Citizen participation in monitoring phytoplankton seawater discolorations

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1. Introduction

Phytoplankton blooms in marine ecosystems correspond to high concentrations of eukaryotic single-celled (protist) photosynthetic organisms. Single species of typical bloom-forming microalgal groups such as dinoflagellates or diatoms, react relatively rapidly to environmental changes (variation of nutrient concentration ratios, water mixing, etc.) due to their high duplication rates, physiological plasticity and life strategy adaptations (Smetacek 2002). Under favorable environmental conditions which allow cellular duplication, blooms can be observed, generally with high biomass production (Cloern 1996). The remineralization of this high biomass by bacteria can cause anoxia/hypoxia phenomena, leading to mass mortality of the marine fauna inhabiting the zone where the bloom occurred. Mass mortality of marine fauna can hit wild populations or farmed stocks (Hallegraeff 2000). If anoxia induced by high biomass-production blooms occurs in aquaculture exploitations, the linked economic activities are strongly affected, with large-scale losses of live fish or shellfish destined for human commercialization and consumption (Zingone and Enevoldsen 2000). Massive biomass accumulation can also cause surface seawater discoloration (i.e. green, red, brownish or whitish colors) or foam production, thus altering the appearance and aesthetics of coastal waters. These impressive and sometimes eye-catching natural events can hinder tourism activities (i.e. water sports, leisure, beaches, hotels, restaurants) whose economic benefits depend on the good aesthetics of the water in the coastal area (Zingone and Enevoldsen 2000). Tourists are reluctant to visit areas where discolorations are more frequent and intense, hence affecting the local economy. Some blooming species can also metabolize toxins which are directly harmful when released outside the cell (hemolytic, ichtyotoxic, cytotoxic effects) to marine fauna or indirectly for humans who can suffer from Diarrheic (DSP), Paralytic (PSP), Neurotoxic (NSP), Amnesic (ASP), and Azaspiracid (AZP) Shellfish Poisoning as well and Ciguatera Fish Poisoning (CFP) through the consumption of seafood that has bio-accumulated toxic substances. Finally, skin irritations and respiratory problems have been reported in humans who have gotten into contact with aerosols developed after blooms of toxigenic species. All phenomena connected to phytoplankton developments that are detrimental to the ecosystem and/or human health and/or economic activities are classified and known as Harmful Algal Blooms (HABs) (Hallegraeff 2000, Zingone and Enevoldsen 2000).

Countries in possession of fishery and aquaculture sectors are particularly aware of HABs, and in particular of the toxigenic potential of some phytoplankton species. They therefore implement monitoring activities for toxic phytoplankton species in zones inhabited by natural and cultivated shellfish populations.

Despite the problems that phytoplankton discolorations may cause to tourism and wildlife, phytoplankton monitoring systems are not designed for this kind of HAB phenomenon. This is for example the case in France of the REPHY (*REseau de surveillance et d'observation du PHYtoplankton et des PHYcotoxines*) (http://envlit.ifremer.fr/surveillance/phytoplancton_phycotoxines/presentation) which, since its launch in 1984, is designed to monitor toxic species and not water discolorations. Seawater discolorations can affect relatively small and patchy areas, or can extend across very large (hundreds of kilometers) areas, rendering them visible by satellite (Cloern 1996). These phenomena occur in different regions of the World Ocean, both in offshore areas (i.e. coccolithophore blooms), and, more frequently, in coastal areas, mainly in semi-confined zones (harbours, estuaries (Hallegraeff 2000, Zingone and Enevoldsen 2000). They can develop rapidly, locally and die out relatively quickly (within a few days) (Cloern 1996). The ephemeral nature of seawater discoloration phenomena hinders the experimental design of their monitoring. Local phytoplankton monitoring systems are based on fixed sampling stations, with surveys scheduled at regular intervals. This static organization of monitoring systems (with stations often located near shellfish farms to monitor toxic species for sanitary reasons) can cause seawater discolorations to be overlooked. These can occur either between scheduled sample collections (which generally take place every fortnight) or in sites or during periods not usually sampled. Seawater discolorations are often reported in a sporadic and random way, based on personal observations of individuals (scientists or otherwise) aware of the environmental issues associated to such an event.

Citizen observations can potentially provide complementary information to ongoing sanitary monitoring programs of phytoplankton or field campaigns (Castilla et al. 2015). They contribute towards a better grasp of both the spatial and temporal scales at which water discolorations occur in coastal waters, particularly during the summer. This is the time of year when these phenomena are most likely to develop, which corresponds to the period when there are more people present on the coast. Citizen science is a nexus between science and society, being both a new opportunity for scientists to acquire new data and for the public to interact with science (Jarvis et al. 2015; Martin et al., 2016). Although the citizen science movement is well-established, (Miller-Rushing et al. 2012), particularly in terrestrial monitoring programs, the engagement of non-professional actors in scientific investigations has dramatically increased in recent years, especially in environmental sciences (ornithology, paleontology, marine and terrestrial biodiversity) (e.g. Bodilis et al. 2014) that all require large amounts of data from heterogenic sources (Kelling et al. 2009). Citizen science have been lauded for: i) the education of voluntary participants to environmental issues, ii) providing low-cost data useful for sustainable management decisions (Jarvis et al., 2015), iii) empowering citizens to participate more actively in local conservation and management decisions (Martin et al., 2016), and iv) engaging stakeholders in conservation planning (Jansujwicz et al. 2013).

Marine citizen science monitoring programs are increasingly common, with the public now being able to get involved in the detection and identification of: a) marine macrofauna easily observed from the sea surface (i.e. marine mammals, sharks, jellyfish) or b) marine organisms, which can be observed by 'citizen' SCUBA divers (i.e. Goffredo et al. 2010; Holt et al. 2013). However, the use of a citizen science approach for studying plankton is not frequently chosen as a tool, compared to the number of classical sanitary monitoring programs for plankton existing worldwide. Nevertheless some examples of the use of a citizen science approach to study phytoplankton exist. Volunteer HAB monitoring programs were launched along the west coast of United States in the early 1990's (Anderson et al. 2001) and more recently along Canada's west coast (McIntyre et al. 2013) in response to the onset of human poisoning syndrome (ASP and DSP) events. In 2001, the Phytoplankton Monitoring Network (PMN) was established by the National Oceanographic and Atmospheric Administration of the United States department of Commerce (NOAA), initially as part of South Carolina's *Pfiesteria* Harmful Algal Bloom (HAB) surveillance program. The scientific objectives of all these programs concern the distribution, phenology and managing of toxigenic species. As for water discolorations, structured management systems implementing a citizen science approach are not common. An example exists in northern Europe, but it is mainly focused on the identification of marine cyanobacteria blooms (e.g. Kotovirta et al. 2014) and not on eukaryotic microalgae. Other citizen-monitoring programs, whose main goal is the detection of changes in sea colour, have been adopted (i.e. the Citclops project (http://www.citclops.eu), or Plymouth University's Secchi App – (ref http://www1.plymouth.ac.uk/marine/secchidisk/Pages/default.aspx). Indeed, people directly (beach activity owners, aquaculture fishermen, scientists) or indirectly (environmentally-aware citizens, non-profit organizations) concerned by water discoloration phenomena point out the absence of a clearly identified interlocutor (institutional or non-government organization) who could receive observations and process the biological and ecological information in order to better manage these phenomena. This shows the need for a structured management system for water discoloration events, coupled with better awareness-raising about the causes and the effects of water discolorations on humans and the environment.

In 2013, a citizen monitoring program focused on water discoloration observations was launched across Brittany (France) waters in parallel to the ongoing phytoplankton and biotoxin monitoring network REPHY. This project, named *Phenomer* (an acronym for 'visible phenomena at Sea', combined with 'Phenology', in French) (http://www.*phenomer*.org/) has been put into practice by both public scientific institutes and non-governmental organization partners (Curd et al. 2014). Beyond communication and outreach objectives on phytoplankton and HABs, the overall aim of *Phenomer* was to introduce citizens to HAB management and scientific analysis. From a marine coastal management point of view, *Phenomer* creates a working relationship between volunteers and researchers, with the aim of improving and structuring the observations of water discolorations. Indeed, the major objective of *Phenomer* was to establish if a citizen science approach aimed at the detection of water discolorations may complement sanitary monitoring systems (such as the REPHY in France) which were not specifically conceived for the analysis of such a phenomena (http://www.*phenomer*.org/). Information gained through *Phenomer* could also contribute to the economic development (shell farms, tourisms) in coastal areas where water discolorations are less frequent or absent. From a scientific point of view, *Phenomer* aims to explore the possibility to acquire scientifically valuable data on water discoloration and HABS in general, in particular by means of citizen alerts and with both ecological and sociological scientific purposes. Through the help of volunteer participation, *Phenomer* aims to i) extend the monitoring survey area for coastal water discolorations and structure their observations, ii) identify general trends where HABs and water discolorations in particular are more likely to occur, thus providing scientific data for current and future research, iii) promote an increased awareness and education of the public on HABs, and iv) analyze the perception of visible phytoplankton blooms by inquiring in what way contributors perceive the harm (i.e. environmental, human health, personal) provoked by these phenomena. This study reports the results from the first three years (2013-2015) of this project.

2. Materials and Methods

2.1. Communication and outreach on the project

The understanding of a project subject and the acquisition of scientifically valid data through citizen participation are directly dependent on communication actions through appropriate media (Wehner 2011). In order to recruit a broad spectrum of participants to the *Phenomer* project, a number of procedures were developed. A project coordinator together with a scientific communication officer were assigned the development and distribution along Brittany's coastline of 30 000, 32 000 and 38 000 leaflets and 1000, 800 and 700 posters presenting the *Phenomer* project in 2013, 2014 and 2015 respectively. The communication on the project objectives was stepped up prior to the summer period of each year, when water discolorations were presumed to occur more frequently. Stickers, postcards (1000 prints of each per year) and a board game for children in 2013 were also developed to ensure the best possible attentiveness to the project. Lectures, interviews on radio shows, articles in the regional press as well as meetings with volunteers at a number of marine events across Brittany over the course of the summer months were organised. A website (http://www.phenomer.org/), and social media page were also developed and regularly updated. Finally, in 2015, a smartphone application (Phenomer©) (Supp. Fig.1) was developed to facilitate the sending of water discoloration photographs taken by citizens thanks to immediate geolocalisation. The geolocalised picture is sent to the scientific team of the consortium via the application, which improves the rapidity of the intervention in the field.

2.2 Warning protocol of water discoloration detections by volunteers

Citizens were invited to report and take pictures of all HAB events they may have observed (water discolorations, foam production or fauna mortalities) across Brittany's coastal waters, either by calling a land-line, using the smartphone application, or via an on-line form present on the website (Fig. 1). A group of scientists from the three research institutes in the partnership filled out a duty roster on a weekly basis, during which time they committed to responding to all *Phenomer* alerts as quickly as possible. Observations made by the general public were analyzed by the on-duty scientist in order to filter out false alerts, such as macroalgae accumulations, river runoff, etc. (Fig. 1). It was part of the scientists' responsibilities to respond to any email or phone correspondence related to the project he or she received during the week they were on-duty. Some valuable information could be obtained over the phone, for example establishing whether the observed phenomenon was provoked by macroscopic organisms (visible to the naked eye, e.g. small jellyfish, other gelatinous zooplankton, macroalgae) or by inorganic particles (e.g. sand). On the occasions where the information provided made it plausible that the water discoloration was caused by phytoplankton, either the research team of the project network located closest to the bloom promptly reached the area and took a sample, or the volunteers were asked to follow a sampling and storage protocol (Fig. 1). In 2013, few samples of water discoloration were collected (Table 1), either because water discolorations occurred in areas far away geographically from phytoplankton research laboratories, which limited the rapidity of the intervention of scientists, or because citizens were not able within a short time-frame to transport samples themselves to the nearest research station. In order to overcome this problem, as of 2014 a network of nearly 60 relay structures was created to make it easier for observers to deposit samples somewhere in the vicinity of the observed discoloration. These relay structures are environmental organizations, port and town authorities, water sport clubs, lifeguarding stations or natural protected areas that formally accepted to take part in the project. They were trained by the *Phenomer* scientific consortium (scientists and Non-Governmental organisations) to the steps to take in the event of receiving a water sample taken by an observer (i.e. seawater fixation, preservation and expedition to a scientific laboratory). Once a sample arrived in a relay structure, it was then picked up and analyzed by the nearest laboratory to the water discoloration event (there are 6 dotted around Brittany's 2730 km of coastline). The species responsible for the bloom was identified through light microscopy by a taxonomist of the *Phenomer* consortium. When samples were not collected, the species responsible for the water discoloration was inferred either from data of the REPHY monitoring program or from data of ongoing scientific research projects in areas near the water discoloration event. Feedback was both spread to the scientific community for further research and to the general public on the website, via social media and newsletters (Fig.1). When a toxic species was identified as being responsible for the bloom, the REPHY, the French phytoplankton monitoring program, was informed and precautionary actions were initiated. Citizens were privately thanked by personal direct communication and, with their consent, when using their photographs in *Phenomer* communication medium (Fig. 1).

Fig. 1 here

2.3. Analysis of water discoloration perception by citizens

During 2013-2014, a series of 13 preliminary semi-structured phone interviews were carried out with those observers having accepted to be interviewed. The preliminary results from these interviews made it possible to outline a typical profile of the people taking part in *Phenomer* and to construct an *ad-hoc* questionnaire adapted to this population (Supp. Materiel 1). Composed of a dozen questions, the questionnaire cross-examines the context in which the observation is made, what observers feel in relation to these phenomena and whether, according to them, HABs are likely to impact human health and/or the environment in either a good or a bad way. This questionnaire was then taken by water discoloration observers in 2015. All participants were informed of the data protection legislation protecting their personal data rights, in compliance with the CNIL (*Commission Nationale de l'Informatique et des Libertés*) (CNIL 2016), the French committee responsible for ensuring that information technology complies with national data protection legislation. Participants submitting a phytoplankton bloom observation via the online form or Smartphone application are asked to tick a box certifying they have read and understood the "*charte d'utilisation*" (terms of use), which serves as a statement of informed consent, explaining their rights regarding personal data. When participants reported their bloom observations over the phone, they were informed of their personal data rights over the phone, and a log was kept of the conversation. All participant consent is recorded in the back office of the *Phenomer* website (ww.phenomer.org) where a database kept track of every phone call and completed form. The CNIL approved the type of data collected on participants, and manner in which collecting participant consent is recorded (ref. number 1684966 v0).

3. Results

3.1 Citizen observations of water discoloration phenomena

During the spring-summertime periods (March-August) of 2013, 2014, and 2015, the means of contact most used for *Phenomer* was the internet site, with an increasing number of visitors over time (2621 in 2013, 6987 in 2014, and 11044 in 2015). During the three years of project implementation citizens made 69, 74 and 88 mostly one-off alerts either by phone, smartphone application or via the website form (Table 1). Out of these alerts, 40, 40 and 47 observations reported by citizens were phenomena potentially linked to plankton. The other contacts were mostly general enquiries about various marine phenomena observed in the intertidal zone (macroalgae, bioluminescence, even nudibranch [Aplysia spp.] egg-ribbons). These general inquiries are a normal part of any citizen science program. After discussions by phone with the observers, sample collections and/or data comparison with the REPHY network or other research programs, respectively 24, 40 and 30 observations were considered to be valid scientific observations and potential phytoplankton water discolorations (Table 1). The discarded observations were put aside either after viewing the photos provided and/or talking with the observer. Some were observations of macroalgae. Others either had inconclusive pictures, descriptions more closely resembling zooplankton aggregations, concerned brackish lagoons or were located outside of Brittany in areas not covered by the *Phenomer* network. Many of the observations made by citizens were reported in areas outside the routine phytoplankton monitoring perimeter. In 2013 (10 observations), 2014 (31 observations), and 2015 (15 observations), respectively 42%, 77%, and 50% of potential discolorations phenomena occurring in Brittany were not reported in the frame of the routine phytoplankton monitoring system (Table 1). Out of these potential water discoloration phenomena, 14, 32 and 28 could be sampled and definitively proved to be water discolorations caused by massive phytoplankton development (Table 1). The remaining 10, 8 and 2 observations could not be sampled either because citizens contacted the *Phenomer* program too late or the blooms disappeared, or because the phenomena occurred in remote areas, far from research centers where samples could be quickly deposited. This second bias occurred especially in 2013 (10 water discolorations not sampled) before the setup of relay structures. The confirmed phytoplankton blooms corresponded to red, green, and dark brown discolorations; most of which were observed during July-August. In 2013, 2014 and 2015 respectively, 7, 24 and 14 phenomena were observed outside of routine monitoring points (Table 1).

Table 1 here

3.2 Citizen perception of water discolorations resulting from semi-structured phone interviews

During the 2015 season a total of 25 questionnaires were completed. About 80% of *Phenomer* observers were already informed about the HAB phenomena taking part in the program, and out of these 60% had already observed phytoplankton under the microscope. Observers were then asked to give their opinion about their perception of how frequently water discolorations occur. The majority (52%) of observers considered water discoloration events to occur sporadically, 32% considered them to occur regularly, 12% considered these events to occur frequently, 0% felt them to occur more rarely and 20% felt unable to answer the question because of insufficient knowledge. The vast majority (83%) believed water discolorations to have an environmental impact, in both a harmful and a useful way (Fig. 2A). To a lesser extent (25%), interviewees felt that seawater discolorations have economic impacts and impacts on human health. Few people considered water discoloration harmful from a personal or aesthetic point of view. Observers were driven to report water discolorations events out of environmental awareness (Fig. 2B), to help the program, or to understand the origin and effects of bloom phenomena. People wanted to understand more about water discoloration whether in relation to its effect on mankind, the environment, or in general, in near-equal proportions. No observers wished to complain about the presence of water discolorations.

Fig. 2 here

3.3 Observed water discolorations in relation with monitoring activities

Red discolorations were regularly observed during the three years of project implementation from May to August from at different locations in southern Brittany's coastal waters, across an area of about 150 km in 2013 and 130km in 2015 (Fig. 3, Fig. 4A, C). Red discoloration phenomena were mostly restricted to the shoreline or to the first hundreds meters of the coastal waters (Fig. 4A). Across the three years, 14 over the 28 observations (50%) occurred in areas not monitored by the sanitary monitoring system (Table 1). Given their small surface area, they were mostly observed by tourists on the shore or people working in coastal waters. They were always linked to massive development and dominance in the phytoplankton samples of the protist *Noctiluca scintillans* (200-1200 µm in size, Fig. 4B). In 2013, red discolorations were observed mostly in July-August. In less than a week's time (21^{st} – 26^{th} July 2013), citizen observations were made almost simultaneously across an area of more than 150km, between the Yeu (21^{st} July) and Groix (22^{nd} July) islands in areas not monitored by the REPHY system (Fig. 3A) In 2014 and 2015 red discolorations attributable to *N. scintillans* discolorations were reported in southern Brittany earlier in the summer, in June-July. No observations were made in August in 2014 and 2015 (Figs 3A, 3B).

Fig. 3 here, Fig. 4 here

Green seawater discolorations were the most frequent phenomena detected over the three years (Table 1, Fig. 3, Fig. 4D, F). All warnings corresponded to massive development in phytoplankton samples of the dinoflagellate *Lepidodinium chlorophorum* (Fig. 4E). Green blooms of *L. chlorophorum* were observed in coastal and off shore areas, with some localized and some very widespread discolorations. Across the three years, 25 over the 36 green bloom observations (69%) occurred in areas not monitored by the sanitary monitoring system (Table 1). In 2013 green discolorations were detected four times in a relatively restricted area (between the Bay of Vilaine and the Loire River outlet), in a time window (from the 19^{th} to the 30^{th} of August) not sampled by the REPHY monitoring (Fig. 3A). In nearby REPHY zones, on the 26-28^{th} August, cell counts of *L. chlorophorum*, during the green discoloration phenomena varied between 14 800 cells.L^{-1} and 2.90 X 10^6 cells.L^{-1} (Le Croisic, Coupelasse large). In 2014, 24 observations of green water discolorations were reported almost daily over a period of about one about month (from the 3^{rd} to the 8^{th} of August) across a wider area than in 2013, throughout southern Brittany's coastal waters, remaining however more frequent in the Bay of Vilaine zone (Fig 3B). Discolorations were either limited to the shoreline and reported by beachgoers or largely extended off-shore waters and were observed by amateur yachtsmen and light aircraft pilots. Off-shore phenomena were particularly impressive due to their spatial extension (Fig. 5A). Discolorations occurred generally in surface waters, but a green bloom was also reported by a scuba diver at 23m depth on the 26^{th} July. When heavy water discolorations occurred in coastal waters, 9 citizens out of the 24 observing green water discolorations, reported slimy, dense waters, which emitted a pungent, unpleasant odor. From the 16^{th} to the 19^{th} of July, citizens reported fish (soles, sand eels, weevers), jellyfish, mollusks and crab mortalities both in the water (Fig. 5B) and washed up on the beach (Fig 5C). On five occasions (16^{th}, 17th 19^{th}, 21^{st}, 22^{nd} of July) multiple warnings were received from different locations, demonstrating both the amplitude of the phenomena and the concern of the citizens (Fig. 3B). The highest cell concentration of the species, 7.5 X 10^6 cells.L^{-1} was reported on the 22^{nd} of July (Port Manez), but it is likely that cell maxima during the episode largely exceeded this value. Due to this phenomenon, the 2014 season of the project has the highest number of warnings (Table 1). As in 2013, in 2015, green discolorations were less frequent, less extended, and located mainly outside of the REPHY (Table 1). No event was observed in August (Fig. 3C). Three observations were performed south of the *Phenomer* project's perimeter, demonstrating that these phenomena also occur at lower latitudes.

Fig. 5 here

Other phenomena were observed beyond *N. scintillans* and *L. cholorophorum* water discolorations. On August 12^{th} 2013, two separate citizen observations of dark-brown discolorations were reported from separate shallow locations in the Bay of Vilaine in zones not monitored by the REPHY network (Fig. 3A, Table 1). In phytoplankton samples collected in both areas on the same day following citizen warnings, co-occurring blooms of the marine-fauna toxic raphidophyte *Heterosigma akashiwo* (max 3.00 X 10^6 cells.L^{-1}) and the dictyochophyte *Pseudochattonella verruculosa* (max 1.90 X 10^6 cells.L^{-1}) were observed. Seawater dissolved oxygen concentrations at the sea floor in both locations were very low (4.9 and 5.5 mg L^{-1}), and at one site a mass mortality of bivalves and small crustaceans was observed. Other brown discolorations were attributed to diatom proliferations. On the 20^{th} July 2014 a red discoloration observed in the Bay of Brest, in an area not routinely monitored by the REPHY, was attributed to the massive presence (3.6 cells.L^{-1} on the 21^{st} of July, Penfoul) of the toxic dinoflagellate *Alexandrium minutum* (PSP causative species) (Fig. 3B, Table 1). A pinkish/brownish discoloration was observed by citizens on the 14^{th} June 2014 in the Iroise Sea (Douarnenez Bay). Microscopic analyses made it possible to attribute the discoloration to the massive presence of the dinoflagellate *Ceratium kofoidii* (1.85 X 10^5 cells·L^{-1}, June 14^{th}), associated to the presence of other species such as *Ceratium fusus* (1.26 X 10^4 cells·L^{-1}) and *Leptocylindrus danicus* (3.00 X 10^4 cells·L^{-1}) (Fig. 3B). Two brown discolorations in 2014 from both the English Channel and the Atlantic waters corresponded to a mixture of diatom species with higher concentrations of the species *Leptocylindrus danicus* (4.4 X 10^6 cells.L^{-1}, 16^{th} May) and *Guinardia delicatula* (9,8 X 10^5 cells.L^{-1}, 16^{th} May) among other diatoms (Fig. 2B). One event in 2015 was attributed to the bloom of

Brockmanniella brockmannii (Fig. 3C). On 9 March 2015 foams due the proliferation of *Phaeocystis* were observed in the north-eastern part of Brittany, facing the English Channel (Fig. 3C).

4. Discussion

The citizen science program *Phenomer* deployed in Brittany from 2013 to 2015 represents the first structured monitoring program of water discoloration phenomena in the area. It gives a good example of the validity of this new approach for studying and managing HAB phenomena. The project was an opportunity for a first sociological analysis of the audience and their motivation for reporting these phenomena. In addition, it provides new information useful to analyse HAB species phenology and distribution. *Phenomer* has revealed itself to be very complimentary to the ongoing French phytosanitary monitoring which was not designed for the detection of water discolorations, and has more generally helped to clarify the possible contribution and limits of the citizen science approach for plankton studies.

4.1 Citizen feedback

Citizens who took part in *Phenomer* had heard about project mostly through articles in the regional press and through the internet website. The target audience of Phenomer was composed entirely of people frequenting the Brittany coastline. Our questionnaire shows that people who took part in *Phenomer* were relatively well informed and interested about the aims of the project. Most of the people who took part in the project had heard about water discolorations caused by microalgae before the implementation of *Phenomer*. The majority (60%) of the observations whilst the participants carried out their professional activities (i.e. fishing, performing environmental analyses within Marine Protected Areas,etc.). However, during telephone discussions between scientists and observers some clarifications were given, especially concerning health risks connected to water discoloration phenomena. Often the difference between green macroalgal proliferations (i.e. *Ulva* spp.) and phytoplankton blooms was explained. Massive proliferations of green macroalgae that recurrently wash up on Brittany's beaches are a highly mediatized topic, and the difference between the two phenomena had to be carefully explained in the *Phenomer* communication materials and during phone conversations.

The questionnaire submitted to the water discoloration observers in 2015 helped to better identify the sociological profile of people participating to the project, as already discussed in other citizen science approaches (Martin et al., 2016). These first results show that the audience most receptive to *Phenomer* was a limited proportion of the total population frequenting the marine coastal zone. It was composed of people already informed about the water discoloration phenomena and their development. Their knowledge of this natural phenomenon drove them to call. They participated in the project because they wanted to know more about what they observed and the effects, if any, on humans and the environment. Their wish to help scientists in understanding triggering factors of water discolorations was particularly noticed. Water discolorations were not perceived as harmful phenomena, and the people taking part in the project were not protesting about these phenomena, but instead were people sensitive to and concerned by environmental issues. However, the profile of people participating to *Phenomer* in 2015 has to be considered in the light of the absence of major, impressive phenomena, and therefore as a typical *Phenomer* participant profile. In 2014, pre-analyses of people driven to signal water discoloration phenomena included not only typical profiles of well informed and environmentally concerned people, but also that of people alarmed by the repetitive and impressive green discoloration as well as the fauna mortalities recorded in July. Hence, the intrinsic natural variability of the water discolorations and their effects on the environment may trigger changes first and foremost in the people affected by, and aware ofthese phenomena. From a broader perspective, the nexus between a scientific and sociological analysis of HABs remains inadequate, and prevents the assessment of HAB real impact on human well-being (Wells et al., 2016).

4.2 Ecological analysis of the water discolorations observed

Despite only having been collected over a relatively short time period, and with an innovative approach for phytoplankton bloom studies, our data sheds new light on the frequency and spatial and temporal extension of water discoloration phenomena along Brittany's coastline. The first three years of the project running demonstrate variability in the number, frequency and month of summer in which alerts are reported. If most of water discolorations were signaled during the end of July and August, in 2015 red discolorations of *N. scintillans* were observed mostly in June and the last observation was performed on the 16th of July. The reasons for this variability are not found in a difference in the project implementation (i.e. communication efforts, scientific engagement) but rather in meteorological conditions which affected both phytoplankton proliferations and the tourist season. The end of summer 2015 was particularly cool and unsettled, with heavy rain at times, hampering phytoplankton development as well as tourism along the north Atlantic and English Channel ("Met Office UK Climate Summary - Summer 2015," n.d.). Water discoloration alerts can therefore vary from one year to the next not because of bias in our citizen science project construction, but because of the intrinsic biological variability of phytoplankton bloom phenology.

Most of the red discolorations observed during the three years of the project implementation are linked to the massive presence of the protist *Noctiluca scintillans*. This species is generally considered as an aberrant heterotrophic dinoflagellate, having significant morphological and biological differences with typical dinoflagellates (diploidy, presence of tentacle, absence of condensed chromosomes) (Gomez et al. 2010). *Noctiluca scintillans* can feed upon a large variety of preys (diatoms, dinoflagellates, copepod eggs and small ciliates), but diatoms seem to be its preferred food source for proliferation (Gomez et al. 2010). Cells start feeding and growing in the water column, then move to the surface, where the bloom is visible as a thin red layer. Therefore the red visible discolorations caused by *N. scintillans* actually correspond to the end of the species bloom (Harrison et al. 2011). Red discolorations are typical coastal phenomena as abundance of *N. scintillans* decreases offshore. High concentrations occur along water fronts (Hesse et al. 1989) and wind direction plays a role in concentrating the bloom at the shoreline (Harrison et al. 2011). Blooms of red *N. scintillans* are common and well-known phenomena across all French coastlines, as they have been observed in the English Channel (Boalch 1987), western Brittany (Le Fèvre & Grall 1970), the southern part of the Bay of Biscay (Quevedo et al. 1999; Cabal et al. 2008) and the Mediterranean Sea (Métivier & Soyer–Gobillard, 1988). Red discolorations are observed annually across Brittany waters, always through sporadic, *ad hoc* observations. Despite being visible from an aircraft, studies at large spatial scales are still missing. Le Fèvre and Grall (1970) studied a large bloom (20 nautical miles) which occurred on July 20th, 1967 off the western coast of Brittany (Iroise Sea) and concluded that a surface convergence area due to an outflow of coastal water produced a large bloom of *N. scintillans.* Observations reported by citizens during the summer 2013 within the framework of *Phenomer* project provide a first structured assessment of *N. scintillans* discolorations across southern Brittany waters and an estimate of their spatial extension. It is not possible to infer that all 2013 observations belonged to a unique bloom and population. Single, separate blooms could have occurred locally and/or at different times. Water horizontal transport coupled with wind direction (all 2013 events observed occurred with westerly winds) have certainly contributed to accumulate *N. scintillans* cells, spotlighting red discolorations, either in correspondence with frontal water masses, or in nearshore local embayment. Relatively low (max 3200 cell.L^{-1}) cell concentration counts for a phytoplankton bloom event in areas near observed phenomena argue in favor of a local, patchy accumulation of *N. scintillans* water discolorations across Brittany waters.

Green water discolorations caused by dinoflagellates are poorly scientifically documented (Honsell et al. 1988; Jimenez et al. 1992; Sournia et al. 1992; Paulmier et al. 1995, Elbrachter & Schnepf 1996). The dinoflagellate *Lepidodinium chlorophorum* has been recognized as one potential cause of these discolorations. It is a naked dinoflagellate of the ‘green lineage’ of the dinoflagellate evolution characterized by the presence of chlorophyll *b* as the principal pigment, which gives the green color to the dinoflagellate (Hansen et al. 2007; Siano et al 2009). Green water discolorations caused by *Lepidodinium* spp. can be extensive and spectacular phenomena reported from Italy (Adriatic Sea) (Honsell et al. 1988), the North-West of Spain (Jimenez et al. 1992) and the North Sea (Elbrachter & Schnepf 1996). In France, the species was reported along the West Atlantic coast for the first time in 1982 (Lassus 1988). Since then, the abundance, extent, duration and intensity of the blooms have seemingly increased, with large water discolorations being observed in the Bay of Vilaine (southern Brittany) and in the Bay of Seine (English Channel, Normandy) until 1991 (Sournia et al. 1992).

As reported by Sournia et al. (1992), discolorations caused by *L. chlorophorum* were reported via *Phenomer* as being gelatinous, mucous or slimy. Tourists and swimmers complained about the appearance and consistency of seawater. Depending on the episodes and their locations, mortality of mussels, oysters, smaller mollusks, shrimps, crabs, and smaller crustaceans, werelinked to a decrease of the oxygen availability due to the decomposition of the phytoplankton biomass. Between 1982 and 1991, Sournia et al. (1992) correlated water discolorations with riverine freshwater inputs. Cysts of the species were observed in water samples and daily vertical migration of the species was observed with peaks in concentration varying throughout the water column (Sournia et al. 1992). Discolorations during 1982-1991 were reported in the summer time, except for two episodes which occurred in autumn (October and December) (Sournia et al. 1992). It is acknowledged that *L. chlorophorum* can be an important component of the late summer-autumn phytoplankton community, as reported in the English Channel (Napoléon et al. 2014). Episodes reported by citizens in 2013 and 2014 in the frame of the *Phenomer* project confirmed that the Vilaine Bay and the Loire River output in southern Brittany are high risk areas for *L. chlorophorum* blooms. 2014 observations yielded new information on the areas which could be potentially affected by these phenomena, both to the north and to the south of the Loire River output and the Vilaine Bay (Fig. 3B). Data collected in the frame of *Phenomer* suggest *L. chlorophorum* blooms can be long lasting across southern Brittany waters. Continuous data (almost daily citizen alerts, 24 observations in total) over a period of almost one month suggest that blooms of this species can last at least one month and that a higher intensity of *L. chlorophorum* blooms can coincide with a fish mortality presumably caused by anoxic conditions. Interestingly, *L. chlorophorum* was considered as not being ingested by the oyster *Magallana gigas,*

,after in-situ observations carried out in the Bay of Vilaine, which suggest a potential negative effect on oyster growth during bloom concentrations (Alunno-Bruscia et al. 2011).

Dark brown discolorations caused by diatoms, as those observed in the frame of the *Phenomer* projet, are frequent phenomena reported worldwide. Other microalgae of the phylum Ochrophyta (Heterokontophyta) are responsible for dark brown discolorations, including members of the class Raphidophyta and Dictyochophyta to which *Heterosigma akashiwo* and *Pseudochattonella verruculosa* (ex. *Chattonella verruculosa*, Hosoi-Tanabe S. 2007) belong respectively. Both species have been traditionally associated to fish mortalities (Hara and Chihara, 1987, Yamamoto & Tanaka 1990; Hallegraeff & Hara 1995), but their toxic effect can potentially extend to other marine organisms. Indeed *in vitro* experiments demonstrated that *H. akashiwo* may have lethal and sublethal impacts on shellfish (Hégaret et al. 2011) and that rotifers died when fed upon *P. verruculosa* (Chang et al. 2014). It is hard to discern if the episode of massive mortality of bivalves and small crustaceans observed in 2013 is related to the high concentration of one or both toxic species, or to the anoxic conditions which developed during the bloom.

4.3 Citizen science as a complementary approach to phytoplankton studies and monitoring programs: advantages and limits

Citizen sciences offer the possibility to increase the frequency of observations/samples of a research program providing relatively low cost-data (Jarvis et al., 2015). The example of *Phenomer* showed that the citizen science approach may be applied to plankton data collection and analyses and that the information gained through this method allows the acquisition of information that can be overtaken by routine plankton monitoring. The 61% of water discolorations observed by citizens were sampled outside of areas covered by the REPHY French monitoring system (Table 1). This monitoring network, as with all those classically used for sanitary purposes, was not conceived for surveying and studying water discoloration. Hence, *Phenomer* demonstrated therefore that a citizen science network can complete routine monitoring systems for structuring the detection and analysis of water discoloration phenomena. In addition, *Phenomer* provided new scientific information and pointers for studying the phenology of water discoloration causing species, as well as new information on the biogeography of species capable of HAB events.

Our example of a citizen approach for getting information on plankton, allowed us to better discern identification of the constraints and limits of such an application. Obtaining data on species responsible for seawater discolorations, is dependent on: i) the frequency at which coastal zones are observed and subsequently sampled with respect to other areas (see Jarvis et al., 2015 for the analysis of the importance of citizen science in the marine spatial planning of coastal ecosystems), ii) the perception and identification of an 'anomalous' phenomenon (an unusual color of the sea) by the general public, iii) the awareness, responsiveness and sense of civil responsibility of the citizens towards the marine environment and potential ecological risks, and iv) the rapidity and the quantity of the analysis of bloom samples.

Despite communication efforts about water discolorations remaining constant throughout the three years of project deployment and across the geographic Brittany territory, we cannot ensure that the *Phenomer* program accounts for all discoloration phenomena occurring in Brittany. In the English Channel sector only a few discolorations caused by diatoms were reported in 2014 and 2015. It is possible that other unreported visible blooms may have occurred in this area. Indeed blooms of phytoplankton taxa exceeding for example from 1 to 7 million cells.L^{-1} (*Chaetoceros* spp., *Dactyliosolen fragilissimus*, *Pseudo-nitzschia* spp., cryptophytes, *Thalassionema* spp.) were detected in the northern as well as in southern stations of the REPHY network (REPHY data). Yet, such high cell concentrations do not automatically correspond to water discolorations. Conversely, seawater discolorations do not always correspond to phytoplankton high abundances. Seawater can be colored for instance by pollutants (i.e. oils, petrol), sediment suspension, and other physico-chemical properties. This aspect has been taken into account in the formulation of the protocol and always analyzed during the interview made by scientists to the water discoloration observers. In some ecosystems, natural phenomena (storms, rains, winds, currents, and river plumes) can contribute to re-suspend bottom sediments and increase water turbidity, thus giving the sea a more or less dark/light brown color for example. The color of the sea that a common citizen can perceive as 'normal' is a relative concept, strictly dependent on the ecosystems. People living along stretches of coastline with clear waters can relatively easily identify a drastic change in the color of the sea and react to this phenomenon. However, people living on coastlines with turbid coastal waters are used to a light/dark brown appearance of the seawater. They may therefore have difficulties, first in perceiving 'anomalous' dark brown discolorations and second in attributing them to phytoplankton bloom events. Only a multiannual evaluation of the number and frequency of the alerts collected by *Phenomer,* coupled with an interview analysis of the observers with respect to their ecosystems will smooth the bias linked to coast frequentation and citizen reactivity, eventually allowing a complete census of all discoloration phenomena potentially occurring across Brittany coastal waters.

The rapid analysis of a water discoloration sample and the correct taxonomic identification of responsible species are needed for biodiversity and ecological studies on microalgae. Dark brown discolorations may be caused by different algal species and even classes. Equally, different shades of red discolorations may be provoked not only by *N. scintillans* but also by other dinoflagellates (e.g. *Alexandrium*. spp., *Prorocentrum* spp., *Ceratium* spp.), ciliates (e.g. *Mesodinium rubrum*) and cryptophytes. Whilst it is true that few dinoflagellates may cause green discolorations, other green-pigmented microalgal classes (Prasinophyta and Cyanophyta) are known to frequently provoke green blooms. It is therefore incorrect and a potential risk to associate univocally a color of the water to a single microalga. The collection of water samples and their analysis is of course time consuming and may be discouraging, but it is a key component in the longevity and scientific validity of a citizen science project addressing ecological and biodiversity questions on plankton In the frame of *Phenomer*, if the reactivity and the participation of people after a water discoloration observation was successful, the logistics for ensuring a rapid and efficient sample collection were heavy. In 2013, 10 observed phenomena could not be sampled. In the following years the set-up of the relay structure network revealed to be a good strategy to overcome the problem and fewer phenomena (7 in 2014 and 2 in 2015) were overlooked. The down-sizing of the study area, or a citizen science strategy based on a specific community of people (shellfish farmers, environmental associations) rather than a very broad target audience such as that in *Phenomer*, could probably help in the building trust and loyalty between researchers and citizens, which are the very foundations of a citizen science approach.

5. Conclusions

Results obtained on the Brittany coast of France in the first three years (2013-2015) of deployment of the *Phenomer* project show that our citizen science approach was very helpful for: 1) signaling water discoloration phenomena not observed by the routine, national monitoring, thus showing the complementarity of these two networks; 2) assessing a potential spatial extension of water discolorations, and particularly of those caused by *N. scintillans* across southern Brittany; 3) giving a time frame to the duration of discoloration phenomena, in particular of green ones caused by *L. chlorophorum* in the Vilaine Bay-Loire estuary area. As well as being of regional interest, these data contribute to the study of global biogeography of harmful species and HAB events.

In addition, a first sociological profile of people concerned by water discolorations was elaborated. People concerned by water discoloration phenomena were well-informed citizens, aware of and concerned by environmental issues. Water discolorations are mostly perceived as an anomalous, alarming status of the environment. However the sociological profile of people participating in such a citizen science project can vary accordingly to the gravity of water discolorations occurrences and effects.

Phenomer has shown the potential of citizen science in research on phytoplankton ecology, biodiversity and visible HAB detections and allows the identification of some recommendations. Future application of the citizen science approach to plankton should: i) carefully evaluate, at the time of designing the study, how citizens can help to attain scientific research objectives (information to be collected, sampling frequency, relay points to deposit samples); ii) develop clear and simple communication medium presenting the research objectives and sampling protocol; iii) target the community of people that could be more concerned by the problematic of the project as a guarantee of citizen investment in the project activities. Beyond scientific objectives, the application of a citizen science approach in the frame of a research project has the great unquantifiable value of disseminating knowledge on microscopic organisms, and educating voluntary participants to environmental issues connected to phytoplankton such as HABs. Citizen science could be a new method to helping HABs be recognized as one facet of complex ecosystem interactions with human society. This approach, coupled with research, monitoring, and management of HAB phenomena, could help to find local solutions to a global issue.

Acknowledgments

The authors gratefully acknowledge all *Phenomer* participants (citizens and scientists) who shared discoloration observations and provided data and pictures of the phytoplankton blooms. The communication service of Ifremer/Nantes, and in particular Sophie Pilven, is greatly acknowledged for its support for all communication actions and information dissemination of the project. The authors kindly thank Elisabeth Nézan and Nicolas Chomérat (Ifremer LER/BO Concarneau) for their help in the identification of the species toxic for marine fauna in occasion of the brown discolorations and for providing pictures of *N. scintillans* and *L. chlorophorum* (Fig. 3). The authors also thank Beatriz Beker, Charlotte Soler (LEMAR) and Pascale Malestroit (Ifremer) for their identification of microalgal species. Pierre Bodénès is acknowledged for his help in figure designing. Support for *Phenomer* was provided by the “Quels littoraux pour demain?” grant of the *Fondation de France* (grant n°:00038383), the Loire-Brittany Water Agency, the French Ministry of Environment and Ifremer for supporting all scientific and communication action strategies of the project. The objectives of *Phenomer* tie in to the scope of the French GDR (Groupement de Recherche) on harmful microalgae Phycotox (http://www.phycotox/fr). The anonymous referees are acknowledged for providing major improvements to the manuscript.

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Table and Figure Captions

Fig. 1. *Phenomer* water discoloration reporting process flowchart **(single column fitting)**

Fig. 2. Citizen perception of water discolorations (A) and motivation to report their observations (B). **(single column fitting).**

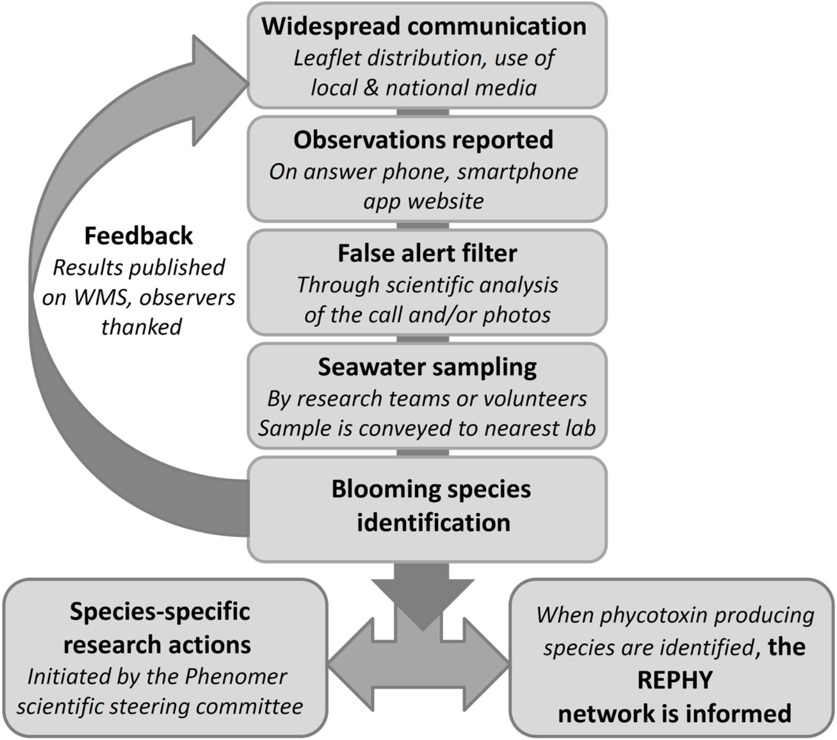
Fig. 3. Water discoloration phenomena reported by citizens in 2013, 2014 and 2015 and dominant taxa identified by the phytoplankton taxonomists of the *Phenomer* consortium in water samples. Sampling stations of the National Phytoplankton Monitoring System REPHY of Ifremer are also indicated. **(two column fitting).**

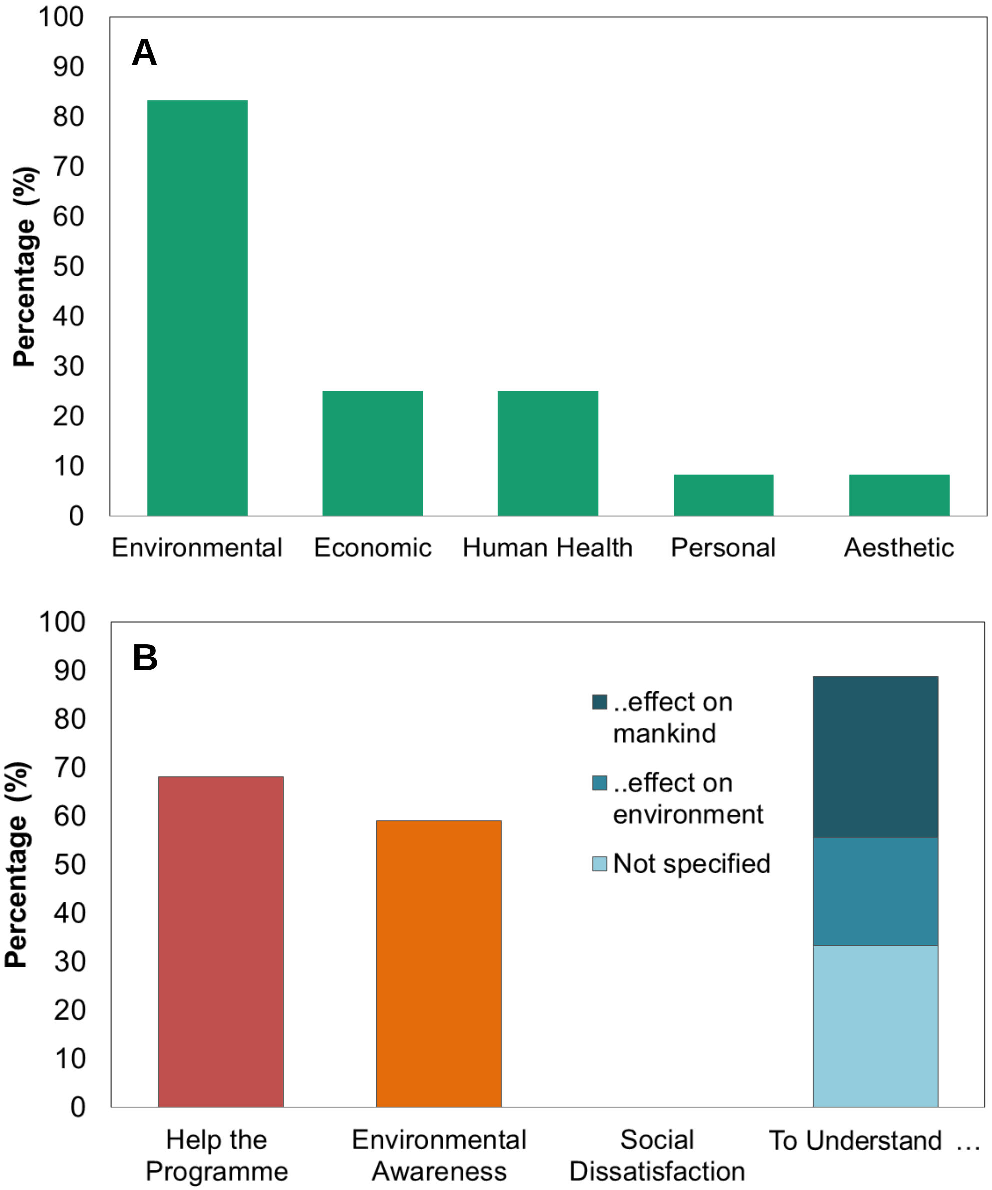
Fig. 4. Red discoloration pictures (A, C), caused by *Noctiluca scintillans* (B, scale bar: 50 µm). Green discoloration pictures (D, F) caused by *Lepidodinium chlorophorum* (E, scale bar: 20µm). Pictures A, C, D and F are taken either by citizens from the coast and or from aircrafts (C). **(1.5 column fitting).**

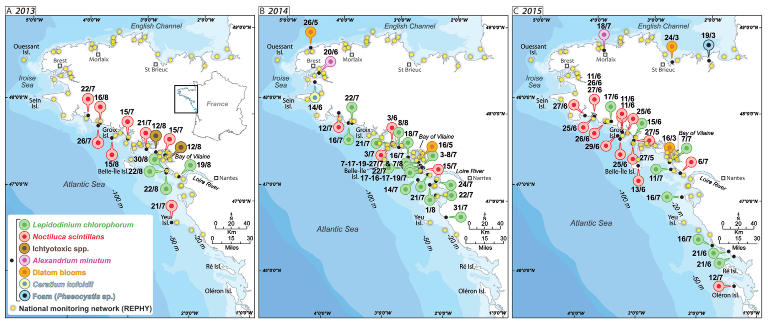
Fig. 5. Green discolorations and fish mortality in the Bay of Vilaine (South of Brittany) in 2014. **(1.5 column fitting).**

Supp. Fig. 1. Screenshots of the iOS Phenomer Smartphone application (available in French only). The third panel illustrates the « nearest relay structures to you » function.

Supp. Material 1. Questionnaire taken by water discolorations observers either during phone interviews or via the on-line form present on the website (French version online).


Widespread communication
Leaflet distribution, use of local & national media
Observations reported
On answer phone, smartphone app website
False alert filter
Through scientific analysis of the call and/or photos
Seawater sampling
By research teams or volunteers
Sample is conveyed to nearest lab
Blooming species identification
Feedback
Results published on WMS, observers thanked
Species-specific research actions
Initiated by the Phenomer scientific steering committee
When phycotoxin producing species are identified, the REPHY network is informed


A
Percentage (%)
100
90
80
70
60
50
40
30
20
10
0
Environmental
Economic
Human Health
Personal
Aesthetic
B
Percentage (%)
..effect on mankind
..effect on environment
Not specified
Help the Programme
Environmental Awareness
Social Dissatisfaction
To Understand …


A 2013
B 2014
C 2015
English Channel
Ouessant Isl.
Brest
Morlaix
St Brieuc
Iroise Sea
Sein Isl.
Groix Isl.
Belle-Île Isl.
Bay of Vilaine
Loire River
Nantes
Yeu Isl.
Ré Isl.
Oléron Isl.
Atlantic Sea
France
-100 m
-50 m
-20 m
Lepidodinium chlorophorum
Noctiluca scintillans
Ichtyotoxic spp.
Alexandrium minutum
Diatom blooms
Ceratium kofoidii
Foam (Phaeocystis sp.)
National monitoring network (REPHY)
Km
Miles
22/7
16/8
26/7
15/7
15/8
21/7
12/8
15/7
12/8
30/8
22/8
19/8
22/8
21/7
26/5
20/6
14/6
22/7
12/7
16/7
21/7
3/6
8/8
18/7
16/5
3/7
16/7
3-8/7
7-17-19-27/7 & 7/8
22/7
17-16-17-19/7
15/7
14/7
21/7
24/7
22/7
1/8
31/7
18/7
24/3
19/3
11/6
26/6
27/6
17/6
11/6
11/6
25/6
27/6
25/6
26/6
29/6
15/6
27/5
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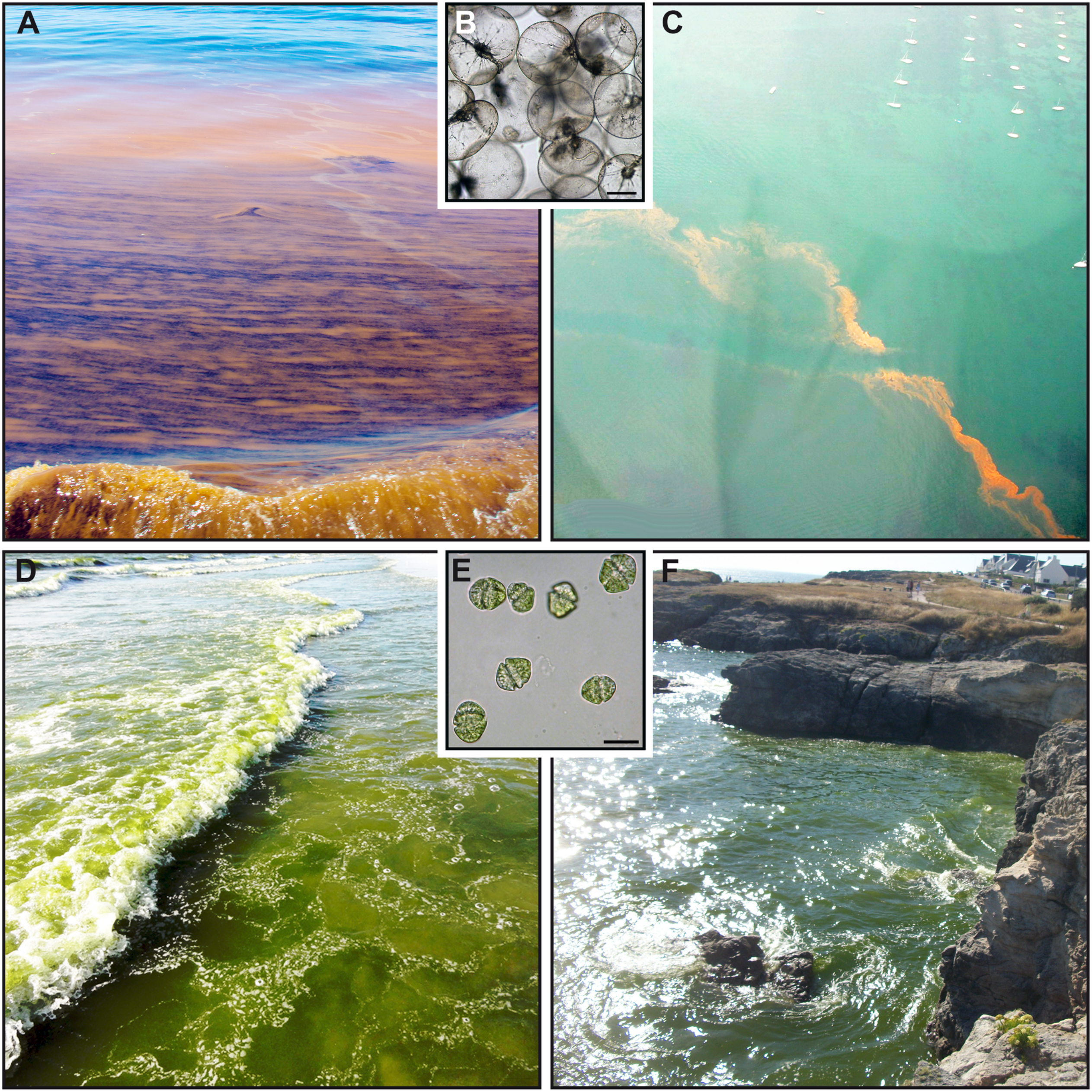
21/6
12/7


A
B
C
D
E
F


A
B
C

	Contacts	n. of different observers	Contact method	False alarms	Plankton-related observations	Potential water discolorations	Discolorations observed within the perimeter of routine phytoplankton monitoring	Discolorations observed outside of the area covered by routine phytoplankton monitoring	Water discolorations sampled	*Noctiluca scintillans* discolorations sampled via routine phytoplankton monitoring vs. Phenomer	*Lepidodinium chlorophorum* discolorations sampled via routine phytoplankton monitoring vs. Phenomer	Other discolorations sampled via routine phytoplankton monitoring vs Phenomer
2013	69	69	Voicemail:29 Online form: 18 E-mail: 22	29	40	24	14	10	14	4-4	3-1	0-2
2014	74	68	Voicemail: 12 Online form: 51 E-mail: 11	34	40	40	9	31	32	1-3	6-18	1-3
2015	88	83	Voicemail: 32 Online form: 48 E-mail: 8	41	47	30	15	15	28	9-7	2-6	3-1