BONUS BALTHEALTH
Final project Report (2017-2020)
Publishable summary

1. Brief description of the project's overall goal(s) and expected final results

BONUS BALTHEALTH is a cross-disciplinary synergism of specialists in toxicology, ecology, biogeochemistry, veterinary science, genetics, epizootiology, quantitative biology and conservation, investigating multilevel Baltic food web impacts of man-made pollutants, animal-borne diseases, and climate change. This require the cumulative flow of data and knowledge among its working groups, each operating at the forefront of their specific field of expertise. One working group is dedicated to unravel spatiotemporal trends in the Baltic food web composition and its dynamics using state-of- the-art biogeochemical and *in silico* methods. This serves as a fundament on which two other working groups add on the knowledge on the presence and food web dynamics of known and unknown man-made pollutants as well as animal-borne diseases. Such information will then be combined with the evaluation of current and novel health biomarkers. A last working group is tasked to combine all information in a comprehensive modelling framework dedicated to identify and evaluate population and ecosystem-level health impacts. Interwoven through all activities are continuous efforts to assimilate existing and organise project-based data and models pertaining the above efforts, and disseminate major outcomes through public media and the participating national history museums. BONUS BALTHEALTH is the first endeavour to identify and quantify powerful indicators of individual, population, and ecosystem health, thus providing novel risk assessment tools for Baltic Sea stakeholders, including the Marine Strategy Framework Directive, the Helsinki Commission, the International Council of Exploration of the Sea, the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas, and the International Union for Conservation of Nature.

2. Work performed and main achievements since the beginning of the project

Work package 1: Sample and data management. This WP has designed a new sample and database to allow a quick and comprehensive overview on the available specimen samples of Baltic key species including metadata, such as sampling year, location, tissue type and conservation procedure, as well as on data available with regard to the information necessary to work on within the other workpackages. Two comprehensive databases have been compiled, one on the available samples and data among the project members (at the start of the project) and one on de novo food web tracer, contaminant, health and disease biomarker data generated along the course of the BONUS BALTHEALTH project (at the end of the project). Data has been extracted from the databases of the International Council for the Exploration of the Sea (ICES) and the Swedish Environmental Research Institute (IVL), pertaining to mercury (Hg), persistent organic pollutants (POPs) and per-and polyfluoroalkyl substances (PFAS). These have been combined in modelling assessment of population effects and multiple stressor approaches (WP6). Samples from Environmental Specimen Banks (e.g. German environmental specimen bank, the Swedish Natural History Museum, Stockholm, Aarhus University and University of Turku) or other research projects have been exchanged between project partners for chemical analyses (WP3). The data from the project has been uploaded to the BONUS BALTHEALTH EPPS webpage as a Meta-database including the output of all the projects workpackages.

Work package 2: Food web dynamics. This workpackage of BONUS BALTHEALTH project have worked on constructing a conceptual food web model, including characteristic Baltic benthic and pelagic food chains, for each of four core regions in the Baltic. The conceptual model started by identifying key species of ecological, economic and cultural importance, which required the compilation of the current-state of knowledge on Baltic food web compositions. This effort resulted in the delivered report, as well as in publication several papers already. A review paper has been conducted on seal diet, synthesising previously published as well as newly generated data on the diet of harbour, grey and ringed seals within the greater Baltic Sea and ultimately having delivered a database on Baltic seal diet. A study of ringed seals was published by BONUS BALTHEALTH where a connection between food quality and quantity and body condition of ringed seals was found in the Gulf of Bothnia. Another paper of Baltic food web was published on reproductive rate of a top predator, the grey seal, as an indicator of the changes in the Baltic food web. This article documented how zooplankton biomass and plankton size, as well as cod abundance, affected sprat and herring

quality, which, in turn, was positively related to body condition of grey seal females. Body condition of females and their birth rate were also positively correlated. Another paper from BONUS BALTHEALTH on "Delayed effects of pup environment on adult size and reproductive rate of Baltic grey seals" was published. This article documented a positive relation between food quality at the birth year of grey seal males and their adult size. A negative relation between winter temperature at the birth year of grey seal females and their birth rate later in their lives was also found. Five decades of food web tracer data for the feeding origin and trophic position of a key Baltic contaminant biomonitoring species, the white-tailed eagle was generated under BONUS BALTHEALTH, in order to support several time series of a wide range of contaminants. A detailed investigation of food web dynamics in the Baltic Proper was carried out using newly collected samples from the Archipelago Sea in order to support investigations of Hg, POP and PFAS dynamics from zooplankton up to avian and marine mammal predators. Also a detailed investigation of the historical record of fish stock dynamics and consumption by humans, seals and birds was performed, uncovering changing food web dynamics from the 1920s up to the present day.

Work package 3: Anthropogenic hazardous substances. BONUS BALTHEALTH has compiled the state-of-the-science knowledge on the exposure of key ecological and commercial species in the Baltic to both restricted man-made contaminants. This effort included a focus on wide range of legacy contaminants, amongst which Mercury, polychlorinated biphenyls, organochlorine pesticides, polybrominated diphenyl ethers, hexabromocyclododecanes and per- and polyfluoroalkyl substances, as well as on emerging ones, such as new brominated, chlorinated and organophosphorus flame retardants, short-, medium- and long-chain chlorinated paraffins, and a suite of new fluoroalkyl susbtances. The physicochemical properties as well production volumes for these compounds have been compiled in a database showing a large bias towards the unrestricted compounds. For this reason, a comprehensive effort was undertaken to analyse tissues of species of long-term biomonitoring importance for the above mentioned emerging compounds, and in addition screen for compounds currently not identified as contaminants but certainly having the potential to be. Finally, responding to the identified knowledge gaps, intensive efforts have started to generate contaminant exposure data for several Baltic populations of the avian species and their food chains. Five decades of exposure data of a key Baltic contaminant biomonitoring species, the white-tailed eagle, was generated for a wide range of contaminants, including Hg, POPs and PFAS. In three scientific papers BONUS BALTHEALTH showed how top predators of the Baltic Sea still carry a high burden of legacy contaminants, which are still believed to impose health impacts, while at the same time some emerging contaminants are on the rise. White-tailed eagle and great cormorant chicks were also sampled to test their capacity as spatial sentinels of environmental contamination, among these hotspots for metal leaching from sulphate-soils, as well as Baltic-wide hotspots for Hg and PFAS. The results show that use of these nestlings is promising to investigate large-scale patterns of these contaminants. Eider duck females and their blue mussel food were sampled for POPs from their breeding grounds along coastal Gulf of Finland, Archipelago Sea and Sea of Bothnia as well as from wintering grounds in Danish waters. As high burden of certain POPs have been reported from breeding ducks in Gulf of Finland, this study will expand on the spatial extent of contamination as well as differentiate between POPs captured while staying in wintering vs. breeding regions. A detailed investigation of food web dynamics of Hg in the Baltic Proper was carried out, determining Hg concentrations from zooplankton up to avian and marine mammal predators. While very low concentrations were observed at lower trophic levels, i.e. fish and their prey, the long lifespan of avian and especially marine mammal top predators seem to result in high levels up, i.e. elevated by several magnitudes. This initial investigation is currently extended to POPs and PFAS. A wide range of emerging contaminants, i.e. chlorinated paraffins (CPs), chlorinated, brominated and organophosphate ester-based flame retardants (CFRs, BFRs, OPEs), and novel PFAS (nPFAS), were screened by BONUS BALTHEALTH for in key species (invertebrates, fish, seabirds, predatory birds, marine mammals) along the Baltic food web. This screening shows they are widely present as well as indications of biomagnification (increasing levels along the food chain) for many. Concentrations of some emerging contaminants are similar as those for legacy POPs in some species. This initial screening is currently further investigated for its temporal perspective. Finally an easy-to-use experimental workflow for non-selective extraction, purification (lipid removal), and non-target GC-MS analysis of biological samples to identify a wide range of biomagnifying lipophilic organic contaminants in the top consumers of the Baltic ecosystem was established by BONUS BALTHEALTH. The experimental workflow was complemented with an appropriate data processing workflow. With the help of these two workflows, the relative biomagnification factors (BMFs) of the contaminants in the species of the food webs in the Baltic Sea were estimated.

Work package 4: Health and biomarkers. Multiple field campaigns on birds and mammals have been conducted to

assess contaminant exposure and health endpoints throughout the Baltic i.e. from Western Danish Belts to Northern Gulf of Bothnia including Finland and Sweden. BONUS BALTHEALTH analysed parasite burdens, health, egg viability and contaminant exposure of common eiders in three colonies in the Western Baltic. BONUS BALTHEALTH showed how exposure and health biomarkers have evolved in a historic perspective in multiple species including marine mammals, seabirds and white-tailed eagles. BONUS BALTHEALTH also showed how bone mineral density and bone pathology have changed over the last century. There are still pathoanatomical changes related to stress and exposure to POPs both natural fluctuations, gender related and polychlorinated biphenyl (PCB) levels affect bone mineral density. BONUS BALTHEALTH also investigated the prevalence of liver lesions in Baltic grey seals between 1981-2015. The study showed that age was an important factor for the development of liver lesions but PCBs burden may be an influencing factor. This agrees with previous studies of marine mammals in the Baltic as well as in the Arctic. In conclusion, the age of the animals as well as exposure to PCBs needs to be taken into account when understanding and evaluating the current health status of Baltic grey seals.

Work package 5: Infectious diseases. Sub serotypes of aviary influenza for H5/H7 is ongoing with the German partner. As much as 750 samples is currently being analysed and that will still take another 4-6 month. The initial data showed that 1% of the eagles (chicks, both males and females), 47% of the pink-feeted geese (all ages and sex) and 56% of the eiders (all adult females) were seropositive. In addition, endoparasites of adult breeding eider females has been investigated showing high burdens during incubation. In addition, acantocephalan parasites, flukes a.o. parasites have been analysed in eiders and in marine mammals showing high numbers. Likewise, PDV genomes have been analysed and bacterial antibiotic resistance assessed. Regarding human exposure to diseases, the emergence of avian influenza prevalence in the serological analyses of geese, white-tailed eagles and eiders clearly show that almost 30-45% of the eiders and geese have been in contact with the pathogen, which may then be transferred to humans (hunters, researchers etc.). In addition, the parasite *Pseudamphistomum truncatum* that has been found in both Baltic seals and eiders have caused concern about the zoonotic potential of this and hunters and biologist are likely to be at risk when handling these species. In addition, seals are seropositive for Brucella spp., which is also a zoonotic pathogen that must be taken into account when handling live animals as well as stranded or by-caught carcasses. The prevalence of Brucella spp. was compared among Baltic seals and Arctic seals. The results showed that ringed seals in the Baltic ecosystem may be exposed to and possibly infected by Brucella spp. Although our initial screening shows a zoonotic hazard to Baltic locals, a more in-depth epidemiological investigation is needed in order to determine the human risk associated with this. BONUS BALTHEALTH conducted a review on infectious diseases in the Baltic ecosystem focusing on important key species. This showed that the occurring pathogens are zoonotic and thus pose a potential risk for human health. Marine mammal handlers, as well as civilians that by chance encounter marine mammals, need to be aware of this risk. It is therefore important to continue the monitoring of diseases affecting key Baltic species in order to assess their relationship to population dynamics and their potential threat to humans. These infectious agents are valuable indicators of host ecology and can act as bioindicators of distribution, migration, diet and behaviour of marine mammals and birds, as well as of climate change and changes in food web dynamics. In addition, infectious diseases are linked to pollutant exposure, overexploitation, immune suppression and subsequent inflammatory disease. Ultimately, these diseases affect the health of the entire ecosystem and, consequently, ecosystem function and services. As global warming is continuously increasing, the impact of global change on infectious disease patterns is important to monitor in Baltic key species in the future. BONUS BALTHEALTH also reported on infectious diseases in eiders from three colonies in the Baltic ecosystem. It showed that parasites were a significant contribution to energetic stress in eiders and that 50% of the eiders are exposed to avian influenza.

Work package 6: Modelling combined population effects. BONUS BALTHEALTH developed an extremely detailed dynamic energy budget model (DEB) to the Baltic grey seals. The model takes metabolic costs of every developmental stage into account and provides a unique tool to investigate population consequences of new stressors such as pollutants, varying food quality and disease. Several mathematical model for analysing the population level response from anthropogenic stressors were also developed under BONUS BALTHEALTH. The first ever age structured population model to the Baltic harbour porpoise was developed and was able to show haw also low levels of pollutants in combination with by-catch can lead the population to rapid extinction. A realistic metapopulation model with local population sizes and migration rates was likewise developed for the harbour seal population. Here we show that also seemingly stable and large populations are very easy to overexploit by hunting and that the age structure and local population sizes must be taken into account. In addition outbreaks of infectious disease makes this population vulnerable in the long term also if they are abundant in the short term. BONUS BALTHEALTH was also

the first to develop a population effect model on marine mammal top predators. Applying an individual and agent-based model predicted collapses of certain killer whale populations from effects of PCB exposure due to effects on reproduction. This work is highly relevant for other populations of high trophic toothed whales. The model predicted ca. 53% (10 out of 19 populations worldwide) of the global populations to be extinct within 30-100 years including the North Sea population bordering the BONUS water bodies. The Baltic harbour porpoise, ringed seal and grey seal will be used to further evaluate the model. An extensive review assessed a wide range of species, including marine mammals, seabirds, birds of prey, fish and bivalves, to evaluate potential population health risks resulting from contemporary (post-2000) Hg exposure, using novel risk thresholds calculated from both literature and de novo exposure data. The main geographic focus is on the Baltic Sea, though data from the same species in adjacent waters, such as the Greater North Sea and North Atlantic, were included for comparative purposes. High risk category (HRC) and Severe Risk Category (SRC) prevalence for marine mammals, birds, fish and bivalves were 23.0%, 2.7%, 25.0% and 8.0%, respectively. Juveniles from all species showed no or low risk. In comparison to the same species in adjacent waters, i.e. the Greater North Sea and the North Atlantic, the estimated risk for Baltic populations is not considerably higher considering post-2000 exposure levels. These findings suggest that over the past few decades the Baltic Sea has improved considerably with respect to Hg exposure to its local species, while it does still carry a legacy of elevated Hg levels resulting from high industrial and agricultural activity and slow water turnover in the Baltic Basin.

Work package 7 Coordination, communication, education and dissemination Under this workpackage we facilitated the communication and coordination framework to guarantee and facilitate the flow of ideas and results as well as the communication within and among work packages, including a large consortium of 16 partners involving about 30 scientists. The *BONUS BALTHEALTH* website has been regularly updated including the deliverables of the project of which 30 scientific articles have so far been published and are available at the BONUS BALTHEALTH web page (https://projects.au.dk/bonusbalthealth/) and another 16 are underway in a special issue of Environment International a.o. Further dissemination of results and activity updates are communicated using our Facebook and ResearchGate pages. A summer school was conducted in Büsum in September 2019 and a broad public BONUS BALTHEALTH's final workshop was planned in Stockholm, Sweden, 11-12 March 2020. Unfortunately, this meeting had to be cancelled due to the outbreak of the COVID-19 pandemic and was reorganised into a half-day virtual online meeting. However, Cynthia de Wit and Rune Dietz help presentations and participated in the following discussion at Baltic Breakfast on 13 May to replace the Stakeholder event planned during the Stockholm Meeting. During the three years of BONUS BALTHEALTH the project participants participated in more than 130 meetings contributing to regulation, policies and management practices, members or observers in stakeholder committees as well as, international, national and regional stakeholder events and Co-operation activities/partnerships with non-Baltic research actors.

Wider societal implications BONUS BALTHEALTH has taken an active part in the public debate on Baltic Sea environmental issues. Particularly, BONUS BALTHEALTH has stressed the importance of detailed scientific studies of consequences of anthropogenic hazardous substances, diseases and climate change and their effects on the Baltic ecosystems in a large amount of scientific conferences, scientific publications, stakeholder meetings, summer school, teaching and education of students as well as interviews and presentations in TV, radio and online conferences.

The continuity plan of the project

BONUS BALTHEALTH has improved our understanding of spatiotemporal as well as biomagnification and risk effects of man-made contaminants. In addition knowledge has been generated on and food web dynamics of known and unknown man-made pollutants as well as animal-borne diseases which also will initiate new research questions that will be pursued in the future. BONUS BALTHEALTH has established a collaborative network among key partners around the Baltic Sea that will be useful for addressing scientific and environmental policy challenges in the future. In the near future, BONUS BALTHEALTH will:

- Continue the legacy of BONUS BALTHEALTH through scientific publications. A total of 16 manuscripts are currently being compiled in a Special Issue of Environment International, which together with already published papers and manuscripts are in preparation brings the total publications well above 50.
- Key scientists from BONUS BALTHEALTH have drafted a synthesis manuscript for the Special Issue of Environment International.
- BONUS BALTHEALTH partners continue to be involved in stakeholder activities, including HELCOM and ICES

working groups.

- New research initiatives have been developed and applied for at national and multi-national level including EU projects and Nordic Council applications. Some follow-up research projects have already been granted and the fate of other proposal is yet unknown.

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