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PRACTICE BRIDGE

Transporting ideas between marine and social sciences: experiences from interdisciplinary research programs

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The oceans comprise 70% of the surface area of our planet, contain some of the world's richest natural resources and are one of the most significant drivers of global climate patterns. As the marine environment continues to increase in importance as both an essential resource reservoir and facilitator of global change, it is apparent that to find long-term sustainable solutions for our use of the sea and its resources and thus to engage in a sustainable blue economy, an integrated interdisciplinary approach is needed. As a result, interdisciplinary working is proliferating. We report here our experiences of forming interdisciplinary teams (marine ecologists, ecophysiologicals, social scientists, environmental economists and environmental law specialists) to answer questions pertaining to the effects of anthropogenic-driven global change on the sustainability of resource use from the marine environment, and thus to transport ideas outwards from disciplinary confines. We use a framework derived from the literature on interdisciplinarity to enable us to explore processes of knowledge integration in two ongoing research projects, based on analyses of the purpose, form and degree of knowledge integration within each project. These teams were initially focused around a graduate program, explicitly designed for interdisciplinary training across the natural and social sciences, at the Gothenburg Centre for Marine Research at the University of Gothenburg, thus allowing us to reflect on our own experiences within the context of other multi-national, interdisciplinary graduate training and associated research programs.

Keywords: interdisciplinary; social science-natural science interface; human-environment systems; marine; climate; global change; blue economy

1. Introduction

The marine environment is currently facing a number of significant challenges, including over-fishing, pollution, eutrophication, coastal erosion and oceans which are at risk of detrimental warming, acidification and hypoxia, all of which ultimately have their roots in anthropogenic influences (Innis and Simcock, 2016). At the same time, increasing attention is being directed towards the immense and largely untapped potential

of coasts and oceans to provide for a sustainable, global blue economy (Spalding, 2016). As a result, the need for producing innovative management solutions for the marine sector, which are environmentally, socially and economically sustainable, has never been more apparent. Consequently, the interest in, and arguably the need for, collaborative multi-disciplinary and interdisciplinary work on marine-centered issues is growing (e.g., Lovelace et al., 2005; Carney et al., 2006; Sievanen et al., 2012; Moore et al., 2013; NordForsk, 2013; Boonstra et al., 2015; Lohmann et al., 2015). Often these types of collaborations are a new experience for many researchers and while building true interdisciplinary collaborations remains the 'holy grail' of such projects, achieving this aim can prove challenging for even the most experienced academics (Viseu, 2015). This challenge is especially true in the context of marine research, traditionally dominated by natural- and technical sciences and often seen as being outside the domain of most human- and social disciplines (Palsson et al., 2013), the exception being the growing body of work that crosses the health-marine science divide (e.g., Lovelace et al., 2005; Kite-Powell et al., 2008; Moore et al., 2013; Aronsen et al., 2016).

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To meet the challenges of the 'brave blue world' of the maritime economy of the 2100s (Vidal, 2012), and to strengthen interdisciplinary research across the ontological and epistemological divide between natural and social sciences, a Graduate School was started in 2012 by the Gothenburg Center for Marine Research in the Department of Marine Sciences at the University of Gothenburg. The overarching aim of the Graduate School is to equip a new generation of marine researchers with the knowledge, experience and skills to work effectively in an interdisciplinary research environment, particularly as it has been recognized that current models for educating doctoral-level marine specialists lack this particular outlook (Langholz and Abeles, 2014; Ciannelli et al., 2014). In the first instance funding was allocated for 14 PhD students to work on seven paired projects, each comprised of graduates and advisors from different faculties. The Graduate School is unique within Europe in terms of its organisational set-up, interdisciplinary ambition, and exclusive focus on the marine environment. To date only a few large-scale interdisciplinary training programs have been initiated that aim to cross the divide between natural and social sciences within the context of marine environmental research, with the flagship Integrative Graduate Education and Research Traineeship (IGERT) program of the USA's National Science Foundation (NSF) funding only a handful of marine-centered themes (www.igert.org). Furthermore, globally, only a few experiences by research teams of large-scale marine-focused interdisciplinary research efforts have been documented (e.g., Bailey et al., 2015). The aim of this paper is to add to this literature by reporting and comparing the experiences from two of the seven projects included in the Gothenburg Graduate School designed for interdisciplinary training between the natural and social sciences. By comparing these projects with the interdisciplinary research experiences of other marine-focused research and graduate training programs, we aim to highlight how the Gothenburg model works in relation to others, as well as to catalogue what we perceive as the advantages and disadvantages of natural and social marine scientists engaging with each other in an attempt to transport ideas outwards from the confines of separate disciplines. The analysis of the two projects is informed by the following three main questions, derived from literature on knowledge integration and interdisciplinarity.

1.1. What is the purpose of knowledge integration in the projects?

Even though there is a general need for combining different perspectives and bodies of knowledge in order to meet complex marine challenges, the specific purpose of the integration in different collaborative efforts is not necessarily the same (Frodeman et al., 2012). For example, Knutsson (2006) identified three principal purposes behind academic knowledge integration: *Broadening* is when the purpose of an integrative effort is to take more variables, methods, viewpoints and perspectives into account. *Reconfiguration* is when the aim is to transfer established disciplinary knowledge into a new context in order to make it more applicable and to open up for new

combinations. *Synthesis* refers to the ambition to bring together separate concepts, theories or methods in a new understanding of a phenomena or a problem. Often, but not always, the purpose of knowledge integration strongly influences the degree to which knowledge is being integrated (see Section 1.3). For example, a high degree of knowledge integration is more likely if the purpose is synthesis rather than broadening.

1.2. What forms of knowledge integration have been accomplished by the projects?

Knowledge integration can take place in many different forms, depending on what is actually being integrated (Frodeman et al., 2012). The suggestions of possible forms of knowledge integration in the literature are many. *Theory integration*, for example, is when boundaries between different theories or theoretical/conceptual frameworks are crossed, while *method integration* refers to the combination of different methodologies, data collection techniques and instruments (Klein, 1996). System approaches, on the other hand, can be understood as *system integration*, where integrated subparts are related to each other as well as the system as a whole. For example, resilience research provides system integration as it conceptually and empirically examines how parts that have previously often been seen as separate (e.g., ecological and political processes) can be understood as integrated sub-parts in a joint system: a socio-ecological system (Knutsson, 2006). The acknowledgement that cross-disciplinary collaboration is not only about crossing boundaries of knowledge *per se*, but also the ways in which knowledge is organized, points at the importance of *institutional integration*: the combination and integration of different ways of organizing knowledge. This form of integration can entail, for example, integration across different funding agencies, journals, academic institutions and non-university stakeholders (Frodeman et al., 2012; Rylance, 2015).

1.3. What degree of integration characterizes the two projects?

Apart from the purpose and forms of integration, collaborative endeavours may achieve different degrees of integration. The degree of integration accomplished by projects is often defined and evaluated on a scale from multidisciplinary via interdisciplinary to transdisciplinary integration. *Multidisciplinary* integration is when different bodies of disciplinary knowledge are merely juxtaposed, allowing disciplines to remain separate and to retain their original identity within an existing structure of knowledge. In contrast, *interdisciplinary* integration is achieved through proactive designs that restructure existing approaches by explicit focusing and blending, and by linking issues and questions that are not specific to individual disciplines. *Transdisciplinary* integration can be interpreted in two rather different ways. The first interpretation refers to integration that produces new knowledge which transcends the scope and structure of disciplinary worldviews. The second interpretation, that has been the focus of our work, instead focuses on integration that goes beyond interdisciplinary integration by solving real life problems

through the combination of academic and non-academic bodies of knowledge (e.g., local knowledge, private sector expertise, political goals; Frodeman et al., 2012).

Cutting across the different purposes, forms and degrees of knowledge integration is the question of ontological and epistemological differences. In this regard, Bailey et al. (2015) offer a useful distinction between 'small' and 'large-scale' knowledge integration. While small-scale integration takes place between similar partners (e.g., among natural science disciplines or scientists who use similar methods, e.g., quantitative vs. qualitative), large-scale integration crosses ontological and/or epistemological boundaries (e.g., between natural science and constructivist social science), and is therefore often more challenging. Not surprisingly, to date, in environmental research most collaborative working has comprised small-rather than large-scale interdisciplinary working (German Research Foundation, 2013; Elsevier, 2015).

2. Integrated research experiences: reports from the two projects

2.1. Human health and well-being at risk: Impact scenarios for climate change-induced microbial blooms along the Indian west coast

2.1.1. Introduction

This project examines the risk of climate change-induced harmful microbial blooms along the Indian west coast. More specifically, it combines analyses of long-term oceanographic monitoring data series, controlled experiments on marine microalgal growth and the susceptibility of infection and exposure to algal toxins and pathogenic bacteria in bivalves during elevated temperature (warming) and lowered salinity (freshening), with studies on the influence of rapid urbanization on the use and consumption of bivalves in coastal urban areas. Using the classification of Bailey et al. (2015) this project is an example of large-scale knowledge integration and is arguably the largest scale project among the PhD projects in the research school, as it spans from qualitative social science studies to 'hard core' natural science experiments.

2.1.2. Purpose of knowledge integration

Initially, the purpose of knowledge integration in the project was *broadening*, as it responded to the need to expand on previous natural science studies on harmful microbial blooms along the Arabian Sea coast of India by exploring possible human social, health and economic impacts of a climate-induced rise in outbreaks of such blooms. Hence, the purpose of the project was to broaden the existing knowledge on harmful microbial blooms through the introduction of a social science component, in order to increase the relevance of previous and ongoing studies. However, after the first year of explorative research it became evident that the natural and social science components were not sufficiently connected to each other, either empirically, conceptually or methodologically, which hampered the ability to produce relevant results. Responding to this weakness of the original research design, the two principal investigators (PIs; one natural scientist and one social scientist) devel-

oped an application for external funding that presented a more integrative framework for how the complex risk of climate-induced microbial blooms could be assessed. This framework proposed how, conceptually and empirically, to relate the risk of increased outbreaks of harmful microbial blooms as influenced by climate change to the ongoing, rapid socio-economic changes associated with coastal urbanization in southwest India. The framework not only outlined in detail a joint understanding of the investigated risk, but also clearly revealed a gap in competence in order to empirically connect the natural and social science components of the project.

Subsequently, a core element in the application was the need to bring on board a zoologist (post-doctoral researcher) who could study empirically how the health of the bivalve species consumed by humans along the coast were both directly affected by the physical effects of climate change (warming and freshening of the ocean) as well as indirectly by climate change-induced modifications of the microbial community that forms the basis of the oceanic food web. Through the application, which was later granted, the purpose of knowledge integration changed from broadening to *reconfiguration*, as it presented a conceptual and methodological framework that aimed to combine natural and social science research in a new way. The desire to move from broadening to reconfiguration was an outcome of the learning process of the first year of explorative research.

2.1.3. Forms of knowledge integration

The project has primarily been an example of *system integration*. Driven by the challenge to find a way to combine different sets of natural and social science data, the project outlines and applies a framework for risk assessment that conceptually and empirically brings together parts that previously were seen as separate. For example, the framework presents a relationship between very specific biological processes in the marine environment and large-scale urbanization trends that are rarely seen as related. Thus, the project framework can be seen as a system in which previously separate parts (the biological processes of microbial blooms and the response to physical forces, coastal land use, poverty, infrastructure investments, etc.) becomes integrated and related as subparts. However, the project has not been guided by a corresponding integration of theories, other than general theories on risk. Rather, the different parts of the project framework have been allowed to be informed by different theories from different disciplines and research fields, and to remain as separate. The extent to which the project has combined methods has been limited to the task of configuring different sets of data in order to effectively feed into the joint risk assessment. That is, the project has focused on how data generated by different methods and techniques can be combined within one assessment framework.

Furthermore, the project has successfully managed to transport its interdisciplinary ambition and framework to the Indian academic context, involving senior and junior researchers from natural as well as social science academic institutions and thus is an example of *institutional*

integration. This form of integration has been possible by actively involving the Indian researchers and institutions at a very early stage, building on existing Indian research networks, and making sure that the project's research focus and ambition corresponds to Indian academic needs.

2.1.4. Degree of knowledge integration

As this project is still ongoing (it will be finalized during the first half of 2017), a complete assessment of the degree of integration is not yet possible. Our purpose here is to present the important conclusions that can be drawn based on what has been accomplished already. Initially the project was designed primarily for multidisciplinary integration, following the fact that the main purpose for knowledge integration was *broadening*. However, by redefining the purpose of integration during the development of the project it has become interdisciplinary. The risk assessment framework outlined in the subsequent successful research application is resulting in interdisciplinary knowledge integration, as it pushes all involved researchers to be engaged with and contribute to a joint risk assessment that explicitly links different sets of knowledge to each other. For example, we have had numerous meetings and workshops where the social scientists have been actively involved in the work on how to configure the results of experiments on planktonic microorganisms and bivalves into indicators of biophysical risk. In a corresponding way, the natural scientists have been engaged in the process of defining the determining factors of human and institutional vulnerability to microbial blooms. The joint risk assessment provides a continuous learning process across boundaries based on different disciplinary expertise and a joint ambition to combine insights from different fields.

One additional result of this effort has been that the PIs of this project recently secured substantial funding for a transdisciplinary research project on the spread of antibiotic resistance through aquaculture in India and East Africa (VR:2016–05649), based on the model for interdisciplinary collaboration developed during this project. However, even though the current project has involved discussion of the research results with different, non-academic Indian stakeholders, it has not been transdisciplinary because the project was not specifically designed and developed drawing on the interests and knowledge of non-academic stakeholders. As accounted for above, the main purpose of the project has been to broaden and reconfigure existing academic knowledge, which most probably has limited the project's capacity to achieve transdisciplinary knowledge integration.

2.2. ZORRO: Eelgrass restoration and sustainable management of shallow coastal ecosystems

2.2.1. Introduction

The research program *Zostera* Restoration (ZORRO; www.gu.se/zorro) consists of several projects and includes marine ecologists, environmental legal scholars, and environmental economists primarily from the University of Gothenburg. The goal of the projects within the program

is to improve the environmental status of shallow coastal ecosystems by assessing ecological and legal causes and solutions for the loss of eelgrass (genus *Zostera*) meadows in Sweden and developing new methods for the management and restoration of eelgrass. Achieving and maintaining good ecological status, in order to ensure the societal benefits from the provision of valuable ecosystem services over time, requires not only the prevention of continued environmental degradation but also the restoration of deteriorated environments. Inevitably, such measures are costly, which raises questions about who is responsible for restoring environmental damage and how it should be carried out. ZORRO focuses in particular on assessing the legal, ecological, and economic aspects of restoration and compensatory mitigation of eelgrass habitats. As in the case of the Indian climate change project, this program is also an example of large-scale knowledge integration (Bailey et al., 2015) as it extends from field-based ecological studies and economic theory to the assessment and implementation of legal doctrines. The research in ZORRO is driven by existing management questions and challenges, which need an interdisciplinary approach to be solved, and the research has developed in close collaboration with regional and national managers using a transdisciplinary integration of knowledge.

2.2.2. Purpose of knowledge integration

The original purpose of knowledge integration in the ZORRO program was *reconfiguration*, and as such, compared to the Indian climate change project, had from the beginning a higher ambition for the type of knowledge integration to be achieved. One of the key issues addressed by ZORRO has been to identify the causes of the loss and lack of recovery of eelgrass habitats in Sweden. The direct causes can be explained by biogeophysical changes resulting in part from anthropogenic activities, but the incentives for the activities are to be found in human behavior and the policy intended to influence this behavior. A great challenge for the successful management of the environment is to find the links from the status of the marine environment to people's behavior influencing this status, and further to the management system, and *vice versa*. Successful management solutions can only be found by applying a broad knowledge perspective and, we would argue, by integrating natural and social sciences. In this case managers had for a long time been aware of the ecological problems caused by seagrass loss due to comprehensive research in natural science for several decades. However, there was limited appreciation of how solutions to prevent or mitigate the effects could be implemented. Therefore, this project had a focus on reconfiguring the specialist knowledge from marine ecologists and environmental economists and lawyers.

The original project proposal was designed for a pair of PhD projects, with one centered on marine ecology and one on environmental law supervised by two senior researchers, one from each discipline. However, because another purpose with the integration of knowledge has been to provide managers and policy-makers with tools

and information that will allow them to carry out efficient measures and make informed management decisions, a proposal for a broader project, including economic aspects, was submitted and accepted in parallel to the PhD projects, making it possible to include two additional post-doctoral projects (in environmental economics and restoration ecology). The aim in one of the projects was to develop a new interdisciplinary framework to estimate the total economic value of multiple ecosystem services that Swedish eelgrass meadows provide to society. In this research, an environmental economist and a marine ecologist worked closely together to identify and quantify the links between the ecological functions that eelgrass produce and the economical endpoints that could be valued in monetary terms (Cole and Moksnes, 2016). Another objective was to provide information and tools for a Swedish eelgrass mitigation policy. In this research economic theory was integrated with ecological data to estimate the temporal losses of ecosystem services (i.e., *interim losses*) and the needed ratio between the damaged eelgrass bed and the restored bed to compensate for these losses (Moksnes et al., 2016a).

Thus, in these projects the purpose of collaboration was a *synthesis* of knowledge. To provide managers and policy makers with tools and information that will allow them to carry out efficient management measures requires the synthesis of reconfigured knowledge, for example, by linking the economic cost of eelgrass restoration, the economic value of ecosystem services of eelgrass, and assessments of the current legal system's ability to protect eelgrass as well as demand restoration. In the case of the restoration of deteriorated eelgrass ecosystems this synthesized knowledge allows managers and legislators to make accurate trade-offs between coastal protection and development, including how to spend limited financial resources on environmental protection.

2.2.3. Form of knowledge integration

ZORRO is an example of *method integration*, guided by *system integration*, which is in contrast to the Indian climate change project which was primarily focused on system integration. At the beginning of ZORRO it was clear that method integration would be integral to the success of the project, so 'crash' courses in basic ecology, environmental law and environmental economy were held within the group. This approach provided a way to learn about each other's main concepts and to better understand the rationale of the methodologies used – method integration (Newell et al., 2004). The understanding of the linkages between the key research questions in different disciplines and studies has been facilitated by the Drivers, Pressure, State, Impact and Response (DPSIR) framework, which has been used for the economic and social analysis of the Marine Strategy Framework Directive in the European Union (EU) and Sweden (e.g., COM, 2010; Turner et al., 2010; SwAM, 2012). Regardless of its limitations, for example, in visualizing changes over time, this theoretical framework has been used as a tool for communication between the researchers from different disciplines and for

orientation of the relationships between different studies and parts of a study. The development of this common theoretical and conceptual model can be referred to as system integration.

In many studies that include researchers from different disciplines, disciplinary related methods have been used in parallel. In ZORRO, by taking the starting point as a real-life problem common to both disciplines, the results from one discipline have added new questions and perspectives to the other discipline. The results from inventories of eelgrass showed an extreme decrease in some areas and confronted the legal scholars with new challenging questions about the suitability of the existing legal framework to handle fragmentation. Thus, here the approach of method integration was used not only to deepen the disciplinary studies, but also to explicitly link them to each other and make them even more relevant from a management perspective. Method integration was also used in a study of compensatory mitigation of eelgrass in the USA (K Laas, personal communication) that included an assessment of the legal construction and its implementation, an evaluation of restoration methods used, as well as a quantitative assessment of the success rate in relation to different policies and methods used. This analysis could not have been performed without the specific understanding of both the eelgrass ecology and the policy regime.

Method integration has been common to many projects in the ZORRO program. Decisions to approve exploitation of coastal areas by building piers and marinas were assessed together with the ecological effects of such constructions. The motivation behind the decisions was mirrored by reports on eelgrass distribution to assess if the presence of eelgrass affected the decision (Eriander, 2016). The quantitative study gave substantial input to the more qualitative legal assessment, a combination of methods which is rather rare for legal scholars. Yet another example of method integration from ZORRO is the common presentation of the insufficient implementation of the indicator for eelgrass in coastal water, required by the EU Water Framework Directive. It would have been impossible to understand the consequences of the Swedish legislation without knowledge about both EU law and Swedish law as well as ecology of angiosperms and monitoring methods.

Furthermore, ZORRO is also an example of *institutional integration*, although compared to the Indian climate change project this form of integration has been primarily with local government and policy-making agencies rather than academic institutions. In collaboration with the County Administrative Board of Västra Götaland län and the Swedish Agency for Marine and Water Management, the ZORRO team has produced a national guideline for restoration of eelgrass in Sweden (Moksnes et al., 2016b), a national policy for compensatory mitigation of eelgrass in Sweden, and interdisciplinary report of the ecological, legal and economic aspects of management and restoration of eelgrass in Sweden (Moksnes et al., 2016a). The input from managers challenged the ZORRO team to analyze not only the legislation in theory but also its implementation or lack of implementation. Likewise, the

demand of transforming the knowledge of restoration into recommendations for managers, forced the team to be comprehensive and cover all steps in restoration, both concerning the formal part (e.g., the need for approvals from authorities) and the practical work (e.g., choosing a location for restoration, the transplantation methods etc.).

2.2.4. Degree of knowledge integration

Through additional grants, several new projects have been incorporated into the ZORRO program, which today constitutes an interdisciplinary research platform for 15–20 researchers that continues to address concrete management problems, such as how eelgrass habitats should be protected or restored. In order to handle these types of tasks and to provide recommendations to managers and legislators, disciplinary, interdisciplinary and transdisciplinary research needs to be performed. Thus, ZORRO has arguably achieved the highest degree of knowledge integration, that of transdisciplinary integration, and had held these transdisciplinary ambitions from the start, in contrast to the Indian climate change project. One of the main aims for ZORRO has been to solve real life problems by combining academic and non-academic knowledge, in other words, through integration that goes beyond interdisciplinary integration (Frodeman et al., 2012). However, for ZORRO the goal has not been to merge knowledge into a new discipline but rather to use deep disciplinary knowledge combined with a broad perspective and general knowledge about the research of all team members. By getting the researchers informed and engaged in each other's studies, the ZORRO program has obtained new perspectives on the project's material and raised questions unlikely to have been put forward without this type of collaboration. After four years of collaboration the team members are also trained to present and discuss with managers not only their own disciplinary results but also the joint results on a general level. When such a point is reached it is clear that the interdisciplinary collaboration has been a success and it is no longer as relevant to ask about the disciplinary background of the researcher as long as the management problem itself is addressed.

3. Discussion and conclusions

Both projects discussed here were designed on the basis of large-scale knowledge integration and with high interdisciplinary ambitions. These projects span from qualitative social science and legal studies to 'hard core' natural science experiments and ecological assessments. The main purpose of knowledge integration common to both projects is knowledge *reconfiguration*, which for the Indian climate change project has enabled a conceptual and methodological framework to be built, allowing an interdisciplinary assessment of the risks surrounding climate change-induced harmful microbial blooms. However, the ZORRO program goes a step further, as it incorporates *synthesis* of this reconfigured knowledge for the benefit of managers and policy makers, providing them with the tools and information that will allow them to produce efficient management strategies for restoration of shallow water marine habitats. Both projects have suc-

cessfully encompassed *institutional integration* as a form of knowledge integration, although with different outcomes. For the Indian climate change project its interdisciplinary ambition and framework have been successfully transported to the Indian academic context, involving several Indian academic institutions, whereas ZORRO has succeeded in partnering academics with several non-academic local government and policy making institutions. Of the two projects ZORRO has been transdisciplinary in its outlook from the beginning, which perhaps explains its success across the academic and non-academic divide.

Our experiences have added further weight to the idea that the management of any future 'brave blue world' will benefit from an interdisciplinary approach. However, we have found that we have also gained specific academic benefits through interdisciplinary working that have extended throughout the academic hierarchy of our projects. As similarly reported by participants in the NSF's IGERT program, benefits under the Gothenburg model have been tangible at the student, academic and institutional level (Carney et al., 2006). These benefits have included the successful completion of an interdisciplinary PhD thesis (Eriander, 2016), high impact discipline-specific (e.g., Eriander et al., 2016; Infantes et al., 2016a, b; Kaur Kahlon et al., 2016; Turner et al., 2016; Kadfak and Knutsson, 2017) as well as interdisciplinary publications (Cole and Moksnes, 2016; Moksnes et al., 2016a, b), new successful interdisciplinary grant applications, and individual career progression.

Today many funders of academic research demand that applicants define and integrate the relevance of their ideas to the wider 'real world' that includes managers and policy makers as well as to different disciplines. Consequently, the experience of and competence in doing inter- and/or transdisciplinary research is increasingly valued by the academic community. In other words, research should be inter- and/or transdisciplinary from the start. Our experiences suggest that gaining insight into research designs, theoretical frameworks (e.g., theory integration) and empirical methods (e.g., method integration) used by other disciplines constitutes a highly valued experience and competence. For example, in the case of the post-doctoral researcher working on the Swedish-Indian climate change project, she was able to extend her research portfolio with highly desirable interdisciplinary experience with the result that she was able to obtain a permanent senior academic position. In some sectors of the academic community suspicion of interdisciplinary working persists, with the notion often reported that this approach dilutes efforts away from the study of traditional disciplines (Rylance, 2015). At Gothenburg, while expanding our interdisciplinary pursuits, we have maintained our disciplinary integrities as evidenced by the publishing of intra-disciplinary studies (e.g., Eriander et al., 2016; Infantes et al., 2016a, b; Kaur Kahlon et al., 2016; Turner et al., 2016; Kadfak and Knutsson, 2017). When the Graduate School was established at Gothenburg we followed the same model as that underpinning the NSF's IGERT programs (Carney et al., 2006) with an emphasis on both interdisciplinary and intra-disciplinary outcomes.

This dual emphasis has enabled some of the risk to be abated while allowing both the PIs, the post-doctoral researchers and the PhD students to undertake their work across traditional institutional and administrative boundaries within the university. An important factor that has enabled institutional integration within the project has been the Center's explicit policy to see interdisciplinary collaboration as a complement to existing disciplinary research and structures. For example, the PhD students enrolled in the Center's Graduate School have been allowed to be firmly based in separate disciplines and to write their theses guided by disciplinary quality criteria. Doing their PhDs as part of an interdisciplinary graduate school and within interdisciplinary research projects has not challenged traditional institutional boundaries. By encouraging twinned PhD research projects, where each project has been supported to stand alone and as part of an interdisciplinary collaboration, students have arguably had the best of both worlds – they finish with a qualification in their chosen discipline, but also one that has given them unique insight into working in an interdisciplinary manner, thus ensuring that these Graduate School participants will be viewed as assets to academia and to non-academic positions. Furthermore, our experience is that interdisciplinary work often actually supports 'small-scale' interdisciplinarity due to the frequent provision of opportunities for wider ranging collaboration, for example, within the natural sciences across disciplines such as biology, oceanography and chemistry. The new Department of Marine Sciences at the University of Gothenburg to which the Graduate School of Marine Research is affiliated is a department built around an interdisciplinary outlook specifically to foster both small- and large-scale interdisciplinary research in the future.

We have found that there are some challenges during the creation of the necessary structures for these types of PhD projects. One such challenge is that different disciplines may prefer different thesis structures. For example, legal scholars in Sweden generally write the thesis as a monograph, whereas theses within natural science are primarily based on a number of separate articles. The idea that the legal PhD student within the ZORRO program should present an article-based dissertation was questioned by legal colleagues, although approved by the department in the end. Our experience has been that for a research student, the ideal outcome is to have a selection of discipline-specific and interdisciplinary publications. This outcome again ensures that the PhD student is not perceived as purely a discipline-specific or interdisciplinary specialist. For an interdisciplinary twinned PhD partnership to be successful it is also important to have a clear idea at the start as to what the specific role of each discipline is within the project and how the specialisms of each discipline will contribute positively to answering the research question being asked. In our experience, having this initial clarity will increase the chance of the longevity and success of the collaboration and decrease the risk of any kind of philosophical split. During the project itself, as might be predicted, two-way communication remains key, particularly between the discipline-specific supervisors. This

communication will enable resilience to be built into the research team, thus increasing the ability to deal with any differences that may arise and also result in the provision of a stable research environment for the PhD students. Established researchers are, of course, more than able to take risks in their research collaborations. However, with interdisciplinary projects these PIs, often well established and perhaps even world leaders in their own disciplines, must trust the competencies of the other partner(s), be willing to learn from them, and be clear with themselves and each other when things are not well-understood or no longer working well. This need for trust again highlights the importance of communication. During an interdisciplinary project participants will likely spend time together during activities such as data collection. During interdisciplinary projects such naturally occurring joint activities might not be the case, making it important to schedule times for group interaction and discussion.

The two case studies highlighted here illustrate the variety of purpose, form and degree of knowledge integration that has been achieved in two ongoing interdisciplinary projects hosted by the Graduate School at the Center for Marine Research in the Department of Marine Sciences, University of Gothenburg. Both research teams have recently obtained new grants and are expanding their groups providing a firm foundation for future interdisciplinary and transdisciplinary marine research as we go forward into the era of the 'brave blue world'.

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The authors have no competing interests to declare.

Author contributions

- LMT wrote the first draft and coordinated and synthesised the contributions from the other authors.
- All authors contributed text material to the evolution of the manuscript and provided comments at various stages.

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