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The Impossible Sustainability of the Bay of Brest? Fifty Years of Ecosystem Changes, Interdisciplinary Knowledge Construction and Key Questions at the Science-Policy-Community Interface

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In this contribution, the study of the Bay of Brest ecosystem changes over the past 50 years is used to explore the construction of interdisciplinary knowledge and raise key questions that now need to be tackled at the science-policy-communities interface. The Bay of Brest is subject to a combination of several aspects of global change, including excessive nutrient inputs from watersheds and the proliferation of invasive species. These perturbations strongly interact, affecting positively or negatively the ecosystem functioning, with important impacts on human activities. We first relate a cascade of events over these five decades, linking farming activities, nitrogen, and silicon biogeochemical cycles, hydrodynamics of the Bay, the proliferation of an exotic benthic suspension feeder, the development of the Great scallop fisheries and the high biodiversity in maerl beds. The cascade leads to today's situation where toxic phytoplankton blooms become recurrent in the Bay, preventing the fishery of the great scallop and forcing the fishermen community to switch pray and alter the maerl habitat and the benthic biodiversity it hosts, despite the many scientific alerts and the protection of this habitat. In the second section, we relate the construction of the interdisciplinary knowledge without which scientists would never have been able to describe these changes in the Bay. Interdisciplinarity construction is described, first among natural sciences (NS) and then, between natural sciences and human and social sciences (HSS). We finally ask key questions at the science-policy interface regarding this unsustainable trend of the Bay: How is this possible, despite decades of joint work between scientists and fishermen? Is adaptive co-management a sufficient condition for a sustainable management of an ecosystem? How do the different groups (i.e., farmers, fishermen, scientists, environmentalists), with their diverse interests, take charge of this situation? What is the role of power in this difficult transformation to sustainability? Combining natural sciences with political science, anthropology, and the political sociology of science, we hope to improve the contribution of HSS to integrated studies of social-ecological systems, creating the conditions to address these key questions at the science-policy interface to facilitate the transformation of the Bay of Brest ecosystem toward sustainability.

Keywords: sustainability, land-ocean continuum, Bay of Brest, interdisciplinarity, science-policy-community interface

INTRODUCTION

From the first Earth Day in 1970 to the adoption of "sustainable development goals" in September 2015 at the UN Assembly, through the Brundtland Report (Brundtland, 1987) defining it, sustainable development has become a dominant paradigm of environmental public action, from the international level to national and more local scales. Accompanying these policy changes, new scientific fields and initiatives have emerged like the Resilience Alliance (Holling, 2001) or sustainability science (Kates et al., 2001; Kates, 2011), in which the concept of a social-ecological system is central (Liu et al., 2007; Ostrom, 2009; Collins et al., 2010; Binder et al., 2013). Whatever the conceptual diagrams used to reconnect the natural and social templates that have been disconnected in our modern societies, ecosystem services are most often the means to rationalize this reconnection (Daily, 1997; Millennium Ecosystem Assessment, 2005). To complement these trends, major international scientific programs addressing aspects of global change re-organized in 2012 as the Future Earth Initiative, with the aim to provide a single platform about "research for global sustainability." This is supposed to incentivize a more solution-oriented, interdisciplinary (especially between humanities and natural sciences but also with engineering sciences, Matson et al., 2016) and participatory community by involving policy-makers, funders, academics, business and industry, and other sectors of civil society in co-designing and co-producing research agendas.

One mode of social-ecological governance, called adaptive co-management (Armitage et al., 2009; Plummer et al., 2013), illustrates some of the ways knowledge produced by scientific research, experts and professional communities (e.g., fishermen, farmers) and policy-makers are being integrated. Co-management refers to the sharing of power and responsibility among local resource user communities and resource management agencies; the idea of adaptive management refers to the science of learning by doing (see Kofinas, 2009 and references therein). Such a move from science-based decision-making toward adaptive co-management in social-ecological governance is remarkable (see for example, Butler et al., 2015; Schultz et al., 2015), as it engages cultural diversity, integrated knowledge production, power sharing, social and adaptive learning, which in turns involves the integration of monitoring, research and policy making.

Different frameworks have been developed to overcome the difficulties frequently encountered when trying to put inter- or trans-disciplinary and participatory research into practice. Indeed, despite some very interesting success stories, it is important to acknowledge that in many places there are numerous barriers against interdisciplinary and participatory science. For example, Hart et al. (2015) discussed how the role of universities could be strengthened to address sustainability challenges, by requiring strong institutional changes regarding both how research and training are organized in order to overcome "disciplinary silos." "Disciplinary silos" is a figurative term referring to how the one-discipline/one-department structure of most higher education institutions reinforces and rewards single-discipline researchers and impedes inter- or trans-disciplinary initiatives and careers. One could also mention the difficulties in communication across disciplines or in combining scientific and other forms of knowledge (Kueffer et al., 2012; Lang et al., 2012); all these challenges require new frameworks to facilitate sustainability research. It is therefore important to examine how and where interdisciplinary collaborations and participatory science have been constructed, highlighting how barriers, and conflicts have been resolved during the process. The example we will focus on in this contribution concerns the origins of integrated research approaches within a coastal social-ecological system located in the Bay of Brest (northwestern France).

Ecosystems and habitats in coastal zones supply many valuable ecosystem services (recreation, food production, protection against the sea, nutrient cycling, carbon storage…), providing many benefits in terms of welfare and well-being to society (Turner, 2015). At the same time, they are also very vulnerable to anthropogenic environmental changes which are intensified in coastal zones where human populations are increasingly concentrated and where disturbances are driven not only by activities in the immediate area (e.g., fishing, aquaculture, introduction of alien species, waste disposal, coastline modifications, tourism, development of marine renewable energy), but also by activities upstream (inland) such as, agriculture, urbanization, and industrial production. The pace of change in the highly complex and dynamic coastal zones is much faster than what was anticipated a decade ago (Cloern et al., 2015), creating a daunting challenge to manage these areas in a sustainable way. New forms of management are replacing earlier policies driven solely by science, something that has been characterized as "a generally failed experiment" for coastal environments (Christie, 2011). According to Bremer and Glavovic (2013), the "science-policy interface" in the coastal zone should be framed as a "governance setting," reflecting the multiplication of stakeholders involved and the strong need for inter- and trans- disciplinary research in this area.

The Bay of Brest (France) is an example of coastal ecosystem subject to different aspects of global change, i.e., eutrophication, arrival and proliferation of alien species, and climatic trends (Cloern et al., 2015). The bay is considered a relatively well-studied ecosystem, but major environmental problems persist, such as increasing harmful algal blooms (HABs) (Chapelle et al., 2015) and biodiversity losses have become dramatic since the harvesting of the *Venus verrucosa* clam from maerl beds has begun within the bay (Dutertre et al., 2015).

In this article, we first recount the environmental changes observed in the Bay of Brest over the past five decades, focussing on links between eutrophication, the biogeochemical cycle of silicon (Si), the proliferation of invasive species and their combined effects on local fisheries. In the second section of this article, we relate how interdisciplinary collaborations arose amongst the community of researchers involved in studies of the Bay, emphasizing the importance of geographical proximity (Reckers and Hansen, 2015) and also of the creation of "boundary settings" between different research groups (Mollinga, 2010; Mattor et al., 2014) intended to stimulate long-term interactions among scientists from different disciplines, first within Natural Sciences (NS), then together with Human and Social Sciences (HSS). We close with a critical examination of the present-day unsustainable situation and key periods of strong interactions between scientists and communities of fishers and farmers over the last decades, raising a number of questions about the interactions between the scientific community and other policy and user communities involved. It is suggested that answering these questions now requires actively integrating the social sciences of politics (SSP) with environmental studies to facilitate transformations of coastal environments toward sustainability (Mazé et al., 2015, 2017).

THE BAY OF BREST ECOSYSTEM SINCE WWII

Agriculture and Phytoplankton Dynamics

The Bay of Brest has undergone two major anthropogenic perturbations following World War II: one originating from land, and one from the sea. The French government, faced with an urgent need to augment food production in the aftermath of WWII, promoted the widespread use of artificial fertilizers to increase arable land productivity and modernize (i.e., mechanize) farming. The agricultural system in Brittany underwent significant changes during the 1960's, moving toward intensive monoculture farms centered on vegetables and pigs. As a direct consequence, nitrate concentrations greatly increased in rivers and green tides of mainly *Ulvae* sp. developed along many coasts around Brittany. These episodes became a public nuisance and health problem, leading to 30 years of conflicts between environmental non-governmental organizations and the agricultural sector. They have also been the object of contentious exchanges between the French government and the European Commission in Brussels. In the Bay of Brest, nitrate concentrations in the Aulne and Elorn rivers doubled between the 1970's and the 1990's (Le Pape et al., 1996) reaching concentrations of up to 700 μM, which is more than five times the good water quality threshold defined by the European Water Framework Directive. However, because of the decoupling between nitrogen inputs (winter and spring) and the temperature optimum for the development of the macroalgae *Ulvae* sp. (summer), which leads to the export of 94% of dissolved inorganic nitrogen to coastal waters before spring (Le Pape et al., 1996), and because of the macrotidal character of the bay, these nitrate concentrations did not generate important green tides in the Bay of Brest, except for very localized areas near the mouth of the Elorn River (Le Pape and Menesguen, 1997).

Instead, the indirect consequences of increasing land-derived nitrogen (N) and phosphorus (P) inputs occur through the silicon (Si) cycle. Silicon arrives in the aquatic environment mostly in the form of dissolved silicic acid (dSi), following the natural weathering of silicate rocks (Meybeck, 1982), and as amorphous silica (Conley, 1997), which can also be perturbed by anthropogenic processes (see review in Ragueneau et al., 2010). Constant Si inputs, associated with increasing N and P loads from human activities inland, have decreased Si:N and Si:P ratios in rivers, affecting phytoplankton dynamics in the receiving coastal waters (Officer and Ryther, 1980; Ragueneau et al., 1994, 2010; Billen and Garnier, 2007). Since the review of Smayda (1990), documenting several examples of similar decreasing nutrient ratios, many regions around the world have experienced switches from a diatom-based primary production to a primary production dominated by other phytoplankton groups, e.g., dinoflagellates, which include many toxic species (Conley et al., 1993; Ragueneau et al., 2006a,b and references therein). However, the Bay of Brest did not exhibit dramatic phytoplankton community shifts, despite strong decreases in the Si:N and Si:P ratios, well below the Redfield (1958) or Brzezinski (1985) ratios for diatoms growing under nutrient-rich conditions (Del Amo et al., 1997).

Explanations for the absence of such shifts were provided in the mid 1990's. The intensity of Si recycling both at the sediment-water interface and in the water column (Ragueneau et al., 1994; Beucher et al., 2004) modifies the properties of various diatom species (Roberts et al., 2003). For instance, their degree of silicification (Rousseau et al., 2002) ultimately favors the switch from diatom to non-diatom species when the dSi stress becomes too strong. The combination of Si recycling and macrotidal regime provided a reasonable explanation (Ragueneau et al., 1996) to account for the maintenance of the diatom succession observed throughout spring and summer since the 1980's (Quéguiner, 1982; Del Amo et al., 1997). And this was despite the apparent lack of dSi following the first spring diatom bloom (direct and indirect evidence of dSi limitation is discussed in Del Amo et al., 1997 and Ragueneau et al., 2002). It was proposed at that time that the Bay of Brest sediments could represent a coastal silicate pump (Del Amo et al., 1997), because they retain dSi within the ecosystem, allowing the dSi replenishment of coastal waters following the summer temperature increase and subsequent intensification of Si recycling at the sediment-water interface. As we shall see, the motor of that pump was biologically driven and had to do with the proliferation of a benthic invader in the bay environment.

Proliferation of Invasive Species and Environmental Impacts on the Ecosystem

In parallel with these increasing land-derived N and P concentrations and fluxes, the Bay of Brest experienced several introductions of non-indigenous species following WWII, including macroalgae (*Gracilaria vermiculophylla*), halophytes (*Spartina alterniflora*) and benthic mollusks such as the Pacific oyster *Crassostrea gigas* and the American slipper limpet *Crepidula fornicata* (see review in Stiger-Pouvreau and Thouzeau, 2015). Aquaculture practices and expanding international shipping both increase the opportunities for the translocation of fauna and flora (Carlton and Geller, 1993). Proliferation of introduced species has become a major issue in many areas with unanticipated linkages between terrestrial and marine components of coastal ecosystems being exposed (Van der Wal et al., 2008). Here, we will focus on the effects of one of these introduced species in the bay, the slipper limpet, *Crepidula fornicata* (**Figure 1**), because of its role in the silicate pump (Del Amo et al., 1997). *C. fornicata* is a filter-feeder that proliferates in bay and estuarine environments, and can reach several thousands of individuals per square meter because adults attach to each other in "chains" creating dense accumulations on the seafloor (Blanchard, 2009). *C. fornicata* arrived in the Bay of Brest in 1949; the invasion then progressed from south to north and there was a sharp increase in abundance between 1995 and 2000 when the estimated standing stocks increased by a factor of four (Guérin, 2004; Stiger-Pouvreau and Thouzeau, 2015).

Through these accumulations, the engineer gastropod modifies its local environment by adding new physical and biological substrates and modifying local hydrodynamics along with rates of particle erosion and sedimentation at the sediment-water interface (Moulin et al., 2007). Although suspension feeders have dominated benthic communities in the bay (Hily, 1984; Jean and Thouzeau, 1995; Grall and Glémarec, 1997), *C. fornicata* became the main suspension feeder by 2,000 (97% of total suspension feeder biomass; Thouzeau et al., 2000). Active filter feeders like *C. fornicata* produce a fraction of non-ingested material which is excreted and accumulates at the sediment surface as pseudo-feces (Norkko et al., 2001). This leads to local deposition rates that can exceed passive sedimentation rates in high density filter feeder beds (Dame, 1993), and creates carbon (C) and N enriched sediments (Kautsky and Evans, 1987).

In the Bay of Brest, the impacts of *C. fornicata* on hydrodynamics and transport properties of the benthic boundary layer (Moulin et al., 2007), as well as on benthic biodiversity, demonstrated a gradual shift toward smaller species with a higher turnover rate (Grall and Glémarec, 1997). Locally, biodiversity increased as new microhabitats for other benthic sessile and mobile fauna were created (Chauvaud et al., 2000); but at the scale of the entire bay, *C. fornicata* carpeted parts of the seafloor, homogenizing benthic surfaces, endangering the total biodiversity of the ecosystem (Chauvaud, 1998). It competed for space with the Great Scallop (**Figure 1**) (*Pecten maximus;* Thouzeau et al., 2000*)*, threatening other economically important bivalve fisheries in the region (Frésard and Boncoeur, 2006).

Proliferation of *C. fornicata* and the Silicate Pump Hypothesis

The effects of this shift were studied on the benthic community respiration (Martin et al., 2006, 2007), as well as on the benthic cycling of carbon and several associated biogenic elements, such as N (Martin, 2005; Martin et al., 2006), P (Martin, 2005) and Si (Ragueneau et al., 2002). Combining the importance of Si recycling at the sediment-water interface in the maintenance of diatom blooms (silicate pump) with the major role being played by *C. fornicata* in the recycling of nutrients in the bay, Chauvaud et al. (2000) formulated a working hypothesis (**Figure 2**) about the possible effects of this combination on the ecosystem: when the silicate pump (mostly driven by *C. fornicata*) is active, filtration and biodeposition by benthic suspension feeders would lead to Si retention as Si-enriched sediment deposits. Then, dissolution would continuously replenish overlying surface waters with dSi, allowing diatom succession to take place even in summer. In contrast, when hydroclimatic conditions limit the filtration and biodeposition of benthic suspension feeders (e.g., because of excessive microalgal biomass, high sedimentation, gill clogging and/or hypoxia), Si would be exported out of the Bay, leading to dSi limitation and non-siliceous phytoplankton species during summer (see Chauvaud et al., 2000).

In the decade following the latter article, this hypothesis was tested extensively. Sediment core incubations (Ragueneau et al., 2002) and the deployment of benthic chambers (Martin, 2005) at sites exhibiting low and high densities of *C. fornicata* provided direct evidence of the role played by this organism in nutrient recycling - in particular for dSi. In addition, as this gastropod has no Si requirement, the feces became enriched in Si relative to C and other nutrients, reinforcing the silicate pump mechanism (Ragueneau et al., 2005). Silicon biogeochemical budgets were established at seasonal and annual scales (Ragueneau et al., 2002, 2005), clearly demonstrating the importance played by benthic recycling for diatom growth, particularly during summer. The feedback of enhanced benthic nutrient fluxes on phytoplankton dynamics was then studied with mesocosm experiments (Fouillaron et al., 2007; Claquin et al., 2010) and modeling (Laruelle et al., 2009). The dynamic 2-dimensional physical and biological model included an explicit representation of the benthic-pelagic coupling with *C. fornicata*. The model was used to simulate the effects of removing this gastropod on the ecosystem functioning because the local fishery committee had suggested this to reduce the pressure on the scallop stock (see section Construction of a Basis for Interdisciplinary Knowledge About the Bay of Brest). The modeling suggested that removal of *C. fornicata* would increase the probability for the development of HABs due to a dSi limitation during summer.

What Is the Present State of the Bay of Brest?

HABs have taken place in the Bay of Brest on some occasions but, as mentioned before, this ecosystem has long resisted to the development of dinoflagellate blooms. Since 2012 however, their frequency and magnitude have been increasing: HABs take place every summer in the Bay of Brest, mostly in its

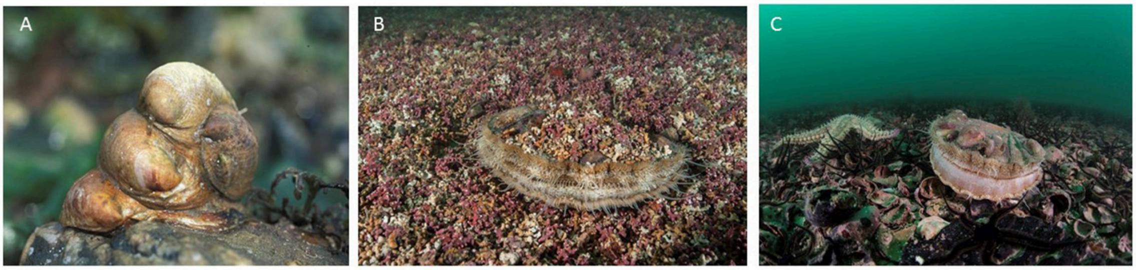

FIGURE 1 | Images of *Crepidula fornicata* **(A)**, of *Pecten maximus,* the Great Scallop **(B)** and of competition for space between those two benthic suspension feeders **(C)**.

southern part with *Alexandrium minutum* (Chapelle et al., 2015). Many processes may contribute to the development of toxic phytoplankton blooms e.g., temperature, tides and the hydrodynamic regime, inorganic nutrients ratios, ratio between organic and inorganic nitrogen (Roberts et al., 2003; Chapelle et al., 2015), and it is difficult to attribute their occurrence to a single cause. Nonetheless, strong decreases in the total biomass of *C. fornicata* have also been reported in the central and southern basins of the bay based on extensive surveys conducted in 2013/2014 (data of A. Carlier as cited in Stiger-Pouvreau and Thouzeau, 2015). Whatever the precise reasons for this decline (which remain to be determined, see section Key questions at the science-policy-community interfaces), it provides plausible evidence for the silicate pump/*C. fornicata* hypothesis proposed in Chauvaud et al. (2000) and agrees with the development of HABs predicted during the modeling exercise, especially dinoflagellates which do not require Si (Laruelle et al., 2009).

The increasing frequency and magnitude of HABs in the Bay of Brest have many implications, especially for the lifecycle of benthic suspension feeders and the benthic ecosystem as a whole (Fabioux et al., 2015; Coquereau et al, 2017). Some benthic organisms, including those of commercial interest, accumulate toxins secreted by these microalgae preventing them from being sold (Belin et al., 2013). In the Bay of Brest, the *P. maximus* fishery has suffered greatly from this type of contamination. Detoxification is longer for the Great Scallop than for other bivalves, and the fishing community has had to find replacement species to maintain the Bay's fishery. One of those replacements has been the clam *V. verrucosa,* which is collected with dredges from the maerl beds of the southern basin (Pantalos, 2015). Maerl beds (**Figure 3**), including those of the Bay of Brest, have a high ecological importance and conservation value (Grall and Hall-Spencer, 2003). They are unique areas because of their high biodiversity, their role as a nursery for targeted species of fish and the Great Scallop, and the role of the bivalves living on/in maerl beds that serve as brood stock for the surrounding areas. Maerl beds are also commercially valuable as their calcium carbonate makes them an excellent soil amendment and waste-water filter. As noted by Pantalos (2015), maerl extraction is mostly a thing of the past in Europe and has been banned since January 1st 2013 under the European Union Habitats Directive (92/43/EEC; 1992 May 21). But both dredging and trawling continue in some regions of the world, despite numerous calls for protection in scientific publications (e.g., Hall-Spencer et al., 2003), and despite the laws and directives already enacted that apply specifically to maerl beds (Amice et al., 2007). This is the case in the Bay of Brest (**Figure 3**), where recurrent dredging activities have affected 50% of the maerl banks (Grall et al., 2009).

To summarize this first section dedicated to the study of the Bay of Brest ecosystem changes over the last 50 years, we have constructed a schematic diagram, or sequence, of this chain of events (**Figure 4**), that will help guide us in the last section Key questions at the science-policy-community interfaces as we ask important questions related to the social-ecological system. The ecosystem apparently initially absorbed the excessive N and P inputs from land, and resisted decreasing Si:N and Si:P ratios, maintaining diatoms in the system probably due to a very active silicate pump. However, if the pelagic ecosystem seemed to remain relatively unchanged, the less visible benthic ecosystem was experiencing important modifications due to high population abundances of *C. fornicata*. While this species' abundance was having negative impacts on the Bay's biodiversity and causing trouble to the Great Scallop fishing community to the point that they wanted to eradicate it by the mid 2000's (see section Construction of a Basis for Interdisciplinary Knowledge About the Bay of Brest), it was also suggested that the presence of *C. fornicata* was helping maintain diatoms in the ecosystem, through its impact on the Si biogeochemical cycle (**Figure 2**) and possibly preventing or slowing down the development of HABs. Following the unexplained drastic diminution of *C. fornicata* abundances in the Bay, HABs have started to develop. Even if this is consistent with the silicate pump/*C. fornicata* hypothesis, it has had important ecological and socio-economic consequences, such as the on-going destruction of the Bay's maerl banks as the fishermen community switched prey and started dredging for *V. verrucosa*.

Obviously, the Bay of Brest is not following a sustainable path, despite decades of strong interdisciplinary studies of the ecosystem and regular interactions between scientists and

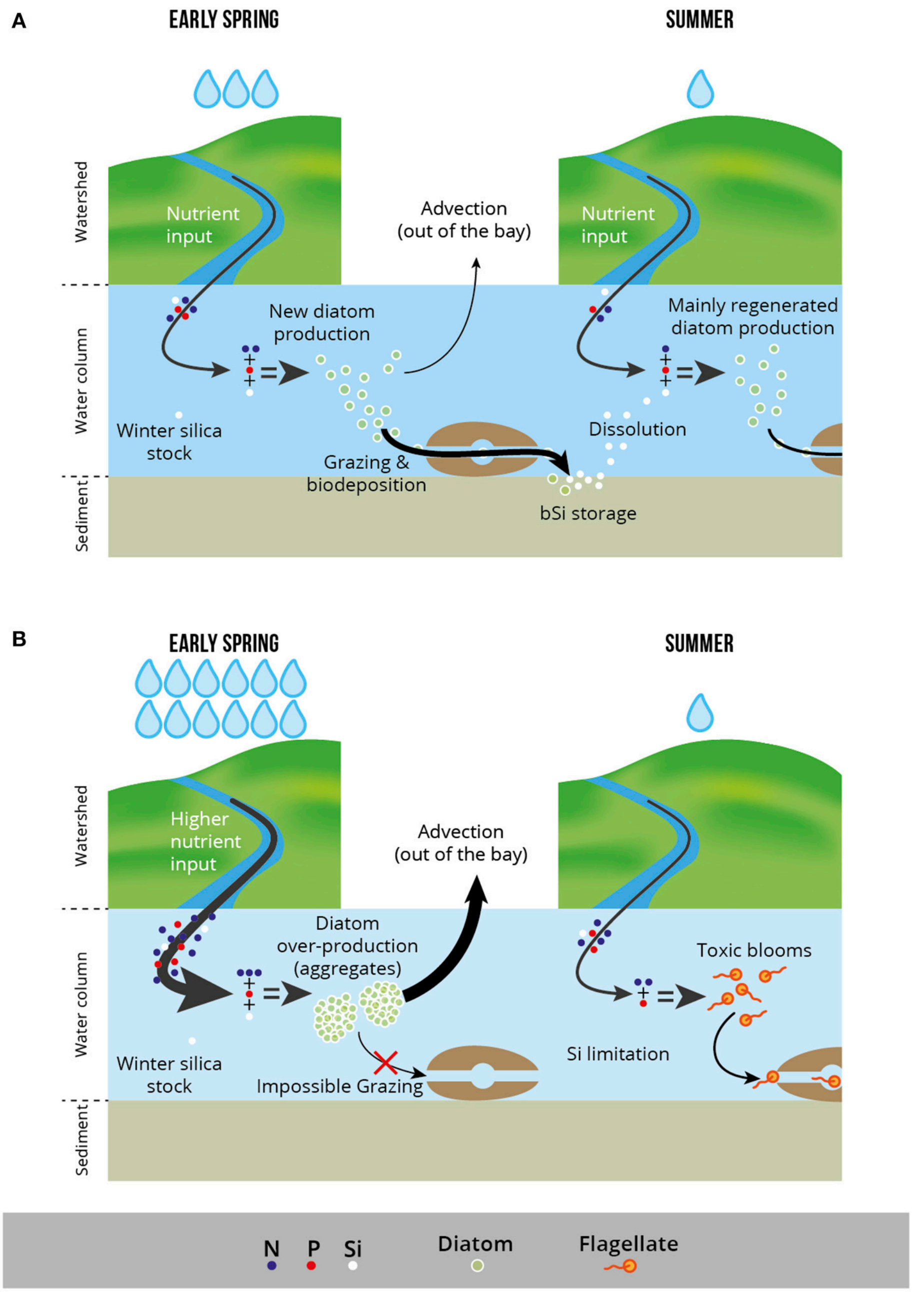

FIGURE 2 | The Crepidula/Si working hypothesis (redrawn from Chauvaud et al., 2000). Two contrasting situations are displayed. On top **(A)**, under "normal" climatic conditions, the diatom spring production is being grazed by benthic suspension feeders, dominated by *Crepidula*; the Si is being stored in the sediment and slowly released as silicic acid during summer, allowing the maintenance of diatoms in the system. At the bottom **(B)**, the spring diatom production cannot be grazed and most of the diatom production is exported out of the Bay, depleting the system in silicic acid and favoring a summer production of dinoflagellates. In this figure, reasons for the impossible grazing are linked to excessive nutrient inputs under heavy rains, and the formation of diatom aggregates, that sediment massively to the bottom and cannot be as easily grazed. Other situations may lead to the prevention of such grazing and biodeposition activities. See text for more details.

communities of farmers and fishers. This raises important questions at the science-community and science-policy interfaces, as we discuss in the last section of this contribution (III). Before that (II), we examine how the interdisciplinary knowledge necessary to understand the ecosystem changes and present the cascade of events (**Figure 4**) was built, first in natural sciences studies of ecosystem complexity; we then show how social scientists have entered into collaborative research programs with NS during the last 10 years to start addressing questions raised concerning the sustainability of the social-ecological system of the Bay of Brest.

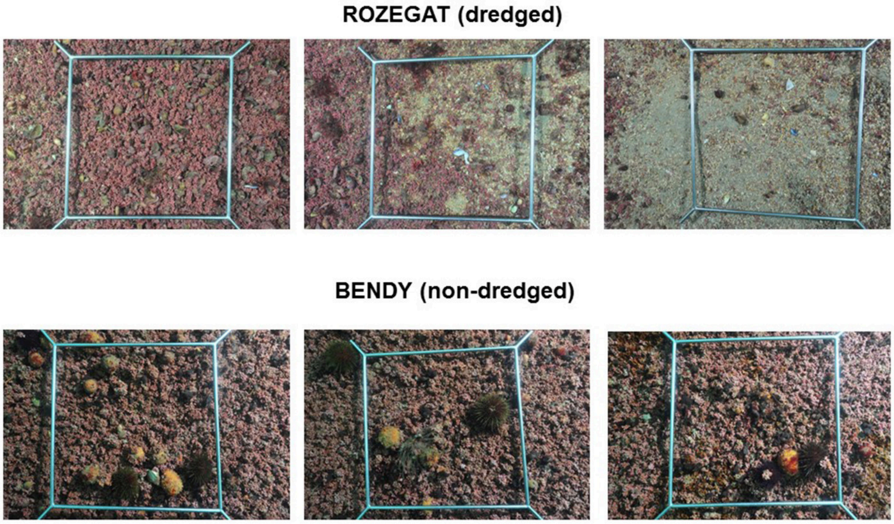

FIGURE 3 | Photographs of 0.1 m^2 quadrats taken on the fished maerl bed (Rozegat) and on the unfished maerl bed (Bendy) in March 2011. Note the differences in habitat structure, live maerl distribution as well as in the presence or absence of associated benthic megafauna.

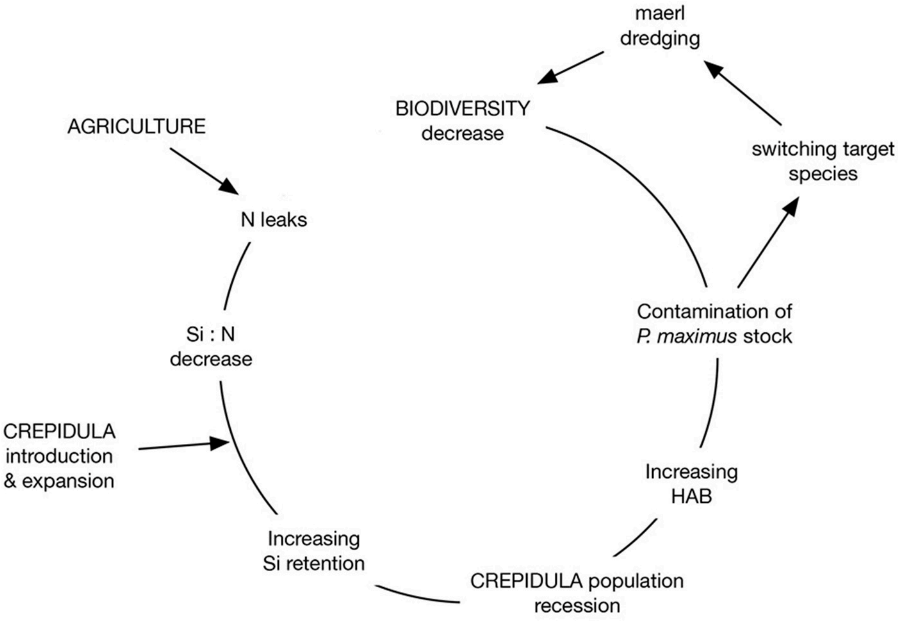

FIGURE 4 | Schematic description of a cascade of events over the last 50 years in the Bay of Brest, from changes in agricultural practices after world war II to present-day threats on biodiversity, including interactions between changing nutrient ratios and the proliferation of *Crepidula fornicata* (see text) and their impacts on the Great Scallop fishery.

CONSTRUCTION OF A BASIS FOR INTERDISCIPLINARY KNOWLEDGE ABOUT THE BAY OF BREST

All the studies described above were led by groups associated with research infrastructures in the Brest region, in particular with the IUEM (*Institut Universitaire Européen de la Mer*, a component of the *Université de Bretagne Occidentale* or 'UBO') and the IFREMER which conducts research on the exploitation of marine resources. We review in the next paragraphs how geographical proximity led to the emergence of interdisciplinary approaches to the environmental issues faced by the larger community discussed earlier. From a science studies viewpoint, it is important to distinguish two main periods: before and after the creation of the IUEM in 1997. Relating the circumstances of the origin of this structure contributes to an on-going debate as to whether interdisciplinarity is orchestrated by funding agencies (Kwa, 2006), is a bottom-up process and "unlikely to be successfully planned" (Rosenberg, 2009), or a combination of both.

When Pelagic and Benthic Scientists First Meet

During the late 1970's and the 1980's, researchers in the pelagic and benthic realms were working almost independently in three different laboratories of UBO. Within the laboratory of chemical oceanography, under the leadership of Paul Tréguer, Professor of biogeochemistry, a group of physical, biogeochemical and biological oceanographers worked on biogeochemical cycles. This group developed a strong expertise on the Si biogeochemical cycle (Tréguer et al., 1995; Ragueneau et al., 2000), due to the importance of this element for the growth of diatoms and the role of diatoms in the functioning of coastal ecosystems (Ragueneau et al., 2006a,b) and in the austral biological pump (Pondaven et al., 2000). Taken altogether, the work produced by this group between 1980 and 2000 provided a description of the pelagic nutrients (Si, N, P) cycles and their relationships with phytoplankton dynamics in rivers, the bay and the adjacent Iroise Sea; it also provided empirical evidence of the benthic-pelagic coupling in the Bay of Brest (Ragueneau et al., 1994, 1996), that led to the suggestion of a coastal silicate pump as a major player in the resistance of the bay to the effects of decreasing Si:N and Si:P ratios (Del Amo et al., 1997).

At UBO, benthic marine biologists were spread between two laboratories: the laboratory of biological oceanography (head, Professor Michel Glémarec) and the laboratory of marine biology (head, Professor Albert Lucas). The most prominent research topic of this group initially concerned marine bivalve aquaculture, and in particular, they accomplished the first successful reproduction and larval rearing of *P. maximus*. By the early 1980's, the group was working on population ecology, larval recruitment, genetics and pathogens. For example, studies were undertaken to characterize, both qualitatively and quantitatively, the benthic macro- and mega-fauna of soft bottom sediments, the importance of benthic biodiversity and the role of hydrological conditions in determining spatial distributions. In addition, the functional roles of benthic species began to be investigated; this includes examining how benthic and pelagic systems were coupled (Hily, 1989; Jean and Thouzeau, 1995) and led to a renewed interest in the role of suspension feeders and their potential influence on phytoplankton biomass by the end of the 1990's (Grall and Glémarec, 1997).

By 1992, the three laboratories were already united under a single name ("*Flux de matière et réponses du vivant*") and led by Prof. Tréguer, but biogeochemists and benthic biologists remained in different buildings. New interactions between pelagic and benthic researchers appeared, such as the official opportunities during quarterly meetings of the "Laboratory Council," as well as additional chances for informal ones during shared cruises on the small research vessel (RV "*Sainte Anne,*" IFREMER). However, these interactions could probably not be characterized as co-construction of scientific questions, but they did contribute to pave the way for the creation of IUEM by the mid-1990's leaded by Prof. Tréguer. When the IUEM building was completed in 1997, the laboratory was renamed "*Laboratoire des sciences de l'environnement marin*" (LEMAR) and installed on one corridor, greatly increasing the opportunities for interdisciplinary exchange. These exchanges occurred both formally (e.g., organization of joint seminars, creation of annual laboratory meetings ("*Les Journées du LEMAR,*" 2001 - present) as well as informally through more regular discussions and debates. It is at this time that the Si/*C. fornicata* working hypothesis emerged.

Origin of the Silicate Pump/*C. fornicata* Hypothesis

Pelagic scientists had looked at the sediment-water interface as a means of replenishing surface waters with nutrients for phytoplankton growth. They suggested the possibility of an active silicate pump that could maintain the diatom populations within the ecosystem (Del Amo et al., 1997). At the same time, benthic scientists looked at pelagic waters and phytoplankton as environmental conditions and food resource influencing the physiology and life cycle of benthic mollusks and ecosystems. They aimed to calibrate shell growth parameters (Guarini et al., 2011) as proxies for environmental variables such as temperature (Chauvaud et al., 2005) or phytoplankton blooms (Lorrain et al., 2000).

Hence, several observations from benthic and pelagic studies led to the formulation of the Si/*C. fornicata* hypothesis. First, if the integrated chlorophyll *a* (Chl-*a*) concentrations did not exhibit major changes during the 1980's and 1990's, phytoplankton bloom compositions did evolve (Nézan et al., 2010, see Chauvaud et al., 2000, Figure 9) and the seasonality index dramatically decreased over the same period: the Chl-*a* annual cycle moved from a typical pattern characterized by a strong first spring bloom and small summer peaks to a succession of higher-frequency but smaller-amplitude blooms over the productive period (Chauvaud et al., 2000). Secondly, the shell daily growth rates of year 1 (1994) and year 2 (1995) cohorts of *P. maximus* exhibited strikingly different patterns between 1994 and 1995, with major growth "accidents" (rate decreases) occurring not only following summer toxic phytoplankton blooms, but also slightly earlier when the spring diatom bloom material sedimented (Chauvaud et al., 1998). The Si/*C. fornicata* hypothesis emerged from the observation of these curves of *P. maximus* shell daily growth rates and the numerous discussions of benthic biologists with phytoplankton experts and biogeochemists, that were facilitated by the new daily interactions among researchers (Chauvaud et al., 2000). The publication of this paper stimulated many studies in the following years, designed to test this hypothesis using experiments (Ragueneau et al., 2002), biogeochemical budgets (Ragueneau et al., 2005), or modeling (Laruelle et al., 2009) and all these studies involved both pelagic and benthic scientists, biogeochemists and benthic ecologists.

We suggest that the construction of the institute "IUEM" represents a good example of the importance of proximity to overcoming barriers to interdisciplinarity. Surprisingly, as noted by Reckers and Hansen (2015), few contributions in the literature on interdisciplinarity have so far analyzed these processes of knowledge construction through the lens of geographical proximity (see Lee et al., 2010, for exception). As such, the IUEM building itself constituted a boundary setting in the sense of Mattor et al. (2014) for the LEMAR laboratory, favoring the daily meeting of scientists from different disciplines and stimulating the emergence of the working hypothesis and the interdisciplinary studies that have been conducted in the 2000's to test it. Clearly, interactions did exist before IUEM, but uniting all the research groups under one roof, increased the opportunities for exchange. As we shall see, the same is presently happening concerning the inclusion of humanities researchers at IUEM today.

The Humanities Enter the Game

The interactions between natural sciences and the humanities around the proliferation of non-indigenous species in the Bay of Brest and eutrophication have become more apparent in the last decade. In the early 2000's, more interaction was stimulated by requests for information from the scallop fishing community facing the effects of the proliferation of *C. fornicata* (see section Construction of a Basis for Interdisciplinary Knowledge About the Bay of Brest). The extremely high abundances of *C. fornicata* were threatening the sustainability of a scallop restocking program started in the early 1980s, through direct (scallop shell scrapping) and indirect (competition for space) effects (Frésard and Boncoeur, 2006). The fishermen needed an economic evaluation for a containment project intended to make the restocking program consistent with the presence of the exotic species, which led to funding a Ph.D. project (Frésard, 2008, under the supervision of an economist, J. Boncoeur, AMURE laboratory "Centre de droit et d'économie de la mer"). Interactions were also encouraged by the French Ministry of the Environment which launched the national INVABIO program (INVAsions BIOlogiques, first call for proposals in February 2000) to fund more humanities-oriented research on non-indigenous species (Dalla Bernardina, 2010). In Brest, two INVABIO projects were funded (2001–2005) to explore the impacts of *C. fornicata* proliferation and its possible containment on the benthic ecosystem (INVABIO I, Coordinator: G. Thouzeau, LEMAR) and on the pelagic ecosystem (INVABIO II, Coordinator: A. Leynaert, LEMAR). Both projects included socio-economic and ethnological components.

These projects yielded important information published separately by the different scientific communities. In the Bay of Brest, the objectives of INVABIO I were to quantify: (1) the impact of small-scale *C. fornicata* removal by dredging on ecosystem functioning (Martin, 2005); (2) the potential changes in predator-prey interactions due to *C. fornicata* and starfish proliferations; and (3) the economic cost and socio-anthropological perception of the invasion (sustainable management). The INVABIO I project was about the restocking of the areas cleaned of slipper limpets with *P. maximus* juveniles (3-cm shell height). The overall cost of the 5-year project was estimated at 3.05 M Euros in the early 2000's. In the end, only the third objective of the INVABIO I project, which also benefited from INVABIO II funding, was fulfilled (Frésard and Boncoeur, 2006), as the local fishermen committee did not get the EU and French funding required for the dredging and restocking operations, for reasons that remain to be understood (cf section Construction of a Basis for Interdisciplinary Knowledge About the Bay of Brest). In the INVABIO II project, the impacts of further proliferation or containment of *C. fornicata* proliferation on phytoplankton dynamics was studied in mesocosm experiments (Fouillaron et al., 2007; Claquin et al., 2010). The costs and benefits analysis published by Frésard and Boncoeur (2006) demonstrated the major importance of indirect effects (competition for space) of the non-indigenous species on the scallop fishery and the importance of combining scallop restocking and local control of the invasion, which could reduce by half the cost of the latter. From an ethnological perspective, another study clearly demonstrated that problems created by non-indigenous species were poorly known by the public, which constitutes a strong impediment to putting in place sustainable management programs for the Bay (Chlous, 2014).

If the inclusion of economists in such programs was expected, the inclusion of an ethnologist was more original. As noted by Menozzi and Pellegrini (2012), the expectation of such sociological studies is related to the perception and representations of biological invasions by different categories of stakeholders as well as to the acceptability of different management options. The aim was then to produce knowledge on human-nature relationships and stimulate thinking about the different ways to manage such invasions (Dalla Bernardina, 2010). Unfortunately, several factors contributed to a clear lack of interactions between the ethnologist and the biologists, according to Chlous (2014), related to the fact that the ethnologist was associated only during the last stages of the proposal writing and that her scientific concerns were poorly taken into account. Indeed, there is a persistent criticism that humanities are being used as window dressing by natural scientists. At the same time, humanities scholars are sometimes reluctant to dive into projects driven by natural sciences. This is a common discussion topic in interdisciplinary projects, including how trust is built between two or more academic communities (Mooney et al., 2013). It is a problem of comprehension that often goes both ways and requires efforts from scholars to take the time to understand the other's objectives, disciplines, language, and way of conducting research (Mattor et al., 2014). There may be historical disparities between disciplines to contend with, such as differences in relative size (in terms of numbers of persons, instrumentation, and funding) and investigative style (especially in the treatment of qualitative information). Staying within disciplinary silos during training does not help with bridging these gaps (Hart et al., 2015). Finally, project durations of only 2–3 years long are too short for trust-building within groups and several boundary settings have been created recently at IUEM to stimulate such interactions.

More Recent Moves Toward Interdisciplinarity at IUEM

If proximity is crucial to overcoming barriers against interdisciplinarity (Reckers and Hansen, 2015), it is not enough, as other barriers extend well beyond a need for frequent interactions. If we are to tackle the complexity of social and ecological systems this requires interactions between very distinct epistemic communities, each of which use different ontologies and epistemologies (Hart et al., 2015, and references therein). They require that scholars take the time and the risk to understand the concepts and tools of other disciplines' cultures, and vocabularies; one also has to admit that developing a shared, if not common, language, or a joint conceptual framework, is not for everyone and strongly depends upon individual commitments or propensities (Mattor et al., 2014). It takes time and it is not rapidly rewarding in terms of scientific articles, which are at the core of a scientist's career progression.

This leads to a second series of difficulties associated with the way universities are organized into academic departments and training programs. Disciplinary divisions within universities are a strong impediment for their having a role in sustainability challenges (Hart et al., 2015). Based on their experience within the Inter-American Institute for global change research (IAI), Pittman et al. (2016) have highlighted the importance of stimulating interdisciplinarity through, not only new incentives using calls for joint proposals but also by: (i) providing space for experiential learning by researchers, (ii) facilitating networking and teamwork across disciplines, (iii) exposing researchers to new concepts and tools, (iv) maintaining persistent mentorship and support for cultivating cross-disciplinary thinking, (v) connecting research to tangible problems, and (vi) monitoring program calls, project selection and implementation. In relation to point (v), it is worth noting that 90% of the researchers involved in IAI's programs indicated the importance of having practical outcomes as a motivating factor for their participation in interdisciplinary research.

Within the IUEM, several interactions between disciplines were already occurring. For example geographers of the LETG-Brest (Littoral, Environnement, Télédétection, Géomatique) laboratory had worked with biologists from the LEMAR laboratory to study biodiversity and human activities, particularly dredging on maerl beds, and lawyers and economists of the AMURE laboratory worked with sedimentologists of the DO (Domaines Océaniques) laboratory to study risks associated with coastal erosion and submersion. For nearly 20 years, a citizen science program to monitor the quality of the water of 13 rivers in region Brittany on a weekly basis has been in existence (Abott et al., 2018) and a forum on citizen science was organized in 2014 to explore scientific, learning and ethical dimensions of such programs.

Nonetheless, if proximity was of major importance for the encounters of scientists working in the parts of the same ecological system, it appeared insufficient for facilitating deeper collaborations on broader topics, and particularly to working on topics in sustainability. Hence, the boundary settings within IUEM itself were moved. Members of the institute undertook several initiatives to identify shared research goals among humanities and natural marine sciences and new paths for conducting joint research and training. First, the *Zone Atelier Brest-Iroise* (ZABrI, part of the French LTER network) was created (in 2012) with the aim of developing conditions for the construction of interdisciplinary projects around the larger objective of understanding the functioning and trends of the Bay of Brest social-ecological system by encouraging stronger interactions between scientists and stakeholders within a sustainability perspective. Entirely new activities arose mixing art and science in the early 2010's, such as for example, the Belmont Forum funded ARTISTICC project which produced unique, hybrid public outreach projects from the mutual investments of artists and scientists. In addition, a trans-disciplinary training module "Science and Society" was introduced in 2012 in the marine sciences Master program (Hubert et al., 2015). A new summer school "Université d'été mer-éducation" was also created that same year, that trains fifty high school teachers in marine sciences and helps them create interdisciplinary courses for their classes.

Three years later, a new core research funding theme on social-ecological systems was added to the LabexMer program (a financial instrument dedicated exclusively to French marine sciences initiatives created in 2011). While, geographers had played a pivotal role in one of its thematic axes since the beginning, as has been seen elsewhere in other interdisciplinary programs (see review in Mooney et al., 2013), the new axis encourages the co-construction of projects involving natural and social and human sciences. For instance, researchers wishing to explore the societal implications of their research using socio-ecological frameworks, such as Ostrom (2009) or Collins et al. (2010).

Finally, a new research group was launched during 2014 within IUEM, "ApoliMer" (Political Anthropology of the Sea). This group associates the SSP with natural sciences studies of marine environments and seeks to integrate both perspectives (Mazé et al., 2015, 2017), primarily through studies concerning the decision-making processes and the sustainable governance of coastal social-ecological systems. These new interactions and perspectives suggested by ApoliMer have raised key questions at the science-policy interface presented in this article that are discussed in the following section.

KEY QUESTIONS AT THE SCIENCE-POLICY-COMMUNITY INTERFACES

In this last section, we put forward key questions about the situation 15 years ago (**Figure 5**) and the present-day situation (**Figure 6**) in the Bay of Brest which arose and arise at the interface between science and decision-making at both the community and political levels.

What Prevented a Containment Project 15 Years Ago?

By the mid-2000s, the fishing community imagined a containment project to protect the restocking program started by the spat hatchery from the excessive abundance of

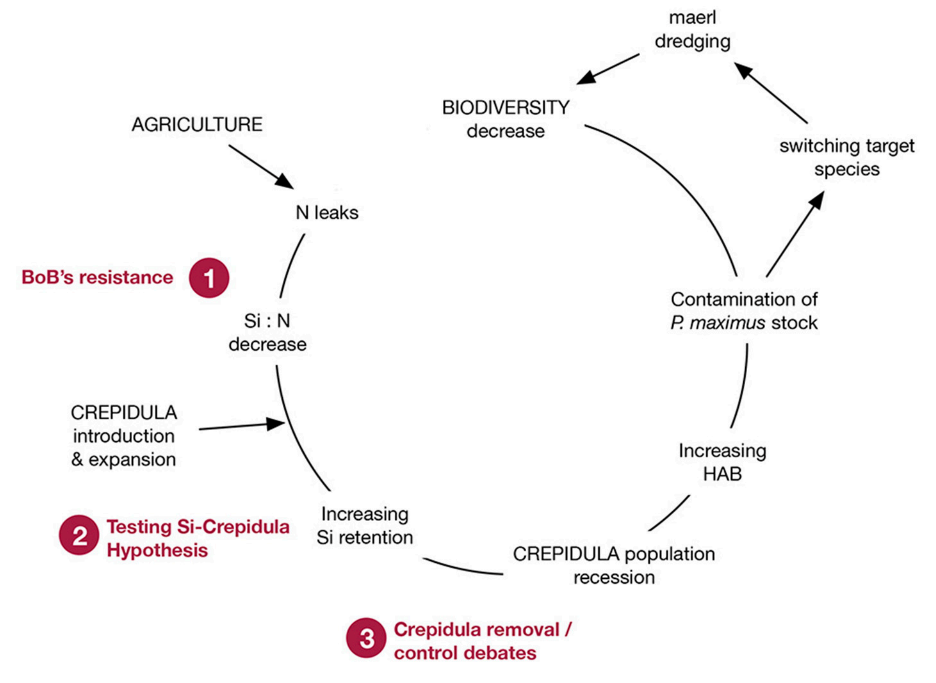

FIGURE 5 | Scientific questions that were raised between 1995 and 2005, concerning the long resistance of the ecosystem to the effects of increasing N delivery from land and changing nutrient ratios (1), the emergence and the testing of the Si/*Crepidula* hyporthesis (2) and the key questions raised at the science-policy-community interface concerning a possible control of the *Crepidula* proliferation (3).

C. fornicata. The scientific community was concerned that an eradication project would cause the collapse of the ecosystem due to the potential role of this species in the prevention of toxic phytoplankton blooms. Many questions were raised (3, in **Figure 5**), by both fishermen and scientists who met to discuss these issues, such as: what to do with the slipper limpets once removed from the seabed and at what cost? Which species would come back following dredging and eradication? What would be the impact on benthic nutrient fluxes and the functioning of the whole ecosystem? How much *C. fornicata* biomass could be removed from the ecosystem without affecting the benthic nutrient fluxes? Controls versus "*laissez-faire*" is always a major management question regarding non-indigenous species (Menozzi and Pellegrini, 2012) and at that time, the latter was chosen. As mentioned earlier, slipper limpet abundances declined monotonically in recent years, with few hypotheses to explain this decrease. But 10 years ago, when *C. fornicata* was thought to endanger the Great Scallop fishery, was this option of "*laissez-faire*" a real choice? Is it because scientists met with fishermen, explained the silicate pump/*C. fornicata* hypothesis? Is it because of the large uncertainties associated with the recolonization of the seabed, or with the impacts on nutrient fluxes and possible toxic phytoplankton blooms? Or is it only because of a lack of funding for removing the slipper limpets and replacing them by scallop juveniles? Answering these questions will require detailed examination by human and social scientists. It implies a reconstruction of the socio-history of the processes at that time and of the interactions between scientists and fishermen, ecosystem managers and decision makers. This socio-history would best be elaborated by crossing political sociology and the sociology of science, bringing another perspective to the new political sociology of science (Frickel and Moore, 2006).

The present situation in the Bay of Brest raises several questions to be explored within natural sciences and human and social sciences, as well as at the interface between these two cultures (Snow, 1959). Within the natural sciences, it will be important to verify that the earlier model (Laruelle et al., 2009) of a link between toxic phytoplankton blooms and a decline in *C. fornicata* abundances is true (4 in **Figure 6**), and to understand the causes of the *Crepidula* recession (4b in **Figure 6**). Answering the first question relates to the validation of the silicate pump/*C. fornicata* hypothesis, now that the C*repidula* numbers are declining; this would imply completing a new inventory of its spatial distribution and biomass, as well as repeating experiments similar to those conducted 15 years ago to test the validity of this hypothesis, in particular those on benthic fluxes and the re-evaluation of biogeochemical budgets. Addressing the second question (related to the recession of the invader) would imply exploring different hypotheses, such as the presence of a pathogen and its possible effects on the *C. fornicata* life cycle, the appearance of a predator for *C. fornicata* (namely starfish), and/or changes in oxygen concentrations at the sediment-water interface. But establishing these links should not overlook additional questions related to the social-ecological system (Liu et al., 2007), more specifically at the interface between science

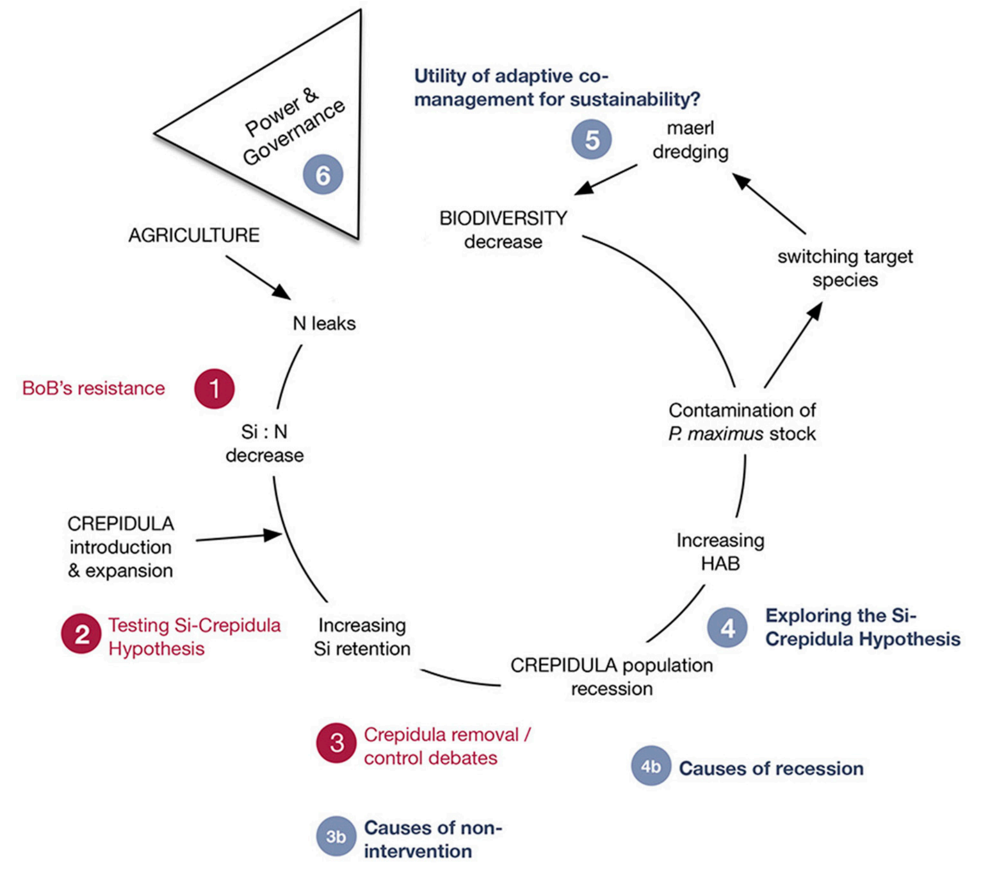

FIGURE 6 | Scientific questions raised today, for natural sciences concerning the causes of the recession of *Crepidula* (4 and 4b) and raised and addressed through an interdisciplinary approach involving the social sciences of politics, regarding the causes of the non-intervention 15 years ago concerning the possible control of *Crepidula* proliferation (3b), the fishing activities on maerl habitat and its impacts on biodiversity (5) and the relations between these fishing activities and agricultural activities on land, that question the governance of the land-ocean continuum (6).

and policy and between scientists and the fishing and farming communities. It is important to recall that the current situation with fishermen dredging on maerl beds arose because toxic phytoplankton blooms prevent harvesting the Great Scallop. These blooms may be linked to changing nutrient ratios modified by *C. fornicata* recession. In addition, the importance of Si in this particular system resulted from the earlier disruption of Si:N and Si:P ratios that originated with the excessive N inputs from intensive agriculture practices in the surrounding watersheds. This cascade of events (**Figure 4**) now yields a fascinating set of interdisciplinary questions at the science-policy interface.

Is Co-adaptive Management a Sufficient Condition for Sustainability?

Why does dredging on maerl beds continue today (question 5 in **Figure 6**), despite the location of these beds within a Natura 2000 area and the clear evidence of their destruction by this technique? How come the tight relationships between fishermen and scientists who have been working together for decades in this ecosystem, have not led to a more sustainable management of these maerl beds? Indeed, interactions between the scientific community and the fishing community have not been restricted to specific interventions in the past. The Great Scallop fishery in the Bay of Brest is relatively small (between 300 and 400 tons per year over the last 15 years) but is very important to the local heritage and economic markets. In the last 50 years, fishermen have had to adapt to several external constraints (Danto et al., in prep.): changes in water quality due to land-derived pollution, invasion of non-indigenous species, epidemics or abrupt climate variations, such as the winter 1962–63 which led to a sharp decline of the scallop standing stock (and a strong decline in landings: from 1,500 tons annually down to <100 tons before the Tinduff hatchery opened).

Since the early 1970's and in collaboration with the local scientific community, fishermen have diversified their activities and experimented developing the stocks or aquaculture of oyster, clam and salmon species. They co-constructed these programs with the scientific community, first with IFREMER (*Institut Français de l'Exploitation de la Mer*) then with benthic marine biologists at the *Université de Bretagne Occidentale*. These programs were funded by local and national authorities who strongly supported this community which was demonstrating a strong capacity to adapt under difficult conditions. By the early 1980's, the "*Ecloserie du Tinduff,*" a spat hatchery, launched a restocking program for the Great scallop. At the time, this hatchery was quite unusual, as there was only one other hatchery in Okaido (Japan). It is beyond the scope of this paper to document the origins and changes in the practice of this activity. Our purpose here is to simply indicate that these experiments and the creation of this innovative structure which have saved the local Great scallop fishery up to now, have been possible only through the tight connection between the fishing and scientific communities. If these exchanges are a good example of what we would call today "adaptive co-management" (Kofinas, 2009), the present-day situation in the Bay of Brest clearly demonstrates that this is by no means a permanent guarantee of the successful management of biological resources.

It will be crucial to investigate the reasons for this dysfunctioning to move toward sustainability in this ecosystem. Again, key questions need to be investigated at the interface between science, policy and communities. How do the different social groups (professionals/corporations, scientists), with their diverse interests, take charge of this case (fisheries entrepreneurs versus biodiversity conservationists)? How have institutions seized the question? What are the different forms of collective mobilization, conflict and conflict resolution? Is there a consensus and who ultimately decides? The question of decision is so crucial that the most recent program devoted to the study of the interaction between dredging and habitat modification in Natura 2000 areas, which was launched in 2016 by the local fishing authorities with participation by natural scientists, is called DECIDER (to decide, in French). This program aims to reconcile the activities of dredging and preservation of the maerl beds, through the evaluation of the interactions between gear and habitat on the Natura 2000 sites.

What Form of Governance Between Land and Ocean?

Moving landward, more questions arise related to the importance of Si in the system and to excessive N inputs encouraged by intensive agricultural practices. For instance, it would be important to investigate the perception of the Si biogeochemical cycle by decision-makers and whether or not it is being taken into account at the same level (e.g., through systematical measurement) as the N and P cycles. Most long-term observations of water quality in the Brittany region do not include this parameter, despite its demonstrated importance in coastal environments. Is it because of poor knowledge transmission between science and management/decision makers, the so-called "knowledge gap" (Jasanoff, 1990)? Is it because managers know that they can control N and P inputs but not Si inputs? More generally, are the regulation services linked to nutrient recycling really taken into account by decision makers, as easily as provisioning services for example? These questions relate to the way complexity of ecosystems is accounted for at the science-policy interface and to the complexity of this interface itself. Indeed, the chain of events as described in **Figure 4** involves the Si biogeochemical cycle and an "invisible" invader. It is more subtle than the direct effect of excessive N inputs leading to visible and odorous green tides. This calls into question the treatment of complexity and the quality of the indicators that are used to evaluate the ecological and biogeochemical status of a given ecosystem. Have we developed the most appropriate set of indicators that can account for this complexity? This is where it is crucial that social scientists have the possibility to work in close interaction with natural scientists, to explore the way scientific knowledge is being produced and used - or not - in the decision-making process (Mazé et al., 2017).

These questions about complexity and the knowledge gap should not prevent action to be taken, as we also often know enough to do so. But other factors, beyond scientific evidence, are to be taken into account. Green tides have been a major public issue in Brittany for the last 50 years, leading to major conflicts at the land-ocean interface which are still unresolved. Here again, national, regional, and local authorities are working apparently side by side with professionals of agriculture and scientists, to promote changing agricultural practices on the watersheds and reduce the impact of this sector on water quality and ecosystem services. Under the aegis of the GIS CRESEB ("Groupement d'Intérêt Scientifique, Centre de Recherche et d'Expertise sur l'Eau en Bretagne") funded by the Brittany Region in the early 2010's, a permanent group of scientists, covering many disciplines from agronomy to marine biogeochemistry, from sociology to law and economics, is meeting regularly to discuss how to best accompany the projects of local territories in the region subject to litigation, to favor the transformation toward sustainability. Scientists involved in this group discuss their role in this transformation, being aware of the difficulty of such an exercise, thanks to earlier experiences with French national plans against green algae proliferation. In parallel to these efforts, important decisions are taken by public authorities that allow the persistence of the agro-industrial agriculture model, already denounced in several reports from NGO's and from the "Cour des comptes." Power issues here play a key role in this blockage between the state, the agro-industrial lobby and the impact on farmers, their practices, human health and ecosystems. What is the role of power relations in the conditions of possibility and impossibility of transformation to sustainability? What is the role of scientists in the process of reflection, accompanying this transformation? The argument about the lack of knowledge continues to be mobilized, thus promoting inaction, and what does it means in terms of instrumentalization? This is where political science could provide major insight into the so-called implementation gap, related to inertia of the institutional and political systems. Many factors have been put forward to explain it. They have been identified through the "path dependency" concept, ratchet effects and other self-reinforcing mechanisms. Within the framework of the new political sociology of science (Frickel and Moore, 2006), we need to address the use of scientific knowledge by decision makers, taking into account the diversity of interests and exploring the decision-making context and process, combining knowledge, and power, something which is too rarely done in environmental studies (Fabinyi et al., 2014) which is especially the case when dealing with transformation more than with adaptation (Olsson et al., 2014).

As tentatively shown in **Figure 6** (6), addressing these questions of power and governance of the land-ocean continuum may be one way to "close the loop" and re-link the communities of agriculture and fishing/aquaculture. For a long time, agriculture and fishing have been closely related in Brittany, often with a single person sharing his time between both activities. Today practices have changed, and nitrate leaks have become an element of division between the two communities. The cascade of events described earlier (section The Bay of Brest ecosystem since WWII and **Figure 4**) demonstrates the complexity of the ecosystem functioning. However, the way we ask the questions at the science-policy interface in this section (5 and 6 in **Figure 6**), from maerl beds to agricultural practices, suggests that we now address the complexity of the social-ecological system, taking into account these retro-actions from sea to land. This implies that scientists, the different stakeholders and decision-makers work together and that interdisciplinarity makes progress, especially between natural and human and social sciences.

PERSPECTIVES

Following the description of the environmental trends observed in the Bay of Brest over the past five decades, a series of questions has been raised at the science-policy-communities interfaces. The social sciences of politics, in close collaboration with marine environmental sciences, will now analyze the decision-making process concerning the management of the Bay of Brest and the adjacent Iroise Sea, benefiting from the new boundary settings described in section Construction of a Basis for Interdisciplinary Knowledge About the Bay of Brest. From the perspective of historical and political sociology, it will be necessary to reconstruct the socio-history of the management of the bay, paying particular attention to the interactions between scientists, naturalists, fishermen, farmers and managers. The interaction between fishermen and farmers seems indeed necessary for negotiations to progress toward the sustainable management of the Bay of Brest because of the inextricable link between eutrophication and the ecological status of the bay which impacts severely fishing communities. This is what is meant in **Figure 6**, by the circular aspect of the figure and the triangle aiming at closing the circle, representing these questions to be addressed at the science-policy interface, which imply that we explore the governance of the land-sea continuum. These questions will have to evolve based on a reflection on the history of science and technology, but even more so in the context of the new political sociology of science so that we can grasp the power games around the question of expertise (Bérard and Crespin, 2010).

Exploring sustainability challenges requires strong interdisciplinary approaches and we have used our study case to derive important insights, particularly on the importance of geographical proximity and the establishment of boundary settings to stimulate a better integration of social and human sciences in the study of LTER sites, turning them into LTSER sites. Here again, the importance of creating boundary settings in immersion within an environment of natural sciences, reflects the role of geographical proximity but, this time at the interface between humanities and natural sciences. The creation of ApoliMer at IUEM and the recent arrival of economists and jurists from the AMURE laboratory within a just-completed extension (opened in 2016) of the IUEM building, achieves now, nearly two decades after the opening of the first buildings, the original intentions of the University to construct facilities suitable for interdisciplinary approaches by bringing together in a single location, researchers concerned with the marine environment.

This observation raises key questions that, we believe, should be taken extremely seriously by those in charge of the politics of science, concerning both research and training. Trust is an essential component of these interactions among scientists from different disciplines, and between science and society, and it takes time to build. We have seen in section Construction of a Basis for Interdisciplinary Knowledge About the Bay of Brest that the interdisciplinary knowledge built, first between pelagic and benthic scientists, and now between biogeochemists, ecologists, and political scientists (all authors on this manuscript), was and is possible mostly thanks to the existence of permanent research staff remaining in place over many years, and to the construction of infrastructures and boundary settings that facilitate long-term interactions among different epistemic communities. It appears that these crucial needs for sustainability science and action diverge strongly from the on-going growth of the scientific field, still favoring positions on soft money, extreme mobility, the precarious place of young researchers, and enhanced competition. Even the scientific careers of permanent staff continue to be evaluated mostly on the impact factor criteria, neglecting the time it takes for these scientists involved in inter- and trans-disciplinary approaches to build trust and fundamental knowledge that needs to be co-constructed, amongst various disciplines, and at the interface between scientific and other forms of knowledge. Last but not least, this evolution toward sustainability raises many other key questions, especially about the training of the next generation of students. Depth *versus* breadth is an important debate in Master and Ph.D. programs. Do we encourage training of "hybrid" students, better able to address complex problems but probably less specialized in one particular field, or do we train very specialized students and find new ways to help them being able to interact with other researchers from very distant fields? When should interdisciplinarity be introduced in a student cursus? Does a student trained interdisciplinary have equal chances to find a position related to his experience, within or outside academia, as one trained in a specific field? Most probably, the emergence of the field of sustainability science offers a wonderful field for the sociology of science, be it concerning training, or the many questions that this field raises concerning our role of scientists on this path toward sustainability.

AUTHOR CONTRIBUTIONS

OR has written the manuscript, with strong inputs from MR, CM, and JC-G regarding the content and the structure of the manuscript. Being native American, JC-G did a lot of editing as well. Other authors are listed in alphabetic order, they have contributed a lot to the research reviewed in this manuscript and provided important comments and suggestions on the manuscript.

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