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Towards better integration of environmental science in society: Lessons from BONUS, the joint Baltic Sea environmental research and development programme

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ABSTRACT

Integration of environmental science in society is impeded by the large gap between science and policy that is characterised by weaknesses in societal relevance and dissemination of science and its practical implementation in policy. We analyse experiences from BONUS, the policy-driven joint Baltic Sea research and development programme (2007–2020), which is part of the European Research Area (ERA) and involves combined research funding by eight EU member states. The ERA process decreased fragmentation of Baltic Sea science and BONUS funding increased the scientific quality and societal relevance of Baltic Sea science and strengthened the science-policy interface. Acknowledging the different drivers for science producers (academic career, need for funding, peer review) and science users (fast results fitting policy windows), and realising that most scientists aim at building conceptual understanding rather than instrumental use, bridges can be built through strategic planning, coordination and integration. This requires strong programme governance stretching far beyond selecting projects for funding, such as coaching, facilitating the sharing of infrastructure and data and iterative networking within and between science producer and user groups in all programme phases. Instruments of critical importance for successful science-society integration were identified as: (1) coordinating a strategic research agenda with strong inputs from science, policy and management, (2) providing platforms where science and policy can meet, (3) requiring cooperation between scientists to decrease fragmentation, increase quality, clarify uncertainties and increase consensus about environmental problems, (4) encouraging and supporting scientists in disseminating their results through audience-tailored channels, and (5) funding not only primary research but also synthesis projects that evaluate the scientific findings and their practical use in society – in close cooperation with science users − to enhance relevance, credibility and legitimacy of environmental science and expand its practical implementation.

1. Introduction

Publicly-funded science is required to achieve as many as possible of the three pillars for successful science − that it should increase knowledge, enhance wealth creation and contribute to the quality of life (Wiig, 1997). Given limited and decreasing resources for environmental research (Borja and Elliott, 2013), it is of paramount importance that the available resources are spent as efficiently as possible and it is recognised that the contribution of research councils and programmes to the generation of evidence to inform policy-making should be enhanced (Holmes and Harris, 2010; Leith et al., 2014). An obstacle in doing so is the large gap between science and policy (Engels et al., 2006; Graffy, 2008; Ormerod and Carleton Ray, 2016) that is characterised by weaknesses in (1) *relevance*, i.e. is the collective new knowledge created in environmental research programmes useful for solving specific environmental problems? (2) *dissemination*, i.e. do the new solutions to specific environmental problems reach all knowledge users in an appropriate way? (3) *practical implementation*, i.e. is the new scientific information utilised in decision-making and environmental management?

To achieve the highest *relevance* of environmental scientific results for societal needs there is a strong demand that ‘science should inform

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policy' but also that 'policy should inform science' (Borja et al., 2016). Accordingly, it is imperative that the requirement for science is informed by the diverse group of stakeholders (in this paper defined as both science producers and users). Another problem in this context is fragmentation of research (Balietti et al., 2015), i.e. key resources are wasted through duplication, dispersion and overlapping among countries, groups, projects, disciplines and topics. Fragmentation is partly induced by absent or insufficient research coordination and because funding sources are diverse and uncoordinated (public, private, national, international, fundamental science, applied science, etc.). Furthermore, there is a notable dilemma between academic career-building and societal needs; in the academic world scientists are graded on the number of primary papers they publish and dissemination of their results elsewhere is given lesser weight. This conspires to produce fragmented science and little synthesis. Furthermore, 'salami-publishing', the ability to get as many papers as possible from a piece of research (Karabag and Berggren, 2016), creates even more fragmentation. Academic career-building may also cause fragmentation due to lack of collaborative spirit among scientists who prefer to highlight their 'own research' rather than collaborate or cite the papers from their peers. Delivery problems are further associated with the inability to produce interdisciplinary science (Mattor et al., 2014; Reid and Mooney, 2016), here including inter-, multi- and trans-disciplinary science in the sense of Bernard et al. (2006), since most scientists are rewarded and encouraged to focus on single disciplines and few have the possibility and breadth of knowledge across fields for linking social and natural sciences.

To achieve the most effective *dissemination* of environmental scientific results the information channels and contents need to be tailored to the audience. Given the urgency to solve many of today's environmental problems to restore ecosystem health, communication must also be as fast as possible so that all stakeholders, both science producers and users, are able to quickly use newly produced scientific results (Mea et al., 2016; Newton and Elliott, 2016), but in many research programmes not all channels for achieving this are opened. This problem is shown in 'The Dissemination Diamond', a concept that was introduced to describe the volume of the information produced and used by different actors in society, ranging from 140-character messages reaching the general public to 140-character messages disseminated by world leaders, with in-between these two extremes an information maximum of 10–300 pages scientific documents (Elliott et al., 2017). At the information maximum, it is a requirement that evidence-based decision-making is made after quality-assurance (peer review) of the science that produced the evidence and subsequent publication in the scientific literature. When scientific results are not disseminated in this way, they remain largely unavailable and so the funding does not contribute to the progress of science nor to evidence-based decision-making. However, this form of dissemination is usually not accessible for knowledge users in society unless the papers are published in 'Open Access', and policy-makers often do not have the time, inclination or facilities to access academic literature. As a result, scientists essentially rely on peer-reviewed articles in international journals, consultants on consultant reports which often are unpublished and not openly peer-reviewed, whilst policy-makers rely on unpublished government reports, occasional self-commissioned reports and very few international, peer-reviewed scientific papers. Although the borders between the different groups of professionals partly overlap, the dynamics of the information flows within science-policy interactions with respect to credibility, relevance, legitimacy and iteration (Heink et al., 2015; Sarkki et al., 2015) are usually far from ideal.

Finally, the *practical implementation* of environmental scientific information for the benefit of society may suffer from a range of obstacles. Even if the scientific results from a research programme are relevant for solving environmental problems, and they do reach policy-makers, it is not certain that they are actually used. This is often related to semantic confusion (Bigard et al., 2017), objectivity conceptions (Kunseler and Tuinstra, 2017), disagreement among scientists (Woodcock et al., 2017) and/or uncertainty of the results (Maxim and van der Sluijs, 2011; Udovyk and Gilek, 2013; Van Pelt et al., 2015). Policy requires well-informed syntheses, which are still scientifically valid but valuable to the user. However, funding usually goes to individual research projects without leaving sufficient means to produce overarching syntheses targeted to societal knowledge use – synthesis is then left to the reader. There are good examples of balanced overviews where scientific results are put into context with respect to stakeholder interests and inclusive towards the scientific society, such as the reports from the International Panel on Climate Change (IPCC, 2015; Yamineva, 2017). However, these types of syntheses from environmental research programmes are still rare and in this paper we strongly argue for producing knowledge syntheses that are relevant and legitimate within the scope of environmental research programmes, not only reporting the results produced by the projects but also putting them in perspective with the wider scientific literature and providing credibility, relevance, and legitimacy to science-users in society for specific environmental problems.

In order to address the above challenges and, in particular, to tackle the problem of inefficiency and fragmentation of European research funding and policy, in 2000 the European Union launched the European Research Area process (ERA; Muldur et al., 2006; Nedeva and Wedlin, 2015). This new process was founded on the observation that over 90% of European research funding was governed at the national level, while only a minor part was channelled to truly transnational projects through the EU Framework Programmes of Research (FPs). Starting from FP6 (the Sixth Framework Programme), new funding instruments (ERA-NET+, ERA-NET Cofund) were established for research programme owners and managers.[1] The aim was to bring national research funders from different countries together to agree on common research strategies within various scientific fields, agree about launching and managing joint calls and funding transnational projects. The ERA was novel in directing research more towards resolving societal challenges and facilitating the transfer of science input to policies by involving stakeholders (science-producers and users) in designing and implementing strategic research agendas (Luukkonen, 2015).

Here we explore to what extent the ERA research policy process, which aims to reduce science fragmentation and to bridge the gap between science and policy through coordination and cooperation, has met the expectations within the BONUS research programme (2007–2020), one of the first ERA programmes, which integrates and coordinates the funding for Baltic Sea research previously used to support isolated national projects and programmes in the eight EU Baltic Sea states. The objectives of our study were: (1) to evaluate the *relevance* of the science produced by the BONUS-funded projects in addressing the environmental challenges faced by the Baltic Sea ecosystem and how the BONUS programme has been instrumental in this, (2) to evaluate the *dissemination* from the BONUS-funded projects to peers and society until December 2016, including the influence of the BONUS programme on research topics and scientific quality of Baltic Sea research, and (3) to discuss how the *practical implementation* of scientific results from environmental research programmes may become better integrated in society through funding syntheses addressing specific societal needs as conducted within the BONUS programme. As such, we emphasise that this exercise has lessons for environmental science coordination, dissemination and implementation in general.

[1] An existing mechanism, stipulated by Article 169 (later Art. 185) in the Treaty of the European Union was not used before the ERA. The main reason was immaturity of the national funding institutions to step into this legislative action. One Article 169 (the number changed to 185 in 2010) programme was implemented within FP6 and four more, including BONUS, within FP7.

2. The BONUS programme

2.1. A transnational policy-driven programme funding environmental research

BONUS, the policy-driven and solution-orientated joint Baltic Sea research and development programme (www.bonusportal.org), was established by the Decision 862/2010/EU of the European Parliament and the Council in September 2010, under Article 185 of the Treaty on the Functioning of the European Union (TFEU) within the EU 7th Framework Programme for Research and Technological Development. The leading Baltic Sea research and innovation funders of the EU member states Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland and Sweden are the BONUS members implementing the programme and in addition the Russian Federation participates in BONUS through bilateral agreements. BONUS aims to generate knowledge to overcome the major environmental challenges faced by the Baltic Sea ecosystem by integrating research activities within the region into a durable, cooperative, interdisciplinary and focused transnational programme.

The Baltic Sea is a semi-enclosed sea which forms a well-defined geo-political area with a long tradition of networking and cooperation. In particular, relevant sectors aim to achieve sustainable Baltic Sea ecosystem services and societal goods and benefits (Scharin et al., 2016). Therefore, the Baltic Sea is an exceptionally suitable target for studying the societal benefits of transnational cooperation in terms of scientific excellence and dissemination, and in transferring science output to policy development and practical implementation. BONUS provides funding for scientific research to support the transnational governmental and non-governmental policy platforms already in place in the area (VanDeveer, 2011; Tynkkynen, 2013), e.g. the Baltic Marine Environment Protection Commission (HELCOM) for coordination within the environment sector, Visions and Strategies around the Baltic Sea (VASAB) for spatial planning, the Council of the Baltic Sea States (CBSS) for the Ministers of Foreign Affairs, the Baltic Ecoregion Programme of the World Wide Fund for Nature (WWF) for citizens, the Baltic Development Forum (BDF) for businesses, the Baltic Sea Parliamentary Conference (BSPC) for politicians, and many more. A further, horizontal coordination is given by the EU Strategy for the Baltic Sea Region (EUSBSR).

2.2. From ERA-NET to Article 185

The BONUS programme has comprised different phases (Fig. 1). After an initial EU ERA-NET phase, it was selected by the European Commission for a so-called ERA-NET Plus action (ec.europa.eu/research/era/era-net-fp7_en.html), providing funding (2007–2011) for a single transnational call named BONUS+. This set out to test the mechanisms of collaboration among national funding institutions. At this stage a legal entity, the BONUS EEIG (European Economic Interest Grouping), was established for the management of the programme. The BONUS+ call (22.3 €M) was launched in 2007 and funded 16 research projects involving 445 scientists from over 100 universities and research institutes. To achieve more endurable collaboration, following the co-decision by the European Parliament and the Council in 2010, the BONUS Art. 185 implementation agreement – including 100 €M funding for the programme – was signed with the European Commission in November 2012. Since then BONUS has launched four major BONUS Art. 185 calls (Fig. 1).

Most BONUS projects will end in 2017–2018, although some of the 'BONUS call 2015: Blue Baltic' projects (starting in 2017) will run until mid-2020 (Fig. 1). This paper focuses on the period from 2009, when the BONUS+ projects were first commissioned, until the BONUS programme's full operation in 2017 (with the 'Blue Baltic' projects commissioned and about to start their implementation in spring/summer 2017). To date, the programme has funded 56 research projects, involving > 1500 scientists, with 102 €m (Fig. 1).

2.3. Defining the BONUS vision, challenges and research themes

At its core is the BONUS Strategic Research Agenda (SRA; Fig. 2) which supports knowledge-based decision-making and management action. This was realised through rigorous bottom-up processes involving scientists, policy-makers and managers as well as top-down responses by the funding organisations (Fig. 2). The SRA defines the BONUS vision as an 'economically and ecologically prosperous Baltic Sea region where resources and goods are used sustainably and where the long-term management of the region is based on sound knowledge derived from interdisciplinary research'.

The main aim of BONUS is to develop, generate and disseminate knowledge and expertise to resolve the 11 challenges defined in the SRA (Table 1) to ensure the future sustainable use of the Baltic Sea ecosystem. The SRA addresses and defines five main strategic objectives, which are translated into 19 problem-oriented research themes (Table 2). They form the programme's overall framework and provide the basis for the calls for research proposals. Whilst most of the challenges are generic and cross-cutting in nature, some (e.g. 'Planning of the use of marine space', 'Making fisheries management effective', and 'Achieving safe maritime traffic') are more focused and sector-specific (Table 1).

In developing the SRA, the stipulation from the European Commission that '*The strategic research agenda shall be developed and agreed upon in consultation among Participating States, a broad range of stakeholders and the Commission*' (European Union, 2010) was interpreted as an encouragement to launch a broad consultation process, including also the Baltic Sea scientific community (Fig. 2), and achieved in several ways. Firstly, during the summer months of 2010, the BONUS web site ran a widely advertised open poll for research topics which yielded nearly 200 suggestions, mainly from scientists. Secondly, in late summer 2010, dedicated national representatives, the BONUS advocates, began work in the eight EU Baltic Sea states. These advocates mapped the stakeholder landscape in each of the states and organised national workshops involving over 600 scientists and policy-makers (Aho and Sirola, 2011). Thirdly, the 'BONUS Forum', established to discuss planning, joint use of infrastructure, outcomes and emerging research needs from the decision-making perspective, had a strong influence on the SRA. Finally, during defining and updating the SRA, BONUS organised strategic orientation workshops (SOWs) that brought together representatives of all involved groups: scientists, knowledge users and research funders. In this way, the BONUS SRA attempted to integrate and balance both of the 'bottom-up' (science producers and users) and 'top-down' (research funders) responses.

3. Materials and methods

3.1. Relevance of the BONUS projects for the BONUS vision

To assess the relevance of the 56 BONUS-funded projects (Fig. 1) for the BONUS vision we considered the potential of each project's expected results to address the 11 challenges faced by the Baltic Sea ecosystem as defined in the SRA (Table 1) by reviewing the expected results – as described in the Research Plans (RPs) of the 16 BONUS+ projects and the Descriptions of Work (DoWs) of the 40 BONUS Art. 185 projects – against each of the challenges. Twenty-one of the 56 projects had ended before 2017, and for these projects we also assessed how well they delivered what they had promised with respect to the 11 challenges by comparing the expected scientific results in the RP/DoW with the achieved results in the Final Project Report (FPR). It is of note that, although the BONUS challenges were not formally defined until after the inception of the initial 16 BONUS+ projects, they were also relevant for assessing the achievements of this first cohort of projects.

Each individual assessment was a value judgement made by one of the authors of this paper (SB), scored on a simple four-point scale (Table 3) representing the level of each project's potential to address

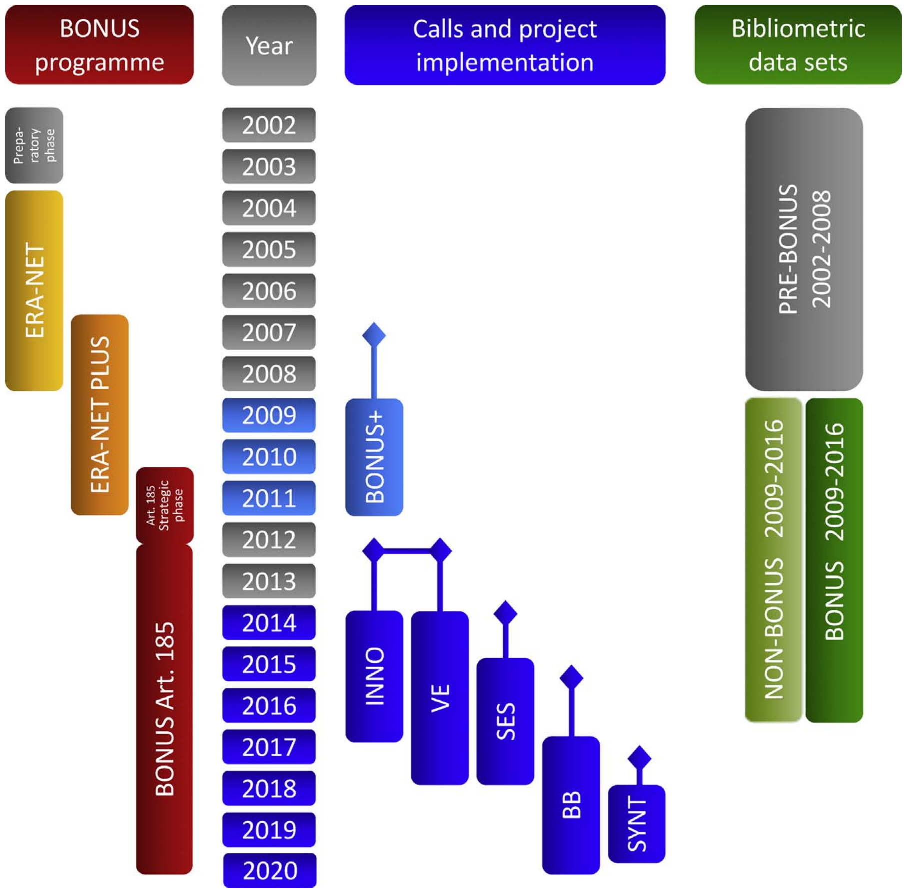

Fig. 1. Timeline showing the different BONUS programme phases, the calls for research applications, the implementation of the BONUS-funded research projects, and the time covered by the three bibliometric data sets compared in the present study. Diamonds indicate the timing of the calls: the BONUS+ pilot Call (22.3 €m, 16 projects, tinyurl.com/gle7wlo), the combined Viable Ecosystem (VE; 26.2 €m, 13 projects, tinyurl.com/j4rglxg) and Innovation (INNO; 6.2 €m, 7 projects, tinyurl.com/hbn7ysg) Call, the Sustainable Ecosystem Services Call (SES; 17.4 €m, 8 projects, tinyurl.com/zfocjb4), the Blue Baltic Call (BB; 30.0 €m, 12 projects, tinyurl.com/jkg6krr) and the Synthesis Call (SYNT) for knowledge synthesis desktop-studies on sustainable use of Baltic Sea ecosystem services (BONUS, 2017a) that was announced on 9 August 2017 (www.bonusportal.org). To date, the BONUS programme has funded 56 research projects with 102 €m (excluding the Synthesis Call).

each of the 11 challenges by their expected and (if applicable) achieved results. The value judgement scores can be considered analogous to the ‘relevance’ of a particular project for each of the BONUS challenges. We realise that these data may be considered biased since the data originate from the research planning and reporting by the projects themselves. However, this bias was reduced by thorough validation (critical review and revision) of the planning and report documents by external expert panels and the BONUS Secretariat.

3.2. Strength of the BONUS programme structure

Another measure of relevance of the science conducted in the BONUS programme is the extent to which the problem-oriented research themes defined in the SRA (Table 2) were addressed by the projects. To be successful in obtaining BONUS funding the applicants had to show in their RP (for BONUS+ applications) or DoW (for BONUS Art. 185 applications) that the proposed research efforts would match one or more of the BONUS research themes, either as a key or supplementary theme. The metrics used to summarise the collective ability of the BONUS-funded projects to address the research themes of the BONUS calls were the number of projects addressing a specific theme (as key or supplementary theme) extracted from these documents.

The research themes of the BONUS+ call differed from those of the subsequent BONUS Art. 185 calls (Table 2) which considered 7 and 19 themes respectively. The BONUS+ call allowed for multiple key themes for the same project to be identified at the project proposal stage, and accepted projects that did not identify any key themes. In contrast, the subsequent BONUS Art. 185 calls were more prescriptive, with projects required to identify one key theme plus a limited number of supplementary themes. These differences required that we considered the research themes of the two phases of the BONUS programme (BONUS+ and BONUS Art. 185) separately.

3.3. Bibliometric analyses of scientific publications

To evaluate the impact of the BONUS programme on Baltic Sea science as a whole, bibliometric analyses of original research papers and review papers published in international scientific journals were performed using the Web of Science™ (WoS). Three data sets (Fig. 1) were compared with respect to publication volume, research topic, number of citations and Journal Impact Factor (JIF): (a) a PRE-BONUS data set containing 2994 WoS-ranked papers published in the seven years before the first BONUS-funded projects started (2002–2008); (b) a NON-BONUS data set containing 4352 WoS-ranked papers that were not funded or co-funded by BONUS but published in the eight years after the first BONUS projects had started (2009–2016), and (c) a BONUS data set containing 504 WoS-ranked papers that were funded or co-funded by BONUS and published in the eight years after the first BONUS projects had started (2009–2016). To compare research topics in the three data sets, the literature references were categorised into topics automatically by the WoS (using the built-in criteria of the WoS) and their respective proportions in the data sets were calculated directly by the WoS.

To identify the papers on Baltic Sea science in the WoS, 25 geographical criteria depicting the Baltic Sea Area were used. The area defined as the ‘Baltic Sea Area’ by HELCOM and BONUS stretches from the inner Gulfs to the Skagerrak-Kattegat front; i.e. the whole area influenced by brackish water (salinity < 30). Not all WoS publications that deal with the Baltic Sea Area can be identified by only using ‘Baltic’ as a search criterion because e.g. ‘Gulf of Finland’ or ‘Kattegat’ may be used but not ‘Baltic’. Therefore, 24 sub-regions of the Baltic Sea Area, were used in addition to the word ‘Baltic’. This WoS search was carried out on 24 March 2017 and yielded a total of 18,769 publications for 2002–2016, of which 13% were omitted as they were conference proceedings, book chapters, book reviews, editorial materials, meeting

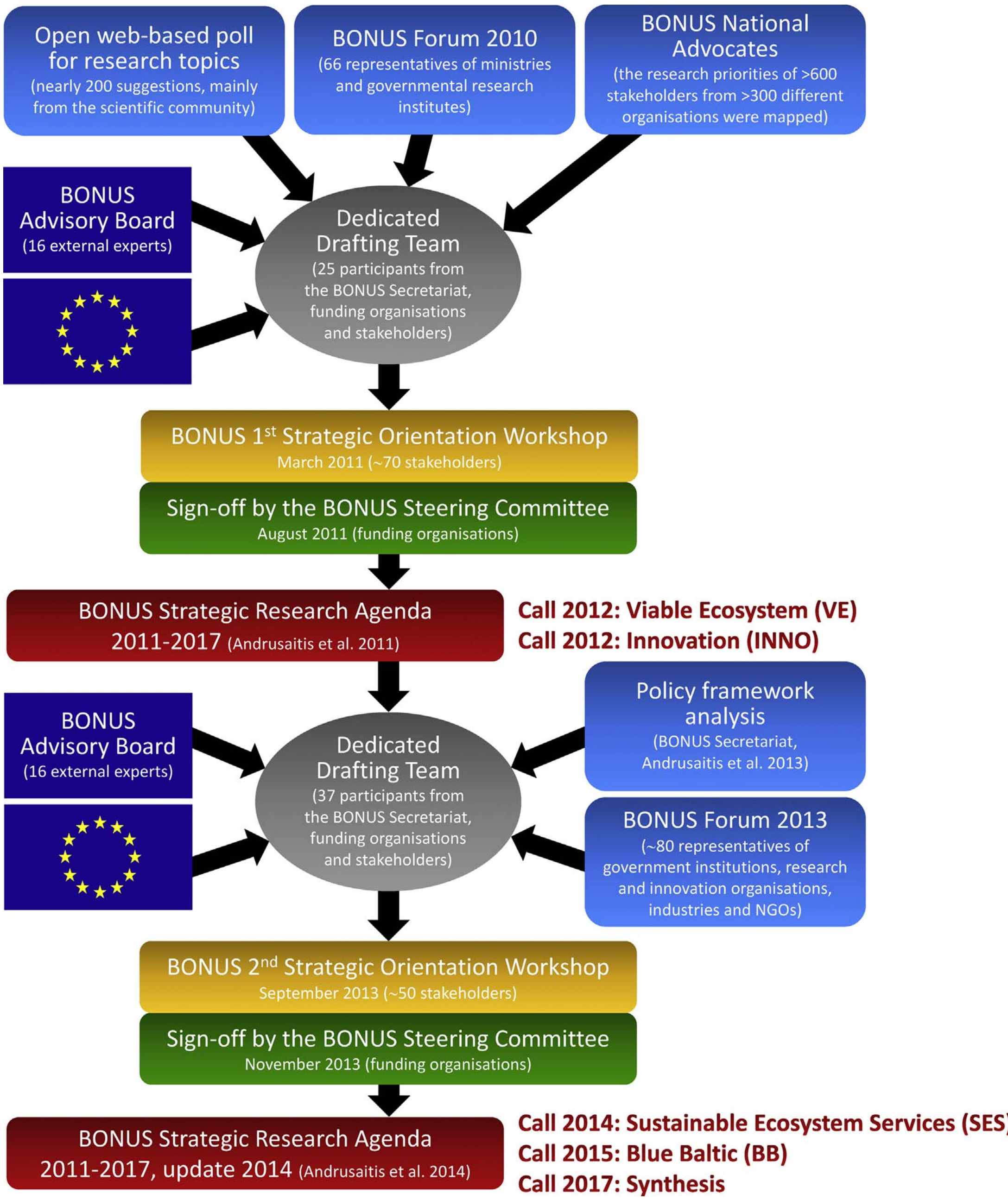

Fig. 2. Development of the Strategic Research Agenda (SRA) of BONUS Art. 185 and its updating process. The outcomes of the SRA are summarised in Table 1 (BONUS challenges) and Table 2 (BONUS strategic objectives and research themes). Note that 'stakeholders' are defined as both science producers and users (Andrusaitis et al., 2013).

Table 1
Summary of the 11 challenges faced by the Baltic Sea ecosystem that underpin the BONUS vision as defined in the Strategic Research Agenda (SRA; Andrusaitis et al., 2011, 2014).

BONUS challenges	Key words used to indicate the challenge in Fig. 3
1. Evaluating and developing relevant policies and collective governance	Policies & governance
2. Adapting to a sustainable way of living	Sustainability
3. Adapting to the effects of climate change	Climate change
4. Restoring Good Environmental Status (GES) of the Baltic Sea and its coasts	Good Environmental Status
5. Mitigating eutrophication that affects today nearly the entire Baltic Sea	Eutrophication
6. Achieving sustainable and safe use of the exploited coastal and marine ecosystem goods and services	Goods & services
7. Planning of the use of marine space that fulfils the intensifying and diversifying needs from society	Spatial planning
8. Making fisheries management effective in order to secure the stability of the ecosystem and reproduction capacity of the Baltic Sea fish stocks	Fisheries
9. Achieving safe maritime traffic imposing no risks to the environment	Maritime traffic
10. Minimising the environmental threat from increasingly diversified use of chemicals and new materials	Hazardous substances
11. Creating cost-efficient environmental information systems	Information systems

Table 2
Overview of the BONUS strategic objectives and research themes of the BONUS+ call (based on Hopkins et al., 2006) and the BONUS Art. 185 calls as defined in the Strategic Research Agenda (SRA; Andrusaitis et al., 2011, 2014).

BONUS strategic objectives	BONUS Art. 185 call research themes (the key words in **bold** are used to indicate the themes in Fig. 4b and Supplementary materials S4)	BONUS+ call research themes, arranged to show associations with the BONUS Art. 185 research themes (the key words in **bold** are used to indicate the themes in Fig. 4a)
SO 1: Understanding the Baltic Sea ecosystem structure and functioning	1.1 **Ecosystem resilience** and dynamics of the biogeochemical processes, including cumulative impacts of human pressures	Understanding **climate change** and geophysical forcing
	1.2 Causes and consequences of changing **biodiversity**	Protecting **biodiversity**
	1.3 **Food web** structure and dynamics	
	1.4 Multilevel impacts of **hazardous substances**	Preventing **pollution**
SO 2: Meeting the multifaceted challenges in linking the Baltic Sea with its coast and catchment area	2.1 Natural and human-induced changes in **catchment** land cover patterns, including the role of *e.g.* agriculture, forestry and urbanisation	Combating **eutrophication**
	2.2 The role of **coastal systems** in the dynamics of the Baltic Sea	
	2.3 Integrated approaches to **coastal management**	
	2.4 Eco-technological approaches to achieve **Good Ecological Status** in the Baltic Sea	
SO 3: Enhancing sustainable use of coastal and marine goods and services of the Baltic Sea	3.1 Enhanced, holistic cross-sector and cross-border **maritime risk analysis** and management, including effects of new technologies, human element, climate change effects in open water and in ice, and interaction with onshore activities	
	3.2 Assessing the effects of air and water pollution and introduction of energy (including noise) by **shipping activities** on the marine environment and integrated water management in harbours	
	3.3 Improving stock assessments and resolving spatial heterogeneity and temporal dynamics of the Baltic Sea **fish stocks**	Achieving sustainable **fisheries**
	3.4 Evaluation framework for **fisheries management**	
	3.5 Sustainable **aquaculture** in the Baltic Sea	
SO 4: Improving the capabilities of the society to respond to the current and future challenges directed to the Baltic Sea region	4.1 **Governance** structures, policy performance and policy instruments	Linking **science & policy**
	4.2 Linking ecosystem **goods & services** to human lifestyles and well-being	Integrating **ecosystem & society**
	4.3 Maritime **spatial planning** from local to Baltic Sea region scale	
SO 5: Developing improved and innovative observation and data management systems, tools and methodologies for marine information needs in the Baltic Sea region	5.1 Developing and improving scientific basis for integrated monitoring programmes for continuous **assessment** of ecological status and human pressures	
	5.2 Developing and testing innovative *in situ*, remote sensing and laboratory **techniques**	
	5.3 User-driven new information and communication **services** for marine environment, safety and security in the Baltic Sea area	

Table 3
Value judgements and associated scores used to assess a project's potential or achieved results to address the 11 BONUS challenges defined in the BONUS Strategic Research Agenda (Table 1).

Value judgement regarding project outputs	Judgement score
Project outputs not likely to be relevant to the challenge, or not likely to contribute to addressing the challenge	0
Project outputs likely to have a low relevance or value in terms of addressing the challenge	1
Project outputs likely to have a moderate relevance or value in terms of addressing the challenge	2
Project outputs likely to have a high relevance or value in terms of addressing the challenge	3

abstracts, letters, news items or corrections. These publication types are only partly represented in the WoS, e.g. many conference proceedings and books are missing, and they are not ranked according to the number of citations as is the case for the international journals in the WoS. Another 45% of the 18,769 publications identified in the WoS were papers published in international journals but did not deal with Baltic Sea research. Most of these were identified because the word 'Baltic' occurred in the reference list. Most non-Baltic Sea papers could be removed on the basis of their title or abstract, but approx. 5% had to be downloaded to find out their relevance for the Baltic Sea.

For all papers in the BONUS data set, BONUS funding was verified through the presence of appropriate referencing within the acknowledgements. During this process we discovered that 6% of the total number of international scientific papers reported by the projects in their FPRs, or after the projects had ended to the BONUS data base, were not published internationally, 1% acknowledged BONUS but the contents had nothing to do with the project, and 14% were relevant for the project but acknowledged other funding organisations – not BONUS. On the other hand, the loss of these wrongly reported papers were almost exactly compensated by BONUS-funded papers that we discovered in the WoS but were never reported to the BONUS data base.

3.4. Analysis of transnational co-publication

The three bibliometric data sets were compared with respect to country affiliation to analyse whether the BONUS programme has decreased fragmentation by increased scientific cooperation between countries relative to non-BONUS-funded Baltic Sea scientific studies. The author countries were extracted from the addresses of all authors and the proportions of the respective country contributions were calculated. For example, a paper co-authored by two authors from Estonia, two from Germany and one from Denmark scored proportionally 0.4, 0.4 and 0.2 for these countries, respectively. When one author had addresses in different countries, the scores were also proportioned to the countries. These calculations were made for all 504 papers in the BONUS data set and for 504 randomly selected papers in each of the larger PRE-BONUS and NON-BONUS data sets.

3.5. Analysis of other types of dissemination than scientific papers

Dissemination of scientific results by means other than scientific publications include presentations at scientific meetings, papers in conference proceedings, scientific books and book chapters, and technical reports directed to peers. In addition, scientists are obliged to disseminate their scientific results to students and society. This includes textbooks, PhD courses, PhD theses, stakeholder meetings, reports directed to knowledge users, public events, popular science publications, web sites, public media, etc. These other dissemination pathways could only be analysed for the 16 BONUS+ projects because this is the only cohort of BONUS-funded projects that was finalised before 2017.

The data, consisting of the number of times a specific dissemination activity (out of 17 defined activities) was carried out within a specific project, were obtained from the self-reported performance statistics in the 16 FPRs. Each activity was specified by the projects (e.g. titles of publications, names of participating persons, which policy documents were modified) and thoroughly verified by the BONUS Secretariat. As there was up to a factor 2.5 difference in the amount of funding from BONUS among the projects, the dissemination activities were re-calculated to the number of dissemination activities carried out per €M for each activity. The 17 activities were subdivided into four categories according to dissemination target group: (1) peers (other scientists), (2) students, (3) societal knowledge users (e.g. policy-makers and managers) and (4) general public. The data were analysed by comparing the average numbers among dissemination activities and ranges among projects.

3.6. Questionnaire on stakeholder views

A stakeholder (science-producers and users) perspective of the extent to which the BONUS programme has been successful in bridging the gap between environmental science and policy was gained via an online questionnaire targeted at scientists participating in the BONUS projects ('*participants*') and policy-makers ('*users*'), with recipients identified from the data base of the BONUS Secretariat. An invitation to participate in the questionnaire was sent to 289 persons identified as *participants* and to 166 persons identified as *users*, of which 59 (20%) and 8 (5%) responded, respectively. These response frequencies were very low, especially that of the *users* group. However, it should be noted that the 59 responding *participants* mainly comprised those that were most active in the projects and that the eight responding *users* each represented different major knowledge-user organisations in the Baltic Sea Area. Thus, given the high number of potential respondents that were initially contacted, and the randomising effect of self-selection that was inherent in the questionnaire invitation process, it was concluded that the responses received would not be likely to be subject to any systematic bias.

The stakeholders were asked to consider four Statements relating to the application of science to policy development, and to record how strongly they agreed with each Statement: (1) Compared to the situation before BONUS, the extent to which science-based thinking and argument is used and incorporated into the policy-making process has increased, (2) Compared to the situation before BONUS, the perceived level of scientist direct involvement in the provision of advice at the policy-making level has improved, (3) Compared to the situation before BONUS, the speed of uptake of scientific knowledge into policy-making and management has increased, and (4) Compared to the situation before BONUS, policy-making and governance have evolved from insular, sectoral processes to ones that are now more integrated and cross-sectoral. The respondents were also asked to what extent they considered that the BONUS programme has been instrumental for each Statement. Further methodology used for the questionnaire is described in detail in Supplementary materials S1.

4. Results

4.1. Societal relevance of the scientific results from the BONUS programme

All 11 challenges faced by the Baltic Sea ecosystem, that underpin the BONUS vision as defined in the SRA (Table 1), were addressed by the expected results from the 56 BONUS projects collectively (Fig. 3a). The two challenges covered to a significantly higher extent than the others were 'Restoring Good Environmental Status (GES) of the Baltic Sea and its coasts' and 'Mitigating eutrophication that affects today nearly the entire Baltic Sea'. The two challenges covered to a significantly lower extent than the others were 'Making fisheries management effective in order to secure the stability of the ecosystem and reproduction capacity of the Baltic Sea fish stocks' and 'Achieving safe maritime traffic imposing no risks to the environment'.

Generally, the 21 BONUS projects that had ended before 2017 had promised scientific results that were more relevant for the BONUS vision than they actually delivered; only four of the projects yielded the same total judgement scores for their expected and achieved results and no project delivered more than expected. Although the 11 BONUS challenges of the SRA were still well-covered by the achieved results, the average judgement scores were approx. 25% lower than those for the expected results to address the challenges (Fig. 3b). The decreases were significant for six of the challenges: 'Adapting to a sustainable way of living', 'Adapting to the effects of climate change', 'Restoring Good Environmental Status (GES) of the Baltic Sea and its coasts', 'Achieving sustainable and safe use of the exploited coastal and marine ecosystem goods and services', 'Achieving safe maritime traffic imposing no risks to the environment' and 'Minimising the environmental threat from increasingly diversified use of chemicals and new materials'.

The BONUS+ Call included seven research themes (Table 2), of which 'Linking science and policy' and the related 'Integrating ecosystem and society' were covered by most of the 16 projects (Fig. 4a). Also 'Understanding climate change and geophysical forcing' and 'Combating eutrophication' were addressed by most projects, but more often as supplementary themes. The lowest coverage was recorded for 'Achieving sustainable fisheries', 'Protecting biodiversity' and 'Preventing pollution' which were key themes in three of the 16 projects and supplementary themes in five to seven projects.

The BONUS Art. 185 calls had 19 research themes (Table 2), trebling those in the BONUS+ call but more narrowly defined and the projects were restricted to only one key theme and a limited number of supplementary themes. The themes best covered by the BONUS Art. 185 projects (key themes in seven projects each) were 'Eco-technological approaches to achieve good ecological status in the Baltic Sea' and 'Developing and testing innovative *in situ* remote sensing and laboratory techniques' (Fig. 4b). Two of the 19 themes were not identified as a key theme by at least one project: 'Ecosystem resilience and dynamics of biogeochemical processes, including cumulative impacts of human pressures' and 'Evaluation framework for fisheries management'. Whilst the former is specified as a supplementary theme by nine different projects, the latter is poorly covered across the suite of 40 projects, being specified as a supplementary theme by just one project.

The comparative analysis of research topics (as assigned by the WoS) reflected that the BONUS-funded WoS-ranked papers consisted of

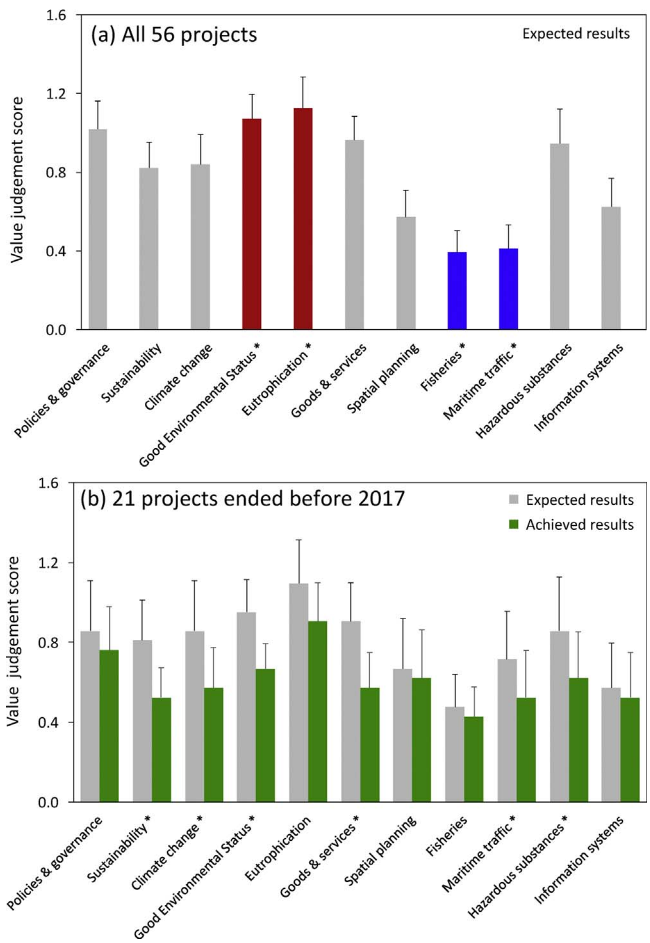

Fig. 3. Collective relevance of the BONUS-funded projects for the 11 challenges faced by the Baltic Sea ecosystem that underpin the BONUS vision (Table 1). (a) Average value judgement scores for the expected scientific results from all 56 BONUS projects funded by August 2017 to address the challenges. A Kruskal-Wallis test showed that there were significant differences ($p < 0.001$) in the degree to which the 11 challenges were addressed and post-hoc multiple comparisons pointed out that two challenges (Good Environmental Status and Eutrophication) were addressed to a higher extent than average ($p < 0.05$) and two challenges (Fisheries and Maritime traffic) were addressed to a lower extent than average ($p < 0.05$). (b) Average value judgement scores for the expected and achieved results from the 21 BONUS projects that had ended before 2017 to address the challenges. A Friedman's two-way analysis of variance by ranks showed that the average judgement scores for the achieved results (0.61) were approx. 25% lower ($p < 0.001$) than those for the expected results (0.80). The six challenges with a significant difference between value judgement scores for expected and achieved results in a post-hoc Kendall test ($p < 0.05$) are indicated with an asterisk. Error bars denote the standard error of the mean. Statistical analyses were performed with Statistica™ Version 13.2. The data on which this figure is based is presented in Supplementary materials S2.

a higher proportion of papers on policy and technical solutions for dealing with the environmental problems of the Baltic Sea ecosystem than the PRE-BONUS and NON-BONUS papers. For example, policy was dealt with in papers categorised by the WoS as 'social sciences', 'interdisciplinary research' and 'transnational relations', while papers on technical solutions were categorised as 'environmental engineering' and 'biodiversity conservation' and partly also as 'technology' and 'toxicology' (Table 4). The topics boosted most by BONUS-funding were social sciences, evolutionary biology, genetics and environmental engineering. Social sciences constitute a special case; here this topic is represented with only a very small total number of papers because social sciences by tradition publish even primary data more in books (not included in this analysis) than in international journals. Three research topics that increased very much with time, but above that were stimulated by BONUS funding were interdisciplinary sciences, technology and transnational relations. In contrast were research topics that were clearly under-represented in the BONUS-funded WoS-ranked papers, some with relevance for BONUS (fisheries, remote sensing) and some more reflecting fundamental science with low relevance for solving the environmental problems of the Baltic Sea (plant sciences, chemistry, zoology).

4.2. The effect of BONUS on scientific output and impact

During 2009–2016 the BONUS projects produced 640 international scientific publications. The 478 publications from the cohort of 16 BONUS+ projects could be followed for eight years, and we found that 70% were published in the five years after the projects ended (Fig. 5a). According to the publication lists reported to the BONUS Secretariat by the projects, publication was faster, with approx. 50% published after the projects ended, but since we checked all acknowledgements and deleted papers not acknowledging BONUS funding but found unreported papers in the WoS that did acknowledge BONUS funding, this changed to 70%. In 2009–2016, the yearly average open access publication (± SD) of the BONUS-funded projects was 45% (± 9%).

Of the 640 international publications, 566 (88%) were published in WoS-ranked journals, i.e. they were published in recognised international journals after a peer review process. However, 62 of these 566 papers could not be included in the bibliometric analyses as, although they report scientific results that may be relevant for the Baltic Sea ecosystem, they did not mention any part of the Baltic Sea Area in the text (Fig. 5b). These papers deal with general phenomena, theories and methods, or reported on species or processes that occur in the Baltic Sea but were studied in the Skagerrak (North Sea) or in rivers. Such BONUS-funded papers had to be excluded from the bibliometric comparison between BONUS-funded and non-BONUS-funded Baltic Sea scientific dissemination because they were not identified by the WoS using the 25 search criteria. The remaining 74 (12%) of the 640 international publications were published in non-WoS-indexed journals, conference proceedings or books (Fig. 5b), i.e. they are generally much less accessible, possibly not peer-reviewed and have no JIF and so were excluded from our analyses. Given these constraints, the final BONUS data set used in the bibliometric analyses consisted of 504 WoS-ranked papers reporting on Baltic Sea science.

The average number of citations, i.e. a quantification of the influence of a specific paper on the research field measured as the frequency of its usage in other papers by the peer group, was significantly higher for the BONUS-funded papers than that for the non-BONUS-funded papers before and during the BONUS programme (Fig. 6a). The average JIF, i.e. the number of citations, received in a specific year, of articles published in that journal during the two preceding years, divided by the total number of articles published in that journal during the two preceding years, was also significantly higher for the BONUS-funded papers (Fig. 6b). The JIF showed a significant increase with time, as shown by the difference between PRE-BONUS and NON-BONUS papers, while the number of citations only showed a small increase with time one year after the publication year (Fig. 6a). Especially the BONUS papers, but also the PRE-BONUS and NON-BONUS papers had higher average citation rates (Fig. 6a) than the JIFs of the journals in which they were published (Fig. 6b). This indicates that Baltic Sea science has a high impact on marine science in general.

Analysis of co-publication between countries showed that transnational cooperation increased, and thus fragmentation of environmental research on the Baltic Sea ecosystem decreased, through BONUS funding. More than half (52%) of the BONUS-funded WoS-ranked papers were the result of transnational cooperation, compared to only 33% and 32% respectively for the PRE-BONUS and NON-BONUS papers. Given that the BONUS programme by definition was international then this finding was expected. The increase in transnational co-publication as a result of BONUS funding was large for all nine Baltic Sea countries (Fig. 7). The proportion NON-BONUS papers produced within a Baltic Sea country was ≥50%, except for Denmark with 33%. For the BONUS-funded papers this

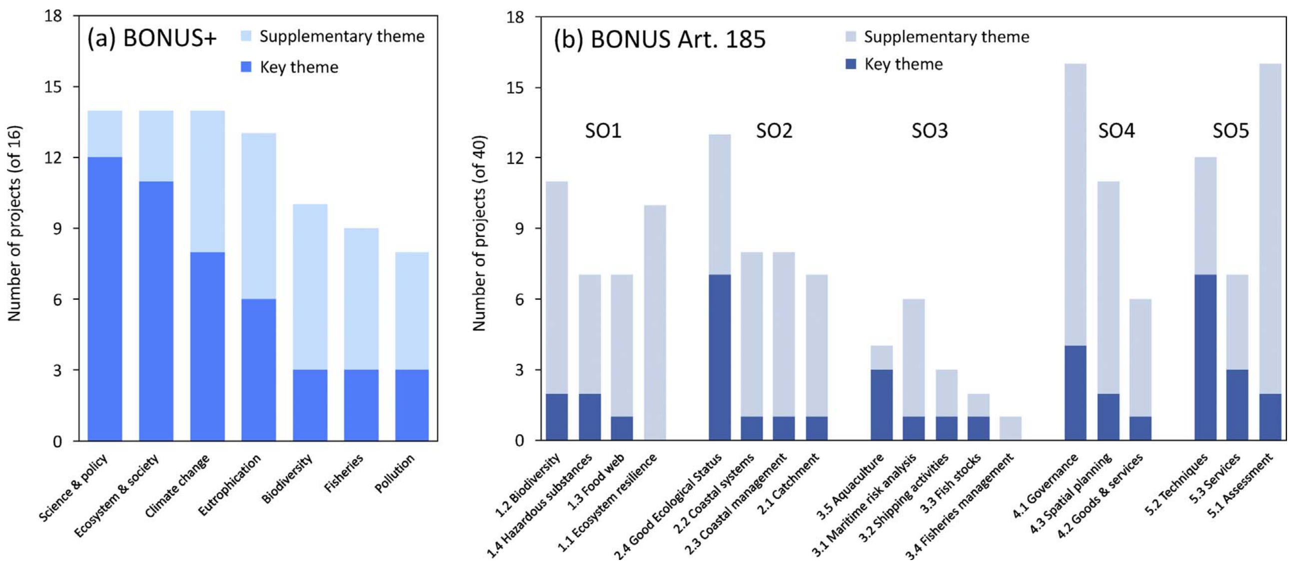

Fig. 4. Collective strength of the BONUS programme in addressing the research themes of the calls (Table 2) as key theme or supplementary theme. The themes are indicated by key words as defined in Table 2 and for BONUS Art. 185 they are subdivided into five groups according to the BONUS strategic research objectives of the SRA (SO1-SO5, Table 2). Note that in the BONUS Art. 185 call there were almost three times more themes than in the BONUS+ call, they were more narrowly defined and each project was restricted to only one key theme and a limited number of supplementary themes. The data on which this figure is based is presented in Supplementary materials S3 and S4.

was approximately halved for all countries, except for Estonia where within-country publication decreased proportionally less, from 61% to 44%. Denmark was the Baltic Sea country that showed greatest transnational co-publishing in 2009–2016, both with and without BONUS funding. Countries from outside the Baltic Sea region scored very high in transnational co-publishing on Baltic Sea science in the BONUS data set (97%) through co-publication with Baltic Sea countries.

The average JIF increased with the number of countries per paper in 2009–2016, both for NON-BONUS and BONUS papers (Fig. 8). This shows that scientific papers produced by transnational cooperation are generally of higher scientific quality, and that stimulating transnational cooperation (as done by BONUS) is a way to strengthen scientific excellence.

Table 4

Results of the comparative WoS analysis of the main research topics for the three data sets PRE-BONUS (2002–2008), NON-BONUS (2009–2016) and BONUS (2009–2016). The first three data columns show the percentage Baltic Sea papers produced within different research topics in the three data sets, categorised into research topics by the WoS and calculated directly by the WoS with literature references as input data. Note that the percentages do not add up to 100% because one paper can fit into more than one research topic. The last two data columns show the percentage change between two data sets calculated from the data in the first three data columns; +100% means that publication was doubled, −50% means that publication was halved. First 10 research topics: bold indicates that the topic increased by 50% or more, last 6 research topics: bold indicates that the topic was halved or more than halved.

Research topic	% PRE-BONUS (of 2994)	% NON-BONUS (of 4352)	% BONUS (of 504)	% Difference between PRE-BONUS and NON-BONUS	% Difference between NON-BONUS and BONUS
Social sciences	0.03	0.05	0.20	39	**330**
Evolutionary biology	2.34	1.61	5.95	−31	**270**
Genetics (heredity)	1.24	1.31	3.57	6	**173**
Environmental engineering	4.48	3.63	9.13	−19	**151**
Interdisciplinary sciences	0.33	3.45	6.35	**932**	**84**
Technology	0.47	4.09	6.55	**774**	**60**
International relations	0.17	1.06	1.59	**533**	**50**
Biodiversity conservation	1.54	2.00	3.77	30	**89**
Interdisciplinary geosciences	9.89	9.97	16.27	1	**63**
Toxicology	2.97	1.95	3.77	−34	**93**
Geology	10.96	12.57	18.25	15	45
Ecology	13.83	12.62	16.27	−9	29
Environmental sciences	34.47	35.75	45.04	4	26
Oceanography	27.76	24.17	28.97	−13	20
Economics	0.53	0.67	0.79	25	19
Geochemistry geophysics	1.70	1.75	1.98	3	14
Marine and freshwater biology	36.17	29.14	31.55	−19	8
Meteorology atmospheric sciences	4.48	4.99	5.36	11	7
Business economics	0.57	0.80	0.79	42	−1
Biochemistry molecular biology	2.24	1.82	1.79	−19	−2
Microbiology	4.74	3.77	2.98	−21	−21
Physical geography	3.44	4.02	2.98	17	−26
Water resources	2.71	2.80	1.39	4	**−50**
Fisheries	9.45	8.04	3.37	−15	**−58**
Plant sciences	2.24	1.47	0.60	−34	**−60**
Chemistry	3.31	3.24	0.79	−2	**−75**
Zoology	3.61	2.78	0.00	−23	**−100**
Remote sensing	1.44	1.38	0.00	−4	**−100**

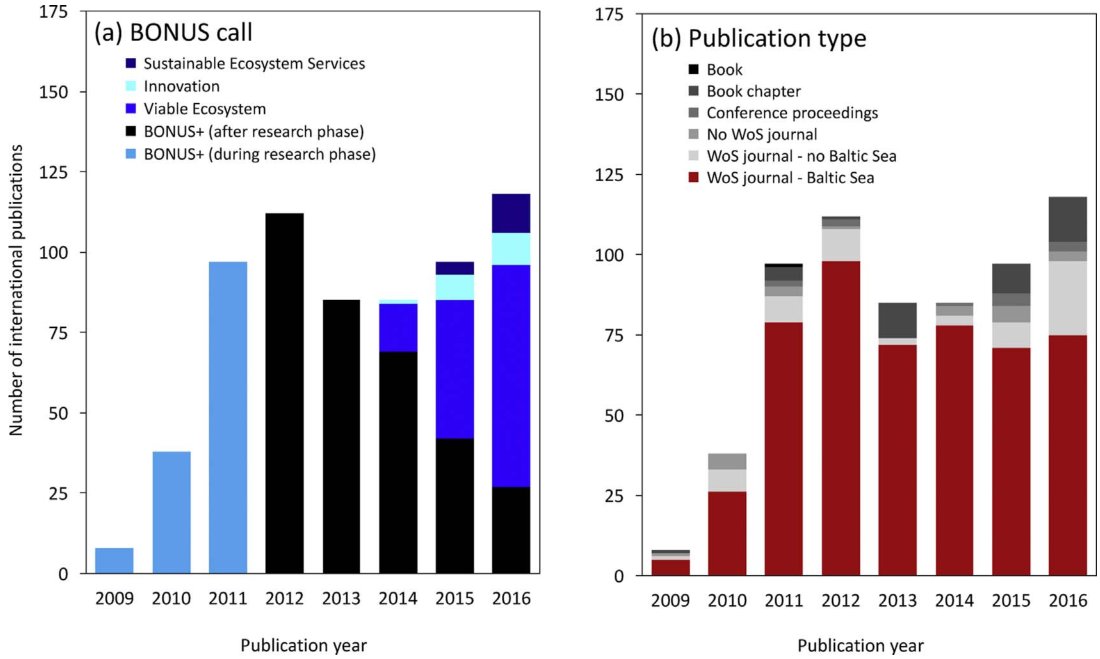

Fig. 5. Summary of the 640 International scientific publications funded or co-funded by the BONUS Programme in 2009–2016. (a) Number of publications per year by BONUS call: BONUS+ Call with research phase 2009–2011, Viable Ecosystem Call with research phase 2014–2018, Innovation Call with research phase 2014–2017, Sustainable Ecosystem Services Call with research phase 2015–2018. (b) Number of publications per year by publication type. WoS journal = published in a journal ranked by the Web of Science. Baltic Sea = the Baltic Sea or one of its subareas is mentioned in the contents of the paper.

4.3. Dissemination by other means than scientific papers

The verified dissemination activities from the BONUS+ projects (the only cohort of BONUS projects finalised before 2017 and that could be analysed here) show that the total dissemination performance of the BONUS+ projects to peers, students, societal knowledge users and the general public was pervasively high (Table 5). However, there was large variability between projects; the number of international scientific publications varied between 6 and 39 per €M of BONUS funding among the 16 projects. The variability was even higher for several other dissemination activities: e.g. the number of persons participating in PhD courses organised by the project varied between 0 and 48 per €M,

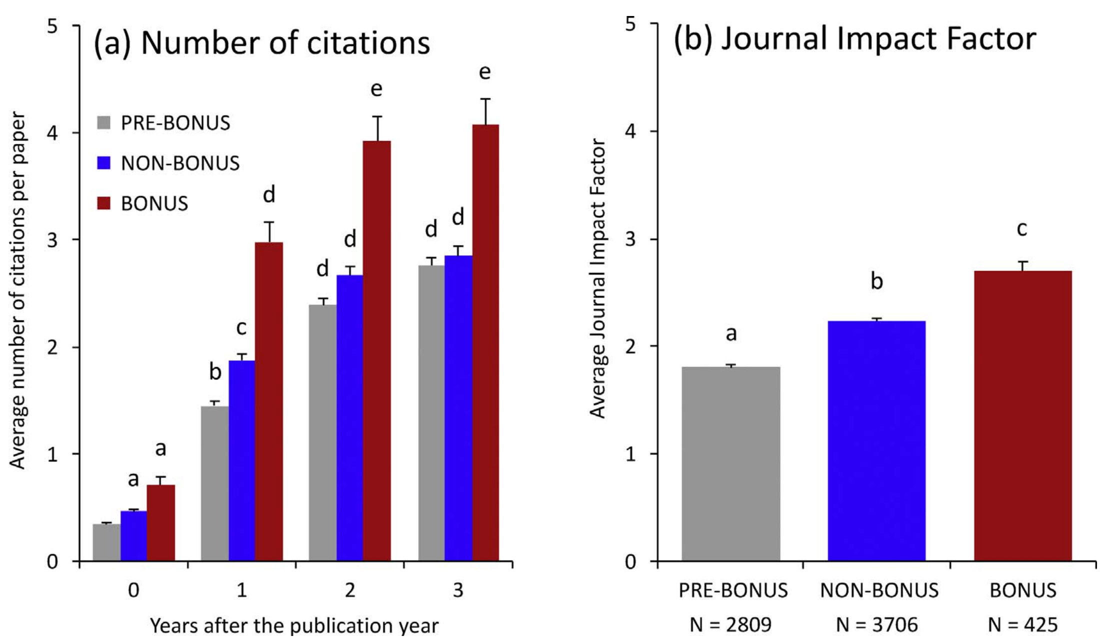

Fig. 6. Comparisons of scientific quality of the Baltic Sea papers published in WoS-ranked journals in the three data sets PRE-BONUS, NON-BONUS and BONUS, based on data downloaded from the Web of Science on 24 March 2017. A different letter above the error bar denotes a significant difference in a post-hoc Tukey test following ANOVA. Error bars denote the standard error of the mean. (a) Average number of citations in years 0–3 after the publication year showing significant effects of time and data set (two-way ANOVA, $p < 0.001$). Only data for 2009–2013 could be used because for this time period three citation years were available after the publication year (years 0–3), which is necessary for the number of citations to stabilise as can be observed in the figure. The figure is based on 5857 papers and 44,366 citations. (b) Average Journal Impact Factors (JIFs) of the journals in which the PRE-BONUS, NON-BONUS and BONUS papers were published, showing significant differences between the three data sets (one-way ANOVA, $p < 0.001$). The figure is based on 6940 papers in 905 WoS-ranked journals. Since JIFs vary from year to year, the JIF of the publication year was used for each paper. Only data for 2009–2015 could be used because the JIFs for 2016 were not yet published on 24 March 2017 when the data were downloaded from the WoS. Statistical analyses were performed with Statistica™ Version 13.2.

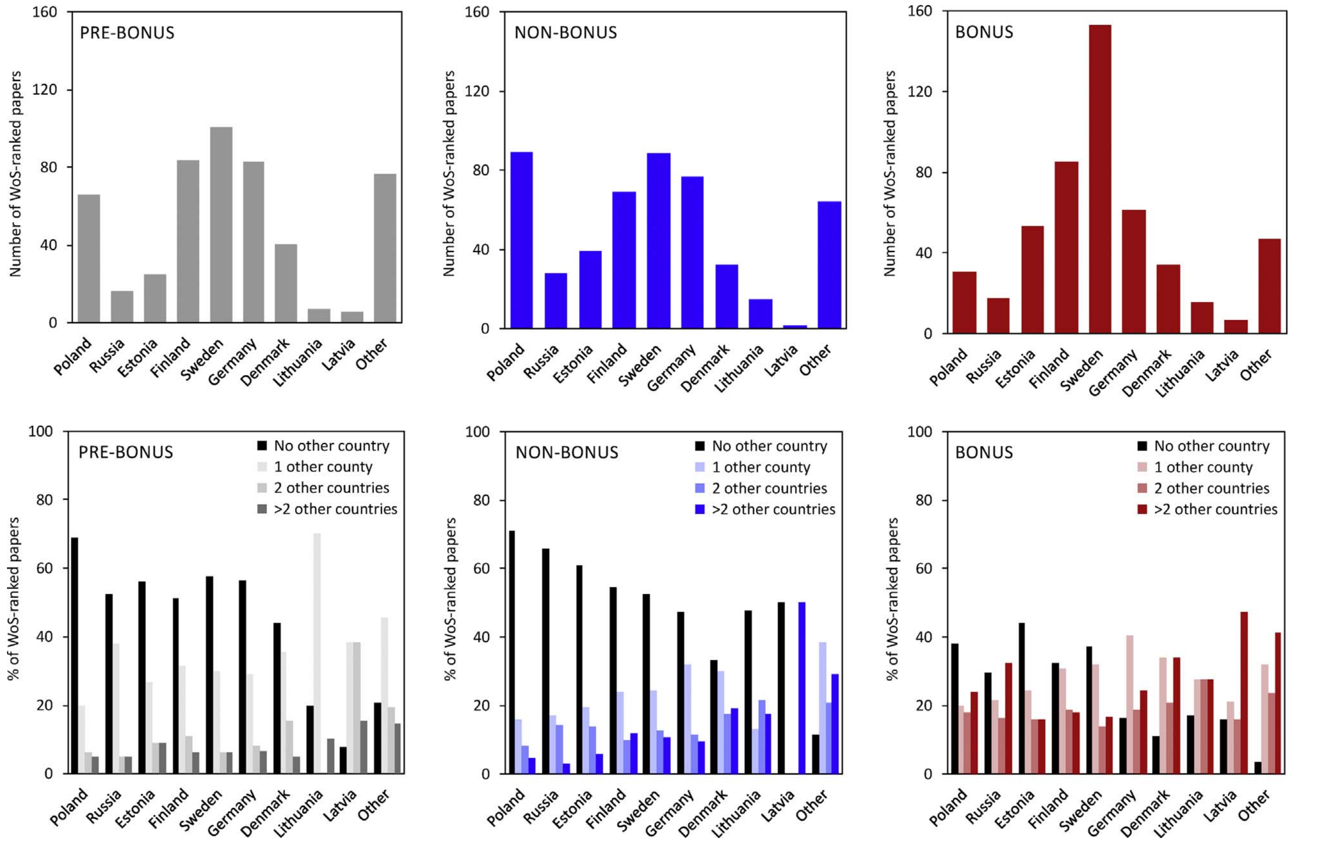

Fig. 7. Production and transnationality of Baltic Sea papers published in WoS-ranked journals in 2009–2016 by the nine Baltic Sea countries and all other countries on earth lumped in the category 'Other', based on 504 papers in each of the three data sets (= all papers in the BONUS data set and 504 randomly selected papers from the PRE-BONUS and NON-BONUS data sets). Upper panels: Number of papers produced per country with calculations based on the relative contributions of each country to each paper. Lower panels: Transnationality of publication per country. The black bars show the proportion of the papers produced within a specific country ('No other country') while the other bars show co-publication of a specific country with one, two, or more than two other countries, respectively.

the number of times the scientists working in the project had served as members or observers in stakeholder and scientific committees varied between 0 and 74 per €M, and the number of interviews to media given by members of the project's consortium varied between 3 and 40 per €M (Table 5).

Dissemination from scientists to policy-makers and managers is of specific relevance to bridging the gap between environmental science and policy. Altogether, the BONUS+ projects contributed to consultations for the European Commission committees 37 times and the scientists working in the projects have served as members or observers in stakeholder and scientific committees 570 times (Table 5). Furthermore, the projects modified relevant policy documents and action plans 49 times and in 153 cases suggested design, implementation and evaluation of the efficacy of pertinent public policies and governance.

The BONUS programme also required the research projects to produce practical deliverables of direct use by policy-makers and managers. These deliverables are in addition to the contributions to the general knowledge for solving a particular environmental problem. They included different types of evaluation, assessment and risk management tool-boxes, guidelines, maps, indicator spreadsheets, reports, web sites, Wikipedia pages, etc. (Supplementary materials S5). However, this list of practical BONUS deliverables does not consider their use in society.

4.4. Stakeholder views on the societal impact of BONUS

The stakeholders, 59 scientists participating in the projects ('*participants*') and eight policy-makers ('*users*'), agreed to the questionnaire Statements 1, 2 and 4: that due to the BONUS programme the extent to which science-based thinking and argument is used and incorporated into the policy-making process has increased, that the perceived level of direct scientist involvement in the provision of advice at the policy-making level has improved and that policy-making and governance have evolved from insular, sectoral processes to ones that are now more integrated and cross-sectoral (Supplementary materials S1). With respect to Statement 3 the two stakeholder groups disagreed. The *participants* showed a moderate agreement that the speed of uptake of scientific knowledge into policy-making and management has increased as a result of BONUS. However, the *users* indicated the opposite; according to them the speed of uptake has decreased but independently of the BONUS programme.

5. Discussion

5.1. Decreasing fragmentation of environmental science

In terms of the ERA target of reducing fragmentation in research funding and policy, BONUS has been influential. At its inception in 2003 as an ERA-NET funded programme, 11 separate national Baltic Sea research programmes were listed and in most of the countries Baltic Sea research was based on isolated thematic or non-thematic bottom-up calls (BONUS ERA-NET Proposal no 510204). Today all national funding institutions participating in BONUS (22 funding institutions from eight EU Baltic Sea states) have suspended their national Baltic Sea programmes. Instead, basically all programmatic, competitive Baltic Sea funding within the Research, Technology Development and Innovation (RTDI) sector is today funnelled through BONUS thus encouraging thematically- or geographically-coordinated research in

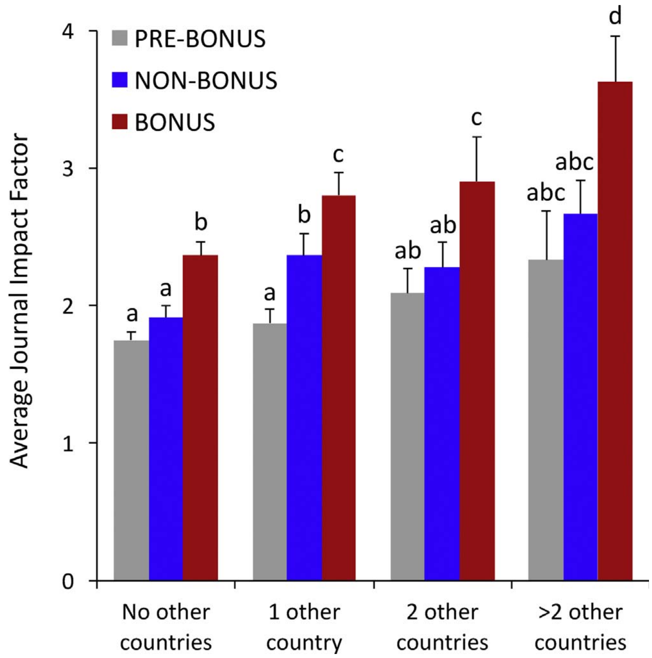

Fig. 8. Average Journal Impact Factors (JIFs) of the PRE-BONUS, NON-BONUS and BONUS papers used in Fig. 7 for 2009–2015, showing significant effects of number of co-publishing countries and data set (two-way ANOVA, $p < 0.001$). A different letter above the error bar denotes a significant difference in a post-hoc Tukey test following ANOVA. Error bars denote the standard error of the mean. Since JIFs vary from year to year, the JIFs of the publication year were used for each paper. Only data for 2009–2015 could be used because the JIFs for 2016 were not yet published on 24 March 2017 when the data were downloaded from the WoS. Statistical analyses were performed with Statistica™ Version 13.2.

single or multiple disciplines. Hence, nationally, BONUS has led to different ministries supporting different funding lines for Baltic Sea or marine research in a coordinated and often integrated way (BONUS, 2017b).

Research programmes, such as BONUS, are required to avoid fragmented science whether by country, discipline or approach, and the benefits of the sum are greater than of the individual parts. With its collaboration and clustering strategy, BONUS is designed to ensure that scientists and projects work together. Our bibliometric data demonstrate an intended consequence of this design, showing a clear shift in scientific publications from single-country to transnational papers. Some circularity was expected in the analysis of transnational cooperation for BONUS papers compared to others given that the project selection criteria included transnationality. In addition, non-Baltic Sea countries participating in BONUS were required to have transnational cooperation with Baltic Sea countries.

The bibliometric study also showed that BONUS funding increased scientific excellence of Baltic Sea research. It is acknowledged that the JIFs may represent an element of circularity as an individual highly-cited BONUS paper will influence the overall JIF of the journal. Also, the higher ranked journals will prefer to take papers from a transnational and wider-geographic group (in this case Baltic Sea scientists from different countries working together) rather than from single-country, geographically restricted case studies. Hence it is suggested that BONUS papers by definition will reach high JIF journals. However, the number of citations and the JIFs showed the same patterns, thus reinforcing the higher scientific excellence of the BONUS papers compared to non-BONUS papers.

5.2. Increasing societal relevance of environmental science

We have shown that the science produced collectively by the BONUS-funded projects largely meets the environmental challenges faced by the Baltic Sea ecosystem although some topics, notably fisheries and maritime traffic, are less well covered by the programme. Through the careful consulting procedures during the development of the SRA (Fig. 2), BONUS successfully integrated a balanced input from all involved parties, i.e. the science producers and users (bottom-up) and the funders of the programme (top-down). Typical examples of contributions to the development of the BONUS SRA that needed scientific insight were the issues of achieving Good Environmental Status (GES) (*a la* the EU Marine Strategy Framework Directive) under future climates, effects of multiple stressors on the marine ecosystem, gaps in knowledge on the spatial ecology of living resources necessary to achieve efficient fisheries management and the importance of intraspecific biological diversity for setting proper conservation measures. However, such open methodology of combining bottom-up and top-down approaches presumes a rigorous review, screening and generalising of the often fragmented, contrasting and competing signals incoming from different stakeholders. In the BONUS case, the task of transforming the originally 'noisy' bottom-up input into a structured and coherent programme content was performed by a dedicated drafting team of experts representing both academia and the potential knowledge users. Similar processes in thoroughly assessing the supply and demand for science have been described as highly successful in the production of collaboratively-derived science-policy research agendas (Sarewitz and Pielke, 2007; Holmes and Savgård, 2009; Sutherland et al., 2012).

Given that most of the programmatic funding for environmental research on the Baltic Sea ecosystem is now channelled through BONUS (see 5.1), and that the BONUS programme is policy-driven and solution-orientated, it is expected that BONUS increases the publication of scientific results of high societal relevance. This is supported by our bibliometric study of research topics, which reflected that BONUS funding has increased the societal relevance of Baltic Sea science, notably by proposing solutions for environmental problems but also by providing users with valuable instruments for environmental monitoring and decision-making. However, the relevance we assessed does not consider the 'salience' aspect, the perceived relevance of information, i.e. does the science provide the information that decision-makers think they need, in a form and at a time that they can use it? (Fritz, 2010).

Although the BONUS research covered the challenges faced by the Baltic Sea ecosystem, the discrepancy in the relevance of the promised and achieved scientific results from the first 21 BONUS-funded projects is a warning sign. There is risk of scientists over-promising and under-delivering even in an ambitiously coordinated environmental programme such as BONUS. While there remains of course a need for curiosity-driven research, this might not necessarily fulfil the requirements of implementing policy such as, for example, EU Directives; hence the importance of applied studies. In the type of projects funded by BONUS, scientists would need to avoid focussing on the curiosity-driven '*nice-to-know*' and give policy-makers the required '*need-to-know*', and would have to consider the relative merits of producing very detailed material on a limited topic compared to the information needed by policy-makers who are forced to look across many aspects. There is a difficult-to-solve contradiction in that a scientist career is focussed on outputs (numbers of papers, citations, etc.) whereas policy-driven science has to be measured by outcomes. Another factor that can have influenced on the discrepancy in the present study is that scientists may have funding for related projects from different sources with different demands on societal relevance and that one publication can be produced with funding from both BONUS and these different sources. However, an analysis of co-funding was not included in the present study.

Capacity-building of scientists to influence policy-makers (Laing and Wallis, 2016) and raising awareness of scientists in management and policy contexts (Fernández, 2016) is of course valuable but usually does not help building an academic career. More effective is that public funders of science are increasingly demanding that the science is

Table 5
Summary of dissemination activities directed to other scientists (peers), students, knowledge users (e.g. policy-makers and managers) and general public by the 16 BONUS+ projects (funded by BONUS with 22.3 €M) during three years of project implementation 2009–2011. All activities were specified by the projects and verified by the BONUS Secretariat. As there was up to a factor 2.5 difference in the amount of funding from BONUS among the projects the dissemination activities were re-calculated to the number of dissemination activities carried out per €M.

Target group	Dissemination activity	BONUS+ (total number)	Average per €M ± SD (N = 16)	Range among projects (per €M)
Peers	Number of international scientific publications produced by the project	504	22 ± 10	6–39
Peers	Number of datasets the project has delivered to the common metadata base of the BONUS programme	239	10 ± 15	0–54
Peers	Number of scientists that attended international workshops, working group meetings, conferences, intercalibration exercises etc., paid by BONUS	1203	51 ± 30	9–104
Peers	Number of working days spent by foreign scientists on research vessels participating in the cruises arranged by the project	1421	52 ± 84	0–271
Peers	Number of working days spent by foreign scientists using other major facilities involved in the project	2057	80 ± 111	0–421
Students	Number of persons participating in PhD courses organised by the project	371	15 ± 15	0–48
Students	Number of modifications made to current PhD course programmes that resulted from the work of the project	31	2 ± 2	0–5
Students	Number of student visit days from the project to other BONUS-funded projects	255	10 ± 15	0–50
Knowledge users	Number of times the project has contributed to consultations carried out by the European Commission	37	2 ± 3	0–10
Knowledge users	Number of times the scientists working in the project have served as members or observers in stakeholder and scientific committees	570	25 ± 23	0–74
Knowledge users	Number of times the effort of the project has resulted in modifications made to relevant policy documents and action plans (in particular, Baltic Sea Action Plan)	49	3 ± 3	0–14
Knowledge users	Number of suggestions for designing, implementing and evaluating the efficacy of pertinent public policies and governance originating from the work of the project	153	8 ± 12	0–47
General public	Number of popular science papers produced by the project	163	8 ± 7	2–32
General public	Number of interviews to media given by members of the project's consortium	526	22 ± 12	3–40
General public	Number of multi-media products and TV episodes produced by the project with dissemination purpose	44	2 ± 2	0–7
General public	Number of times the project team has issued a recommendation how to improve the general public's comprehension and priorities regarding the Baltic Sea	98	4 ± 5	0–18
General public	Number of times the project has contributed to dissemination products/events addressed to the general public concerning coupling between marine environmental quality and human health and well-being	286	12 ± 10	0–35
General public	Number of other dissemination products produced by the project	586	26 ± 36	0–142

relevant and useful to society (Holmes and Clark, 2008; Clark and Holmes, 2010). It is increasingly notable that national evaluations of scientists and university academic performance use metrics based on the societal value of science (Bornmann, 2012). In particular, while it is often easier to measure 'outputs' from the science (e.g. metrics related to number of papers, citations, JIFs, amount of research income or expenditure), it is much more valuable for policy-makers and managers to determine its value to society such as being used to modify policy or create techniques or technologies. However, the outcomes are much more difficult to determine and to create a metric and the outcomes may not be apparent until several years after the research has been completed. As an example, the UK Research Excellence Framework (www.hefce.ac.uk/rsrch/REFimpact) requires researchers to create 'impact statements' that give a narrative of the value of the research to society; that narrative requires evidence over a long period, e.g. 15 years, to show how the research has been used by society. As such impact statements have to be included in a university research submission, they contribute to the grade that is awarded; as this then translates into subsequent research funding there is a clear incentive for scientists to ensure (and demonstrate) that their research is of societal relevance.

5.3. Disseminating environmental science

We have shown that the science produced by the BONUS programme on the whole is largely effectively disseminated to peers (scientific papers), students (courses), knowledge users and the general public. In the latter two cases the scientists were stimulated, assisted and coached by information officers and intermediaries from the BONUS Secretariat. However, the dissemination from a few individual BONUS projects was remarkably low. This was partly related to the different nature of the projects, e.g. most innovation projects produced only few WoS-ranked papers and partly due to a few projects concentrating mainly on producing WoS-ranked papers and hardly using any other dissemination channels.

While knowledge users identify their needs mostly based on their current agenda of policy and management, scientists bring in the necessary breadth of perspective, understanding of complexity and consequential relationships among different factors and timescales, which needs a long time to develop. Thus, the users require the information quickly compared to the time necessary for producing and disseminating peer-reviewed papers (Cooke et al., 2016), with a consequence that peer-reviewed dissemination may be achieved after the project has ended but by then the scientists have moved on to other projects. Responding to our questionnaire, the scientists thought that uptake of scientific knowledge into policy-making and management had increased as the result of BONUS but the knowledge-users thought that the speed of uptake had decreased independently of the BONUS programme. This is a warning sign indicating that there is a miss-match in satisfying the needs of the societal users and that the scientists do not realise that this miss-match exists. The BONUS+ projects provided a unique chance to follow publication behaviour, which showed that while communication between scientists and stakeholders was intensive during the research phases of the 3-year BONUS+ projects, using appropriate channels for different target audiences (Mea et al., 2016), and demonstrably impacted policy-making and ecosystem management, 70% of the peer-reviewed scientific papers were published after the research projects had ended and direct dissemination from the projects to the stakeholders had ceased. It is a normal feature that a large proportion of the scientific publications from a research project is published after the project has ended while scientists are already working with new research projects, but there is a risk that not all of the relevant knowledge produced reaches the potential users. This lag effect gives rise to a peak in publication volume after research projects have ended, followed by a 'tail' of publications that, in the current study, was seen to last for about five years, whilst single papers can be published even after that. Such a very long-term perspective in dissemination hampers the use of the scientific results in society.

The problem-oriented themes of the BONUS SRA-promoted interdisciplinary research, as shown by our bibliometric study, although this was expected as the programme had selected the projects for funding with this in mind. Given the range of BONUS themes, projects have generally been designed (and selected) to integrate natural and social sciences, and to identify policy-makers as the users of the science, and the programme recognises that a knowledge of ecosystems is important in determining aspects of societal benefit. For example, it is reassuring that the themes 'Linking science and policy' and the related 'Integrating ecosystem and society' were covered by most of the 16 projects in BONUS+.

Despite this, interdisciplinarity is hampered by the different disciplines using different publication means; for example, social scientists by tradition (and also in the BONUS projects), publish even primary data more in books and book chapters than in international journals. Books and conference proceedings are often difficult to obtain, download and access and in many cases not as thoroughly peer-reviewed as journal articles. Indeed, the outputs of the more social-sciences orientated (parts of) the BONUS projects yielded one single book and/or book chapters in different books rather than a selection of papers in journals. This tradition is slowly changing, but today still much important knowledge generated through public funding is largely 'lost' for further use in science in this way. The outlets with low accessibility for scientists may be used more by policy-makers and managers; without access to journal subscriptions through university libraries it may be easier to order a few expensive books. This differential use of the literature then creates a problematic further separation between science and society that should urgently be mitigated.

5.4. Practical implementation of environmental science

Evaluation of research impact on society is recognised as important but is a neglected area and significant methodological difficulties are involved as identified by Holmes and Savgård (2008): (1) it is difficult to trace the uptake of research in policy-making and regulatory decision taking as the research result will be just one of the considerations taken into account and it may be the coalescence of outputs from several projects which has the influence, (2) it can be some time after the completion of a research project before the impact is realised, (3) a lot of research is aimed at building conceptual understanding rather than at instrumental use, which is generally easier to evaluate, (4) the relevance of a project or programme may be reviewed against its starting conditions or the context pertaining when it is completed, and (5) programme and project objectives tend not be precisely defined, making achievement of objectives difficult to evaluate.

These factors are also valid for the BONUS programme and despite the positive answers to our questionnaire about increased societal use of Baltic Sea science as a result of the BONUS programme and the self-documented influence of the BONUS scientists on policy (e.g. the 16 BONUS+ projects provided 37 consultations to the EU, 49 modifications to policy documents and action plans and 153 suggestions for designing, implementing and evaluating the efficacy of pertinent public policies and governance), it is not − and will never be − possible to quantify how and how much specifically the BONUS programme improves the ecosystem health of the Baltic Sea. The BONUS projects cover only part of the total Baltic Sea scientific research volume. In 2009–2016 BONUS funded 10.4% of all WoS-ranked papers published on the Baltic Sea (504 of 4856), which is expected to rise to 20–25% in 2018–2022 if the BONUS Art. 185 projects will be equally successful as the BONUS+ projects (estimated from the amount of BONUS+ funding, the publication output of BONUS+, and the amount of BONUS funding of the Art. 185 projects). While the BONUS papers collectively score higher in societal relevance than the non-BONUS papers, many papers with high environmental relevance are produced outside

BONUS, as well as many basic science papers that greatly add to the understanding of the functioning of the Baltic Sea ecosystem.

Although the discrepancy between the research phase and the following peer-review dissemination tail (see 5.3) is partly buffered by scientists being engaged by authorities as expert advisers, the investment of society in funding policy-driven research projects could be more profitable by promotion and improvement of the use of the scientific results in a wider perspective. One way of intensifying the science-to-policy dissemination is to produce critical syntheses that are relevant and legitimate within the scope of environmental programmes, not only reporting the results produced by the projects in the programme but also putting them in perspective with the wider scientific literature and providing credibility, relevance and legitimacy to science users in society for specific environmental problems (Heink et al., 2015). This lies outside the traditional 'service sphere' of most research funders. By collecting from all projects information on direct expert adviser activities, BONUS emphasises that this is important. BONUS has gradually increased such syntheses by clustering projects and by a recent call for knowledge synthesis desktop-studies addressing the challenges for sustainable use of Baltic Sea ecosystem services (BONUS, 2017a).

5.5. Knowledge synthesis to bridge science and policy

Knowledge synthesis with critical review of research outputs is widely accepted as necessary in bridging science and policy (Carpenter et al., 2009; Pullin et al., 2016). Policy actors view centrally-sponsored synthesis reports as the most influential expert-based knowledge (Lawton and Rudd, 2016). Such syntheses should preferably be published in peer-reviewed international journals, thus supporting both the advancement of science and providing academic merit to scientists. The lag phase in peer-reviewed publication after the end of a research project (as we found for the BONUS+ projects) will also be, at least partly, rectifed by synthesis work.

While the results of individual studies may be contradictory and create uncertainty, syntheses with critical review, unraveling contradictions and uncertainties and at best presenting a robust consensus (Oreskes, 2004), are able to ensure that only credible scientific knowledge is transferred to practice. Moreover, taking a stock of 'what we know and what we do not know' is also needed to develop scientific foresight, horizon-scanning and future research directions. In addition to a detailed examination of the environmental problem itself, this should involve the use of robust and reliable methods of societal impact measurement (Bornmann, 2013) and decision analysis (Winterfeldt, 2013) of the problem. Data collection should include an integrated development of improvements together with knowledge users through intensive two-way, iterative communication seeking consensus and science-based solutions. Policy analysis is a concept in which both communities can play their role by making productive use of their strengths (Duijn and Rijnveld, 2007) and will enhance the practical implementation of the science produced in environmental research programmes. In relation to the total cost of a whole RTDI programme, the cost for producing such syntheses is small and needs only a small group of key scientists and key knowledge users. In addition, they can be carried out rapidly as one-year research projects selected by bottom-up calls and will be of high value to the current scientific research. With access to integrated critical scientific syntheses and knowledge use evaluation, information officers and lobbyists will also be able to do a better job as the scientific base of their information becomes firmer.

In the BONUS programme, the first steps towards knowledge synthesis were made during the final stage of the BONUS+ phase when each of the funded transnational projects was invited to produce a synthesis of its findings (published together in a special issue of Volume 43 of the scientific journal AMBIO). Altogether, eight issues were published in AMBIO Volume 43 with 11–14 papers per issue and by 12 May 2017 the resulting 98 papers had on average received 8.8 citations. The two special issues had the highest average number of citations: 11.5 for the BONUS issue (Kononen et al., 2014) and 27.1 for the other one, while that of the other (non-special) six issues varied between 3.3 and 8.2 citations. This agrees with the comment that papers in special issues are usually more highly cited than are single, isolated papers (Dr Christiane Barranguet, Elsevier Publ., pers. comm.). However, the BONUS+ AMBIO volume has two drawbacks: the syntheses were made by the authors leading the primary research (and therefore the element of external critical review is weak, if present at all), and, even when covering a relatively significant body of science, they were largely limited to the contribution of a single BONUS project (so producing an incomplete knowledge synthesis).

An enduring transnational interdisciplinary research programme should provide exceptionally favourable conditions for synthesising knowledge (e.g. Carpenter et al., 2009). The limited timeframe of the policy decisions to be made requires rapid and updatable synthesis of knowledge. Conflicts of evidence may require involving unbiased actors, i.e. those not related to the individual studies to be reviewed and synthesised. As policy decisions often have to be taken in the context of conflicting values and/or interests of different stakeholder groups, the synthesis methods must be transparent, rigorous and inclusive so that the outcomes are regarded as legitimate by all impacted parties (Cormier et al., 2013). Risks of taking wrong decisions are at times high and so transparent and traceable synthesis methods need to be used to justify a decision and provide a suitable audit trail.

After repeatedly considering the importance of knowledge synthesis and critical review (sometimes confronting limited understanding and scepticism by some national research funders), BONUS has arrived at a 'two-way' model for solving the issue: in cases where the problem requiring knowledge synthesis is shared by several ongoing projects, the projects are encouraged to produce a synthesis as a cross-project collaboration activity. Several such collective efforts are underway. In addition to this, the recent BONUS Synthesis call (BONUS, 2017a) will fund balanced overviews where all existing scientific results on a specific environmental problem of the Baltic Sea ecosystem are put into context with respect to stakeholder interests. The proposed projects are expected to 'perform critical review of research outputs as well as identify the knowledge gaps and further research needs. Each project funded will also be expected to analyse how successfully the outputs of science have been taken up at different levels of public governance and management, and by industry, and suggest ways to enhance the societal significance and impact of research and innovation relevant to the specific topic. Topics selected for this call extend across the strategic objectives and themes of the BONUS SRA; they require an interdisciplinary approach and shall therefore be examined from different angles, e.g. natural science, technology, economy, social aspects' (BONUS, 2017a).

6. Concluding remarks: lessons from the BONUS programme

Research-funding programmes can play an important role in improving the integration of environmental science in society. With this in mind, BONUS went through a long preparation time (the 5-year ERA-NET phase), and a pilot call (BONUS +) to arrive at its present programme design. BONUS established that, acknowledging the different drivers for science-producers (academic career, need for funding) and science-users (fast results fitting policy windows), bridges can be built through strong programme management stretching far beyond selecting projects for funding. The programme's role in facilitation of science-policy communication in all phases of the programme was crucial for success in relevance and dissemination of the science and its practical implementation in policy. Dedicated coordination included coaching, facilitating the sharing of infrastructure and data, iterative networking within and between science producer and user groups, stimulating and assisting scientists with dissemination, alongside practical matters of programme governance. Instruments of critical importance for successful science-society integration were identified as:

(1) A strategic research agenda with strong inputs from the policy and management side defining their needs for solving environmental problems and equally strong inputs from the scientific community providing the scientific basis for these problems.
(2) Provision of platforms where science and policy can meet, such as web site and organising joint workshops and conferences throughout the programme. For these interactions to be fruitful it is crucial to motivate all parties to participate in these interactions, i.e. benefits for the fulfilling the project requirements need to be clear to the scientists as well as the benefits for the societal parties in fulfilling their policy and management assignments.
(3) Obligatory (international) cooperation between scientists to decrease fragmentation, increase quality, increase consensus and clarify uncertainties about environmental problems. This requires networking and coaching of projects throughout the programme.
(4) Encouraging and supporting scientists in disseminating scientific results through audience-tailored channels during the research phase, e.g. through information officers as intermediaries in close cooperation with the scientists so that the scientific results can be assimilated by societal actors but still are scientifically sound. This includes requiring peer-reviewed publication in international journals of all scientific results, i.e. avoiding publication in books and conference proceedings.
(5) Not only fund primary research but also synthesis projects that include evaluation of the practical implementation of the produced science in society to enhance relevance, credibility and legitimacy of science and expand its practical implementation. These projects should produce peer-reviewed critical scientific syntheses in the form of balanced overviews of specific environmental problems, not only reporting the results produced by the programme but putting them in perspective with the wider scientific literature and evaluating the practical implementation in society today and how this can be improved. The latter aspects require intensive and iterative communication with, and data input from, the policy and management side.

Conflict of interest

The authors declare that there is no conflict of interest.

This work has not been published previously and is not under consideration for publication elsewhere.

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Appendix A. Supplementary data

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