseinrichtung nach einem der Ansprüche 4 bis 6, dadurch gekennzeichnet, dass der Wagen WA durch eine Leiteinrichtung LE mit der Teleskopstange TS verbunden ist, wobei die Leiteinrichtung LE einen an einem Drehlager DL und einem

Abstandhalter AH angeordneten, die Teleskopstange TS umfassenden Leitflansch LF und einen an der Teleskopstange TS in beliebiger Höhe oberhalb des Leitflanschs LF fixierbaren Schnellklemmring SK aufweist.

12. Inspektionseinrichtung nach einem der Ansprüche 7 bis 10, dadurch gekennzeichnet, dass der Wagen WA durch eine Leiteinrichtung LE mit der Teleskopstange TS verbunden ist, wobei die Leiteinrichtung LE eine die Teleskopstange TS umfassende und mit einem Sperrriegel SP verschließbare Leitöffnung LO in der Deckplatte DP des Wagens WA und einen an der Teleskopstange TS in beliebiger Höhe oberhalb der Leitöffnung LO fixierbaren Schnellklemmring SK aufweist.

13. Inspektionseinrichtung nach einem der Ansprüche 1 bis 12, dadurch gekennzeichnet, dass das seitlich an dem Wagen WA angreifende Gewicht der Teleskopstange TS und des daran fixierten zumindest einen Inspektionsgeräts IG durch einen an einem längenveränderbar ausgebildeten Ausleger AL an der der Führungsbahn FN abgewandten Seite des Wagens WA angeordneten Auftriebskörper AK kompensiert ist.

14. Inspektionseinrichtung nach einem der Ansprüche 1 bis 13, dadurch gekennzeichnet, dass die als zumindest ein Inspektionsgerät IG vorhandene Unterwasser-Videokamera VK zumindest um die horizontale, einen rechten Winkel mit der optischen Kameraachse KA bildende Raumachse RM schwenkbar ist.

15. Inspektionseinrichtung nach einem der Ansprüche 1 bis 14, dadurch gekennzeichnet, dass als weiteres Inspektionsgerät IG eine mit einem Saugschlauch SL versehene Ansaugvorrichtung AV für Wasserproben an der Teleskopstange TS angeordnet ist.

16. Inspektionseinrichtung nach einem der Ansprüche 1 bis 15, dadurch gekennzeichnet, dass als weiteres Inspektionsgerät IG eine Entnahmevorrichtung für Festkörperproben EF an der Teleskopstange TS angeordnet ist.

17. Inspektionseinrichtung nach Anspruch 16, dadurch gekennzeichnet, dass die Entnahmevorrichtung für Festkörperproben EF als Aufnahmekorb AN mit Korbhalterung KH ausgebildet ist.

18. Inspektionseinrichtung nach Anspruch 17, dadurch gekennzeichnet, dass die Korbhalterung KH schneidenartig ausgebildete Kanten KK aufweist.

19. Inspektionseinrichtung nach einem der Ansprüche 17 oder 18, dadurch gekennzeichnet, dass oberhalb des Aufnahmekorbes AN eine Trennvorrichtung für Festkörperproben TF an der Teleskopstange TS angeordnet ist.

20. Inspektionseinrichtung nach Anspruch 16, dadurch gekennzeichnet, dass die Entnahmevorrichtung für Festkörperproben EF als mechanischer Greifer MG ausgebildet ist.

21. Inspektionseinrichtung einem der Ansprüche 1 bis 20, dadurch gekennzeichnet, dass als weiteres Inspektionsgerät IG eine Vermessungsvorrichtung W aus zwei in einem frei wählbaren Abstand und genau parallel zueinander ausrichtbaren Lasern AL an der Teleskopstange TS angeordnet ist.

22. Inspektionseinrichtung nach einem der Ansprüche 1 bis 21, dadurch gekennzeichnet, dass die Inspektionsgeräte IG durch in Raststellungen von Bedienungseinrichtungen BE fixierbare Bowdenzüge BZ und Rückholfedern RF aufweisen.

Es folgen 6 Blatt Zeichnungen

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Anhängende Zeichnungen

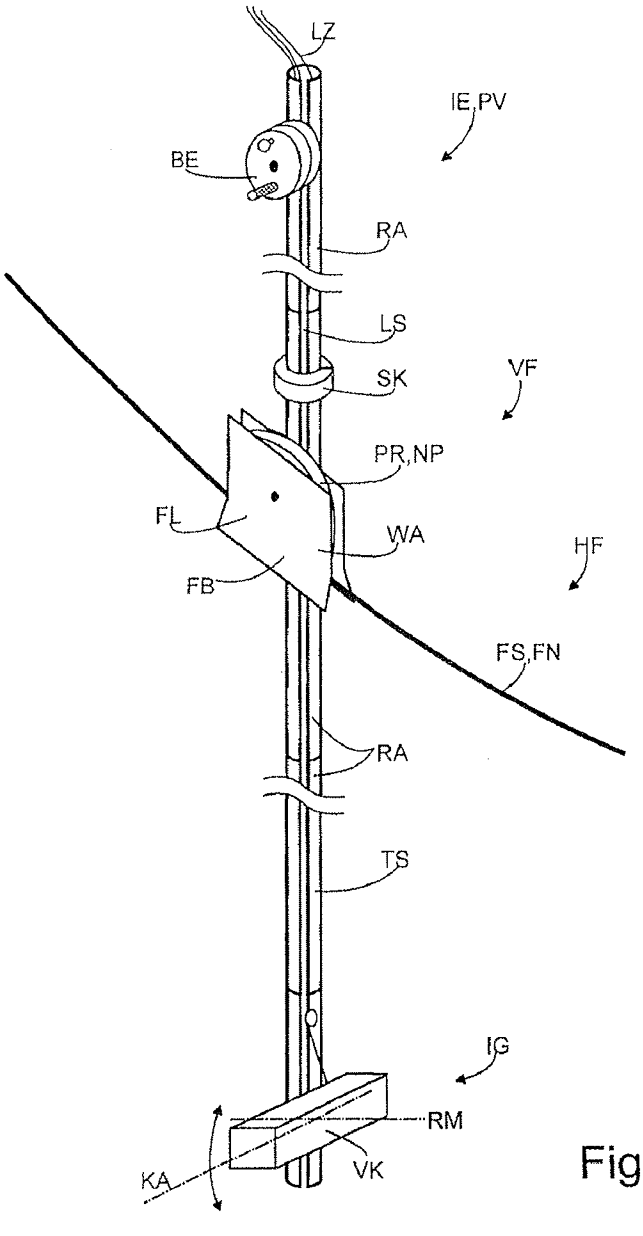

Fig.1

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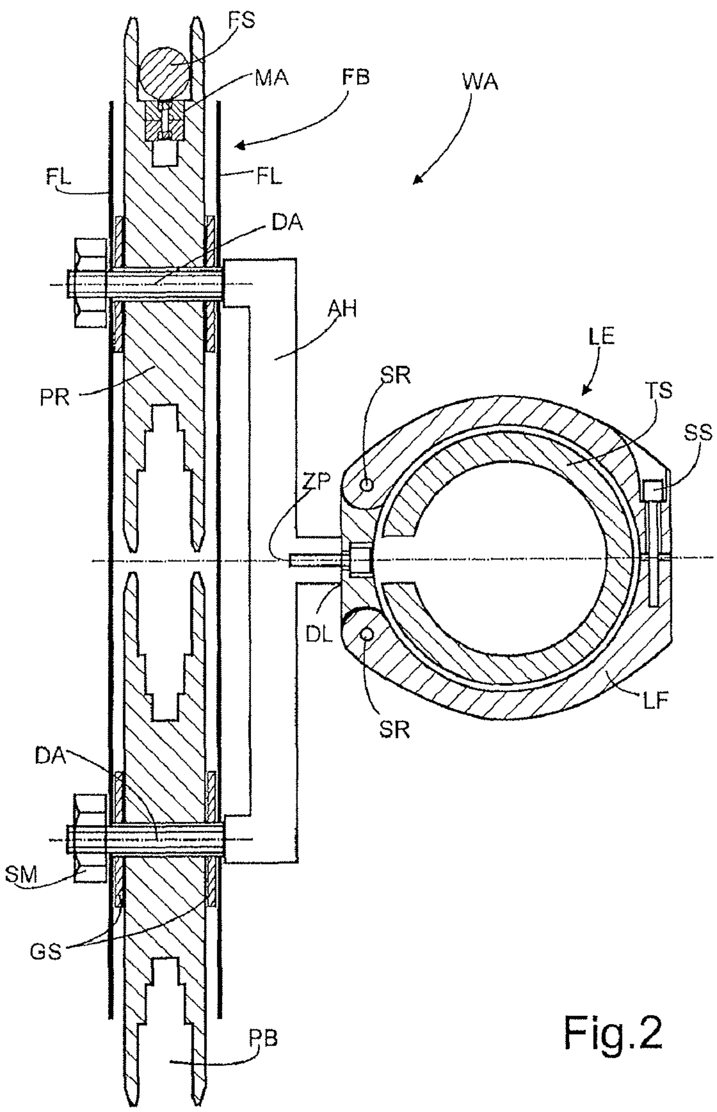

Fig.2

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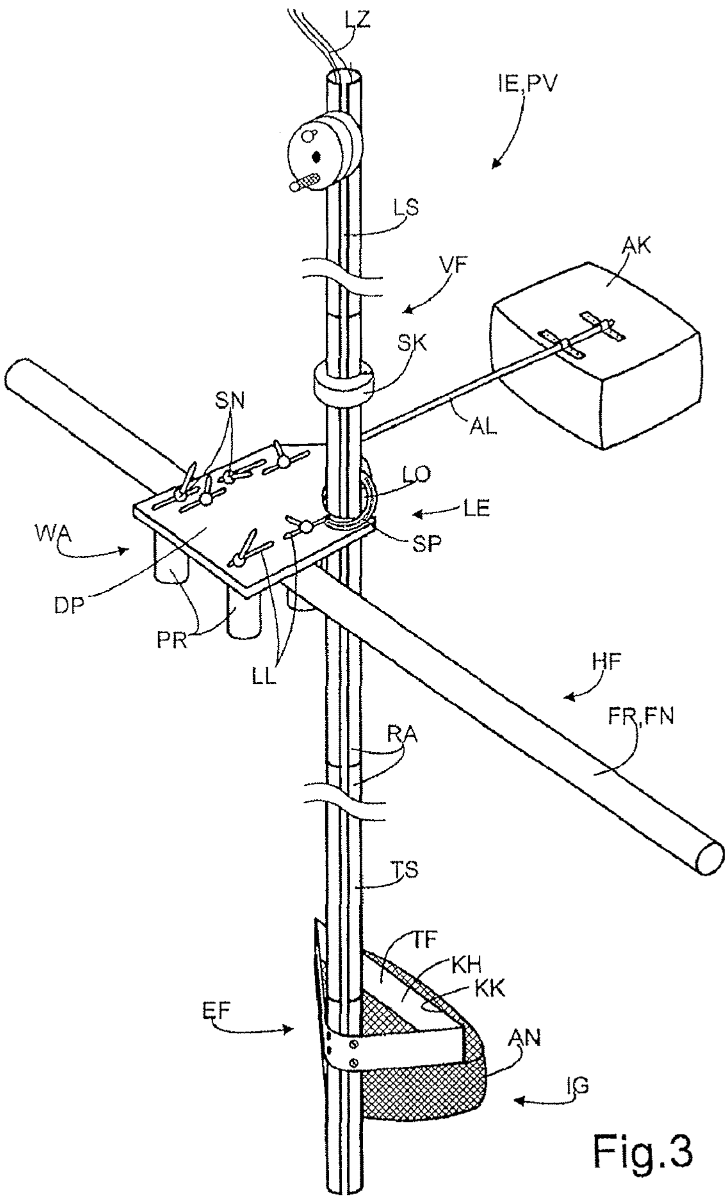

Fig.3

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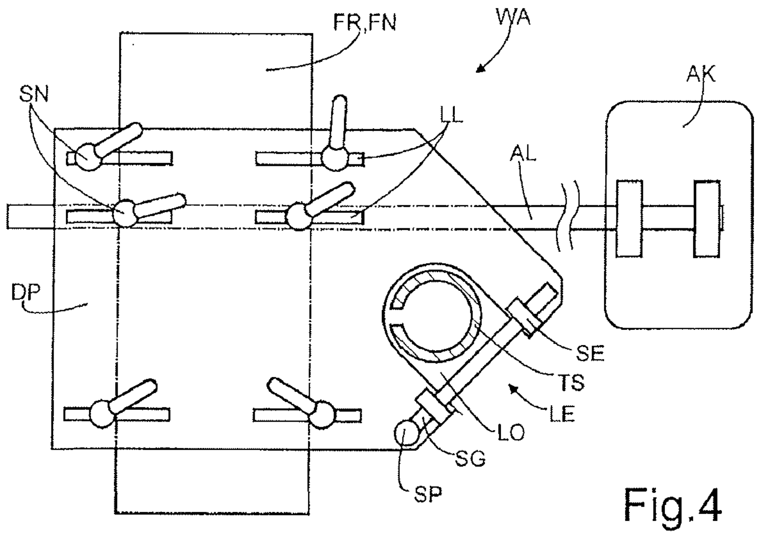
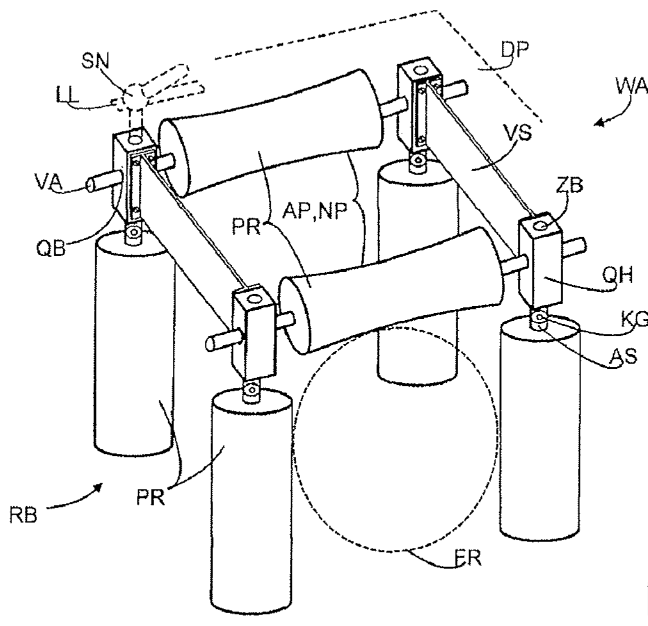


FR,FN
WA
AK
SN
LL
AL
DP
SE
TS
LE
LO
SG
SP

Fig.4



DP
SN
WA
LL
VS
VA
ZB
PR
AP,NP
QB
QH
KG
AS
RB
PR
ER

Fig.5

DE 10 2005 020 070 B3 2006.09.14

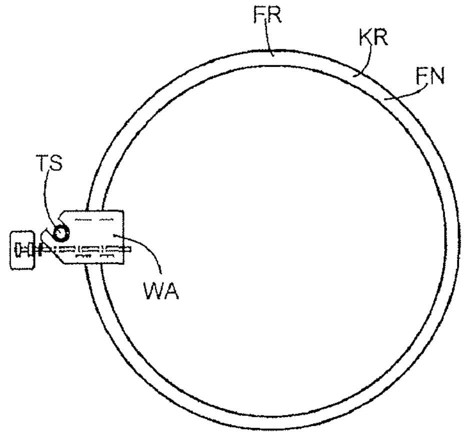


Fig.7

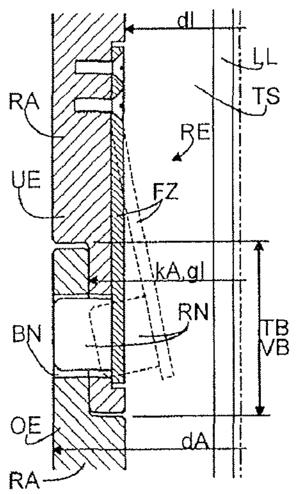


Fig.6

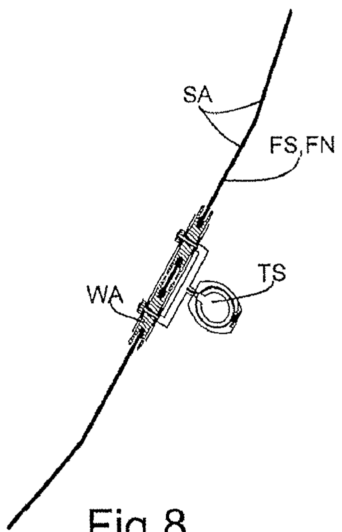


Fig.8

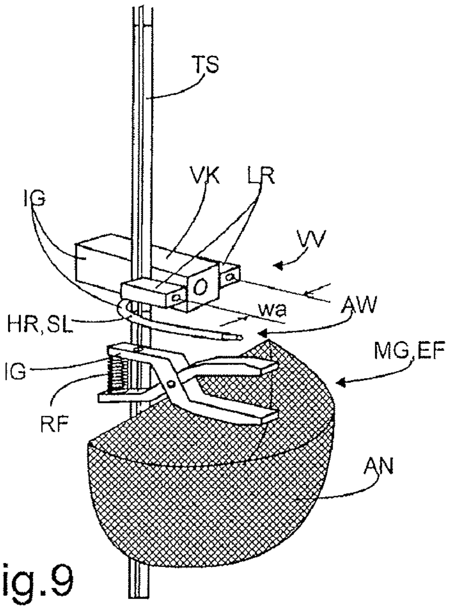


Fig.9

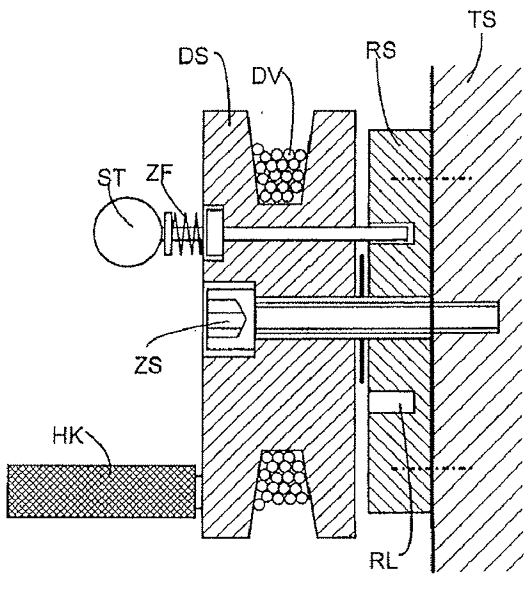


Fig.10