Economic impact of harmful algal blooms on human health: a systematic review

Christian R. C. Kouakou and Thomas G. Poder

ABSTRACT

Harmful algal blooms (HABs) damage human activities and health. While there is wide literature on economic losses, little is known about the economic impact on human health. In this review, we systematically retrieved papers which presented health costs following exposure to HABs. A systematic review was conducted up to January 2019 in databases such as ScienceDirect and PubMed, and 16 studies were selected. Health costs included healthcare and medication expenses, loss of income due to illness, cost of pain and suffering, and cost of death. Two categories of illness (digestive and respiratory) were considered for health costs. For digestive illness cost, we found $86, $1,015 and $12,605, respectively, for mild, moderate and severe cases. For respiratory illness, costs were $86, $1,235 and $14,600, respectively, for mild, moderate and severe cases. We used Quality-Adjusted Life Years (QALYs) to access the loss of well-being due to illness caused by HABs. We found that breathing difficulty causes the most loss of QALYs, especially in children, with a loss of between 0.16 and 0.771 per child. Having gastroenteritis could cause a loss of between 2.2 and 7.1 QALYs per 1,000 children. Misleading symptoms of illness following exposure to HABs could cause bias in health costs estimations.

Key words | cost, harmful algal bloom, human health, QALY, water

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INTRODUCTION

Harmful algal blooms (HABs) produce toxins that can adversely affect human health (Backer & McGillicuddy 2006; Figgatt *et al.* 2016). Human exposure to harmful algae can occur in many ways (Otten & Paerl 2015), i.e., through recreational water (direct or indirect contact), drinking contaminated water, or consuming food (e.g., fish and contaminated seafood) (Vasconcelos 1999; de Magalhaes *et al.* 2001; Lee *et al.* 2017). Potential health problems vary and strongly depend on the level of exposure to the source of contamination (Bláha *et al.* 2009). The main problems encountered are gastroenteritis, abdominal pain, nausea, vomiting, diarrhea, muscle aches, fever, liver, kidney, and intestinal damage, and more (Chorus *et al.* 2000; Koreivienė *et al.* 2014; Wood 2016; Svirčev *et al.* 2017). Cases of death were reported following dialysis with contaminated water (Jochimsen *et al.* 1998; Carmichael *et al.* 2001; Azevedo *et al.* 2002) or after the consumption of contaminated water (Teixeira *et al.* 1993).

Despite the known toxicity of harmful algae, the consumption of some algae (i.e., cyanobacteria) is voluntary in some cases (i.e., blue-green algae supplements) mainly due to their high protein content and some health benefits (e.g., detox, elevated mood and energy, increased alertness and vivacity) (Dietrich & Hoeger 2005; Drobac *et al.* 2013; Ananya & Ahmad 2014). However, some authors found that some algae dietary supplements contained 'cyanotoxins at levels exceeding the tolerable daily intake values' (Roy-Lachapelle *et al.* 2017). Beyond the direct health consequences, HABs also have an impact on recreational activities by degrading the esthetic quality of recreational waters' coloring and producing

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a bad smell (Dodds *et al.* 2009; Carmichael & Boyer 2016), which can affect the quality of life for residents.

The literature is full of articles relating the health consequences of exposure to harmful algae (Pilotto *et al.* 1997; Osborne *et al.* 2007; Hilborn *et al.* 2014; Lévesque *et al.* 2014, 2016). However, fewer are those reporting the economic consequences related to health (e.g., costs of care, economic impacts, and quality of life). This systematic review aims to report the costs and health economic consequences of contamination episodes by harmful algae including cyanobacteria. Precisely, this review aims to document the monetary costs of contamination episodes (i.e., medical consultation, hospitalization, emergency visits, drug expenditures, and loss of productivity) and the impact on health-related quality of life. We chose to do a systematic review of the literature on this topic since it is an effective way to inform decision-makers and help them make a decision based on reliable evidence (Bennett *et al.* 2018).

METHODS

Research strategy

Databases consulted were Medline EBSCO, Scopus, ScienceDirect (Elsevier), PubMed, and the Cochrane Library. A search in the gray literature was carried out via Google, Google Scholar, and the websites of the public health agencies of Canada and Quebec. We also consulted the bibliographical references of the selected articles to collect additional relevant references. Keywords used for research were HAB, harmful algal bloom, toxin, cyanobacteria, blue-green algae, health, economic, economics, cost, QALY, and Quality-Adjusted Life Year. With the Boolean operators 'AND' and 'OR,' we made combinations between the keywords to get closer to the desired meaning. We also performed a search with the entire title of our article ('Economic impact of harmful algal bloom and cyanobacteria on human health') in Google and Google Scholar. No language or date restrictions were used. The search was carried out in English in the databases named above, then in English and French in Google, Google Scholar, and the public health agencies' internet pages. The search ended on 7 January 2019 (see Table A1 in Supplementary Material, available with the online version of this paper).

Studies' selection

In our documentary research protocol, the selection of studies was based on these criteria:

- Studies (e.g., article, review, report, and note) connected with HAB, blue-green algae, toxins, or cyanobacteria.
- Studies including health episodes, public health costs, and healthcare costs.
- Studies including an effect on health-related quality of life.

Excluded studies were those that did not include health effects (e.g., only environment and tourism). We excluded studies about the waterborne or foodborne disease which did not specifically talk about harmful algae.

The first selection of studies was made after two evaluators read the titles and summaries. Studies selected at this stage were then read in full and only kept if they met the inclusion criteria. We had no restrictions on the target population. Data extraction was done by an evaluator and validated by a second. In case of discrepancy in the data collected, a call to an arbitrator was made.

The main information we sought to collect was symptoms related to disease, frequency of healthcare consumption (e.g., consultation, emergencies, and medication), expenses related to these health episodes and the resulting loss of health-related quality of life (e.g., QALY).

Data analysis

We did a descriptive analysis of the data. Cost data were extracted and then capitalized in 2016 US dollars. If an article did not specify the year of reference for the costs, the article's year of publication was considered the reference year. For the capitalization of costs in 2016 US dollars, we used the price index available in the World Development Indicators (WDI) database of the World Bank (WB). Symptoms were grouped according to the major categories. Then, we described health episodes in terms of consultation, care, and medical monitoring. Costs associated with healthcare were calculated based on data available and the size of the sample concerned. As appropriate, we reported the data per case, per day of sickness, or per kilometer of coastline. The quality of each study was evaluated by a grid. We used the NIH Quality Assessment

Tool to evaluate primary studies (NHLBI 2014), AMSTAR for literature reviews (Shea *et al.* 2007), and the grid AGREE II for reports (Brouwers *et al.* 2010).

RESULTS

Studies' selection

The PRISMA flow diagram (Figure 1) presents a detailed process for selecting the articles in our systematic review. In total, 1,524 articles were identified, and 69 were read in full to evaluate their eligibility. Ultimately, 16 studies were selected to include in this review. The reason for excluding studies that were fully read was as follows: studies reported waterborne diseases only without cost data ($n = 22$) or general waterborne disease without linking with harmful algae ($n = 4$); studies reported economic cost but not for health ($n = 6$); study reported willingness to pay for harmful algae health hazard reduction ($n = 1$); studies reported general impact (e.g., biological and ecological) of harmful algae ($n = 9$); studies reported ocean pollution ($n = 2$); studies reported seafood contamination ($n = 5$) and cost of food-borne disease ($n = 2$); study reported health episode and cost data for general waterborne illness ($n = 1$); and study valuing protection against invasive marine species ($n = 1$).

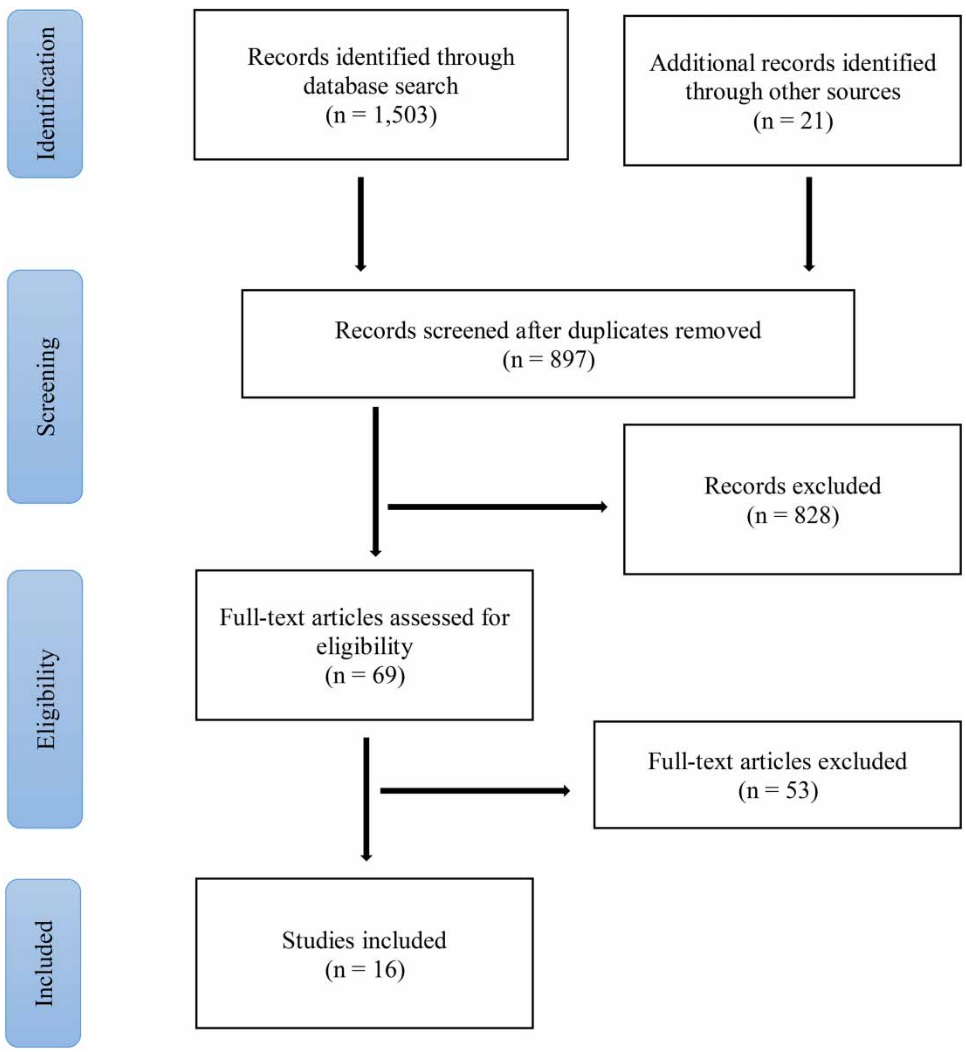

Figure 1 | PRISMA flow diagram for the selection of studies, 7 January 2019.

Characteristics of studies included

Three main types of studies were identified as primary studies ($n = 9$) (Table 1), literature reviews ($n = 2$) (Table 2), and reports ($n = 5$) (Table 3). Most studies were about the United States ($n = 13$), some on the European Union ($n = 2$) and Canada ($n = 3$), and two were about Pacific Ocean Islands (French Polynesia and the Cook Islands). Data were all published in the 2000s except one study in 1995. The studies focused most often on harmful algae, without specifying the type of algae. When reported, the source of water was coastal or salt water ($n = 10$) and freshwater ($n = 2$). While some studies focused on costs at a national level, other costs were by the cause of illness or sick day.

Symptoms developed and health episodes

Symptoms developed

The studies retrieved in this review contain cost data related to health issues following contamination by harmful algae. However, most of the studies do not show explicit information about symptoms developed and subsequent health episodes. This precludes documenting the impact of HABs on health-related quality of life. To document more exhaustively these symptoms and better understand their typology, we had to complete our list with additional studies. These studies were collected from the list of full-text articles assessed for eligibility. The studies selected were those that reported diseases and health episodes due to exposure to cyanobacteria and HABs. We grouped the symptoms identified into six major groups, adapted from Hilborn *et al.* (2014), and the last one which concerns death (Table 4).

Symptoms are related to the type of contact with contaminated water. Among non-food contacts, swimming appeared as the riskiest, with the greatest number of symptoms of all types. Skin symptoms were most frequently cited in the studies. Some cases of death were reported in the literature (Jochimsen *et al.* 1998; Carmichael *et al.* 2001; Azevedo *et al.* 2002). In fact, in Brazil about 50 people died from a deficiency of the liver after receiving hemodialysis treatment with cyanotoxin-contaminated water. People who had indirect contact (e.g., inhalation of water spray) with water had a higher risk, probably because they did not take sufficient protection measures (Lévesque 2009).

Besides the symptoms that generally develop as a result of direct or indirect contact with water, the literature also presents cases of diseases following the consumption of foods exposed to toxins, for most crustaceans, mollusks, and fish (Todd 1995; Andreatta *et al.* 2012; Sanseverino *et al.* 2016). Several other categories of food poisoning are therefore listed under different names, for example, amnesia shellfish poisoning (ASP), paralytic shellfish poisoning (PSP), diarrhea shellfish poisoning (DSP), neurotoxic shellfish poisoning (NSP), Azaspiracids shellfish poisoning (AZP), and ciguatera (ciguatera poisoning). A study in Canada (Todd 1995) calculated an annual estimate of 150 cases of PSP, 50 cases of DSP, and 325 cases of ciguatera. These cases were determined based on a combination of official data (Health and Welfare Canada) and hypotheses established by experts (Todd 1976, 1989a, 1989b, 1989c, 1992).

In addition, long-term (chronic) effects such as liver cancer, colorectal cancer, and even death because of chronic harmful algae exposure are cited in the literature (Lopez *et al.* 2008; Bláha *et al.* 2009; Cheung *et al.* 2013). These chronic effects are, however, 'more difficult to highlight than acute effects' (Belleville *et al.* 2009).

Reported cases of health episodes

Among the health episodes, the study of Hilborn *et al.* (2014) reported some health episodes for the years 2009/2010 in the United States following 11 epidemics associated with freshwater and toxic algae (cyanobacteria). Of the 58 persons surveyed, two were hospitalized, 34 consulted with a healthcare provider, and seven visited the emergency department. No death was recorded. A first estimate of the number of cases of the disease following harmful algae contamination was made (Figgatt *et al.* 2016) over the period 2008–2014 for the state of New York. In this study, the authors found that 228 people visited hospitals over the 5-year period considered. This equals about 32 visits per year. Thereafter, 17 cases of algae contamination for the year 2015 in New York state (Figgatt *et al.* 2017) were listed. These cases included primary care and emergency visits; no hospitalization was specified. A study (Carmichael & Boyer 2016) identified human and animal disease cases

Table 1 | Characteristics of studies included (primary studies)

Authors (year) country	Data source	Water source/algae types or toxins	Symptoms/observations	Estimated costs for health	Cost type	Quality of the study (NIH)
Todd (1995) Canada	Estimated by the author	Coastal water (saltwater)/not specified	Illnesses from seafood	\$590 K annual for 525 cases, or \$1,124 per case of foodborne poisoning by harmful algae \$500 K for death	Illness cost for a person eating seafood. No value attributed to pain, grief, or suffering	6/14
Hoagland *et al.* (2002) United States	Survey of experts, review of literature, authors' calculation	Coastal water (saltwater)/not specified	Shellfish poisoning, ciguatera fish poisoning	Approximately \$20M per year nationwide (\$2000)	Hospitalization, investigation, productivity loss and death	9/14
Hoagland & Scatasta (2006) European Union and United States	Data from published and unpublished studies	Coastal water (saltwater)/not specified	Shellfish poisoning, ciguatera fish poisoning	\$11M for the European Union and \$37M for the USA, per year (\$2005)	Updated cost from Hoagland *et al.* (2002) and Anderson *et al.* (2000)	7/14
Hoagland *et al.* (2009) Florida (United States)	Department of Emergency Sarasota Memorial Hospital and US Census Bureau	Coastal water (saltwater)/*Karenia brevis*	Respiratory illnesses	\$0.52M–\$4.18M over 5 years for Sarasota County only (\$2008)	Emergency department visits and productivity loss	10/14
Hoagland *et al.* (2014) Florida (United States)	Florida Agency for Health Care Administration, Florida Department of Agriculture and Consumer Services, US Census Bureau	Coastal water (saltwater)/*Karenia brevis*	Respiratory illness, digestive illness	\$60 K–\$700 K annually for Florida (\$2013)	Treatment cost (emergency visit, hospital admission) and lost incomes during both treatment and recuperation	9/14
Morin *et al.* (2016) French Polynesia	Survey, hospital data, literature	Lagoon (fresh water)	Ciguatera fish poisoning	\$1,613 for each reported case and \$749 for each unreported case \$1,146 overall for each case (reported or unreported) (\$2016)	Hospitalization fees, medication fees, cost of non-productive days	7/14

(*continued*)

Table 1 | continued

Authors (year) country	Data source	Water source/algae types or toxins	Symptoms/observations	Estimated costs for health	Cost type	Quality of the study (NIH)
Rongo & van Woesik (2012) Southern Cook Islands	Survey, ministry of health, local pharmacists, statistics office	Lagoon (fresh water)	Ciguatera poisoning	$1,400 for an individual with ciguatera poisoning	Hospital and staff time involved in the treatment, price of pharmaceuticals, lost labor productivity	8/14
Nierenberg *et al.* (2010) Florida (United States)	Beach Lifeguard Survey, county public records, and a WTP study by Blackwell & Tunny (2000)	Coastal water (saltwater)/*Karenia brevis*	Absenteeism and presenteeism of rescuers due to illness	Average cost of absenteeism estimated at $3,000. Presenteeism could be estimated at $82,772 ($2009)	Productivity loss and cost of medical treatments	9/14
Ralston *et al.* (2011) United States	Literature, surveillance and monitoring data and a cost-of-illness model from the USDA	Coastal water (saltwater)/not specified	All consequences (pathologies of marine origin, food, recreation)	$900M annual for the whole of the United States, two-third by alimentary intoxication and one-third by direct contact	Costs include lost wages, physician and hospital services, and statistical cost of premature death	9/14

K, Thousand; M, Million.

Table 2 | Characteristics of studies included (literature reviews)

Authors (year) country	Number of studies	Water source/algae type or toxins	Estimated health costs	Quality of the study (AMSTAR)
Fleming *et al.* (2011) Florida (United States)	Two for the health costs section	Coastal water (saltwater)/*Karenia brevis*	Vary according to the studies from $3 K per case to $4M annually for the county of Sarasota (Florida)	0/11
Adams & Larkin (2013) United States, Canada, European Union	Nine studies with health costs	Not specified/various	Vary according to studies from $100 K to $900M annually for countries (or regions)	3/11

K, Thousand; M, Million.

Table 3 | Characteristics of studies included (reports)

Authors (year) country	Population	Symptoms/observations	Estimated costs for health	Quality of the study (AGREE II)
Anderson *et al.* (2000) United States	United States	Diseases caused by seafood, ciguatera, and undeclared diseases	$18.4M–$25M annual ($2000)	3/7
Bauer (2006) United States	United States	Intoxication by the consumption of seafood and ciguatera	$31.5M ($2000)	6/7
Andreatta *et al.* (2012) United States	United States	Not reported	$37M ($2005)	4/7
USEPA (2015) United States	Sarasota County, Florida	Not reported	$21 K–$138.6 K per year ($2012)	4/7
Sanseverino *et al.* (2016) Canada, United States	Canada, United States	Not reported	$20 K–$900M per year	3/7

K, Thousand; M, Million.

for the Great Lakes region of North America. The authors identified 68 region-wide cases over the 2010–2015 period, an average of 12 cases per year. A Quebec public health report (MSSS 2014) on blue-green algae indicated that from 2006 to 2012, the public health department received 34 reports of diseases potentially related to harmful algae. These reports involved 77 people, but only 25 cases were probably related to harmful algae. An epidemiological study (Lévesque 2009) conducted in Quebec in summer 2009 on a sample of 466 people found that, for example, 69% of participants reported respiratory symptoms, 49% reported headaches, and 58% reported gastrointestinal problems. Following a bloom of algae in Sarasota County, Florida, an annual estimate of visits to emergency services between 2001 and 2006 was conducted (Hoagland *et al.* 2009). Emergency services for respiratory diseases received an average of 76 visits per year (min = 39; max = 218).

Diseases reported because of contact with water potentially infected with algae are not all directly caused by algae; there are suspected cases (Figgatt *et al.* 2017). However, some cases are confirmed to be directly caused by toxic algae, including cyanobacteria. These cases of reported diseases are underestimated, according to Todd (1989c), who proposed a multiplier of 10 as a reasonable figure, especially for food contamination cases by toxic algae. According to him, the reported diseases represent only 10% of the total diseases. This multiplier is also used in other studies (Anderson *et al.* 2000; Hoagland *et al.* 2002).

Table 4 | Categories of symptoms developed because of exposure to harmful algae

	Symptoms	References
General	Dizziness, muscle aches, fatigue, sore throat, discomfort, weakness, back pain, tingling, mouth ulcers	Pilotto *et al.* (1997); Osborne *et al.* (2007); Lévesque (2009); Hilborn *et al.* (2014); Lévesque *et al.* (2014); Figgatt *et al.* (2017)
Gastrointestinal	Abdominal cramps, diarrhea, vomiting, nausea, gastroenteritis	Teixeira *et al.* (1993); Pilotto *et al.* (1997); Osborne *et al.* (2007); Lévesque (2009); Hilborn *et al.* (2014); MSSS (2014); Lévesque *et al.* (2014); Lin *et al.* (2016); Figgatt *et al.* (2017)
Skin	Rash, swelling, sores, irritation, dermatological symptoms, itching, redness, burns	Osborne *et al.* (2007); Lévesque (2009); Hilborn *et al.* (2014); MSSS (2014); Lévesque *et al.* (2014); Lin *et al.* (2016); Figgatt *et al.* (2017)
Eye, ear	Tearing, eye irritation, ear pain, visual disturbance, eye symptoms, flow from eyes and ears	Osborne *et al.* (2007); Lévesque (2009); Hilborn *et al.* (2014); Lévesque *et al.* (2014); Lin *et al.* (2016); Figgatt *et al.* (2016, 2017)
Respiratory	Nasal congestion, cough, wheezing, shortness of breath, chest discomfort, respiratory symptoms, cold, flu	Pilotto *et al.* (1997); Lévesque (2009); Hoagland *et al.* (2009); Hilborn *et al.* (2014); MSSS (2014); Lin *et al.* (2016); Figgatt *et al.* (2017)
Fever and headache	Fever, headache	Osborne *et al.* (2007); Lévesque (2009); Hilborn *et al.* (2014); Figgatt *et al.* (2017)
Death	Death	Teixeira *et al.* (1993); Jochimsen *et al.* (1998); Carmichael *et al.* (2001); Azevedo *et al.* (2002)

Costs related to the disease

Different methods were used to estimate costs associated with the disease caused by algae (Table 5). Todd (1995) estimated costs associated with marine food poisoning. This study in Canada was based on an estimate per case of disease of $2,268 for PSP, $1,355 for DSP, and $1,605 for ciguatera. Costs were calculated based on several assumptions and price estimates. The author took the following prices: $158 for a visit or treatment with a doctor, the cost of hospitalization at $788/day and $473/night, and intensive care costs at $2,362/day. The study also considered the cost of emergency transportation and laboratory tests as estimated at $315–$630. Moreover, time spent investigating patients with an epidemic disease was estimated at $788. The value of a lost life (death) was $787,511.

Starting with the basis that only 10% of diseases were reported (Todd 1989b; Hoagland *et al.* 2002), Hoagland *et al.* (2002) found that the cost per case of illness was between $1,951 and $1,533 for unreported diseases. These costs considered the costs of hospitalization and loss of productivity for the sick individual. In addition, this study estimated the cost of one death at $1.4M. Hoagland & Scatasta (2006), in addition to estimating the cost of disease caused by algae, proposed an estimate of the cost of the disease according to the length of coastline available to the countries. With a coastline length of 65,514 km for the European Union and 19,924 km for the United States, the public health cost was $207/km and $2,281/km, respectively. In their study on the costs of respiratory diseases in Sarasota County, Hoagland *et al.* (2009) estimated the cost of respiratory disease with the hypothesis that the disease lasts 3 days (1 day of treatment and 2 days of recovery). This hypothesis was based on the American and British guidelines for the treatment of moderate asthma diseases (NHLBI 2007; British Thoracic Society 2008). The cost of the disease was the sum of the costs of medical services and loss of productivity during the period of illness. According to the severity of the disease, the authors found costs ranging from $572 to $664, with an average cost of $586 per case of respiratory illness that visited the emergency department. This average cost does not differ from that obtained by Nierenberg *et al.* (2010) who found a daily cost of illness of $166 per case ($190 per day for Hoagland *et al.* (2009)). This figure corresponded to the cost of absenteeism, which the authors defined as missed hours of work due to illness or medical conditions. The cost of absenteeism consisted of the cost of medical treatment and the cost of lost productivity due to the illness. They also estimated the cost of presenteeism, such as the amount

Table 5 | Average health costs estimated following exposure to harmful algae

Cost per case	Description of costs	References
$1,770	Costs per case of illness because of food poisoning by algae (This cost includes societal cost, cost to the individual and different affected parties)	Todd (1995)
$787.5 K	Cost per case of death	
$1,951	Cost per case of reported illness	Hoagland *et al.* (2002)
$1,533	Cost per case of unreported illness	
$1.4M	Cost per case of death	
$207/km	Cost per kilometer of coastline for the European Union	Hoagland & Scatasta (2006)
$2,281/km	Cost per kilometer of coastline for the United States	
$572–$586–$664	Min. cost – Avg. – Max. for a case of respiratory illness	Hoagland *et al.* (2009)
$1,025–$2,160	Low and high cost per emergency department visit for RI and DI	Hilborn *et al.* (2014)
$4,670–$15,620	Low and high cost per inpatient admission for RI and DI	
$166	Daily cost of absenteeism per case of illness (cost-of-illness treatment and loss of productivity)	Nierenberg *et al.* (2010)
$253.7	Cost of presenteeism (WTP per beachgoer to have an additional lifeguard during the bloom period)	
$64	Cost per case of gastroenteritis due to direct contact with water	Ralston *et al.* (2011)
$130	Cost per case of illness due to food poisoning	
$5.3M	Cost per case of death	
$1,613	For each reported case	Morin *et al.* (2016)
$749	For each unreported case	
$1,146	Mean cost for each case (reported or unreported)	
$1,464	For each reported case	Rongo & van Woesik (2012)
$423	For each unreported case	

Costs in 2016 (US dollars).
K, Thousand; M, Million; DI, Digestive illness; RI, Respiratory illness.

beachgoers are willing to pay to have one additional lifeguard; this was estimated at $253.7 per beachgoer.

Ralston *et al.* (2011) estimated the cost per case of gastrointestinal illness and diseases transmitted by marine foods in the United States. Starting with an annual base of 5 million cases of gastrointestinal and 3 million cases of seafood-borne illness, they found respective costs of $64 and $130 per case. The authors specified that the largest share of seafood-borne illness is due to premature death, with an estimated cost of $5.3M per death. In the expanded analysis, Hoagland *et al.* (2014) estimated the cost for respiratory illness and digestive illness depending on the severity and healthcare received. Hospital admissions (inpatient) seem to be more expensive (high cost at $15,620) than emergency visits (high cost at $2,160), and digestive illnesses are more expensive than respiratory illness. The treatment cost is the largest share, at over 60% of the total cost. These costs could be higher if lasting illness occurs.

Finally, Morin *et al.* (2016) and Rongo & van Woesik (2012) estimated the cost of ciguatera poisoning for two countries in the South Pacific Ocean (French Polynesia and the Cook Islands). They focused on the cost of reported and unreported cases. For French Polynesia, the authors found a total cost of $1,613 and $749, respectively, for each reported case and unreported case, while the cost was a little lower in the Cook Islands, at $1,464 for each reported case and $423 for the unreported case.

Costs of disease

In general, and according to studies, health costs can be categorized into three subgroups of costs: (direct) healthcare costs, (indirect) costs due to illness, and intangible costs (Faeroy & Barton 2004).

Healthcare expenses. Healthcare expenses are the most-recurring and well-known expenses. These expenses consider costs directly related to the treatment of disease. This includes consultations, hospitalizations, emergency visits, and medications. These costs are usually borne by patients and the healthcare system. For a case of food poisoning in Canada, Todd (1995) estimated the cost for physician consultation and treatment at $158. For hospitalization, the cost was estimated at $788/day or $473/night. Intensive care was estimated at $2,363/day. Hoagland *et al.* (2009) estimated for Sarasota County (Florida, United States), the cost for a visit to the emergency department. The authors found that the cost per visit to the emergency department varies between $281 (25th percentile) and $1,165 (75th percentile).

Hoagland *et al.* (2014) calculated the cost of treatment using total marginal cost by multiplying daily treatment cost by hospitalization days. Doing so, they found for patients visiting the emergency department a treatment cost for respiratory illness varying from $1,025 to $1,430 and for digestive illness from $1,400 to $2,160. For those hospitalized, the cost is higher and varies from $4,670 to $6,630 and from $7,730 to $15,620 for inpatients suffering, respectively, from respiratory illness and digestive illness. Morin *et al.* (2016) used an average hospital admittance of 5 days times daily hospitalization fees of $169. Medication fees were obtained by summing the price of some pharmaceuticals usually used. Rongo & van Woesik (2012) used $134 per day as hospitalization fees and $54 per day for staff fees (physicians and nurses).

Loss of income due to illness. The authors assumed that individuals evaluate their work time in the same way as their leisure time. As a result, the value of an unworked day due to disease amounts to the median daily wage. Todd (1995) used the amount of $236/day to approximate the loss of daily income suffered by an individual due to illness. Hoagland *et al.* (2009) used patients' income distribution to estimate the value of loss of productivity caused by the disease. The loss was calculated at $373 for 3 days of illness. Nierenberg *et al.* (2010) only estimated the cost of loss of productivity due to disease, called the cost of 'absenteeism'. These authors found a value of $136 per day of absenteeism. For the calculation of the cost of presenteeism, the authors assumed that the effect is 'such that each beach loses one lifeguard during each week' of algal blooms. Then, they used the estimated willingness to pay (WTP) for beachgoers to have an additional lifeguard from Blackwell & Tunny (2000). For a WTP of $1.40 per beachgoer, the total value of presenteeism amounted to $91,700. For Rongo & van Woesik (2012), lost labor productivity was estimated on the basis of $5.07 per hour and 8 h per day for 10 days of hospitalization and recovery. Morin *et al.* (2016) also used 10 days as the average number of working days lost due to sick leave, with a daily rate of $17.40.

Cost of pain and suffering. This cost aims to monetarize the pain, suffering, and inconvenience experienced by the person affected by the illness. No studies included in our review estimated the cost of pain and suffering. Only one study (Nierenberg *et al.* 2010) discussed this for lifeguards in another way that was presented as 'presenteeism.' That was the cost of increased risk for beachgoers due to 'reductions in lifeguard attentiveness or reductions in the number of preventative actions taken' (Nierenberg *et al.* 2010). These costs estimated the lack or reduction of the lifeguards' effectiveness. Although the authors spoke about the costs of presenteeism, they did not calculate it.

Cost of a death

Todd (1995) estimated $787,511 as the cost for one premature death due to PSP disease. However, this estimate was based on the author's calculation (Todd 1989a), which may be based on the adjusted WTP/human capital approach of Landefeld & Seskin (1982). This value was $1,397,770 according to Hoagland *et al.* (2002) who also used the human capital approach developed by Todd (1995). For Ralston *et al.* (2011), the value of premature death is estimated at $5.3M. This estimate is based on the Online Calculator for Estimating the Economic Cost of Illness (Economic Research Service, ERS).

Short- and long-term costs

All the studies included only assessed costs related to acute exposure to HABs that is short-term costs observed in a relatively short period (days or weeks). No studies included costs on a long-term basis, such as costs related to chronic exposure to HABs or chronic illness that may be caused by chronic exposure to contaminated water.

Other costs

The costs of investigating sickness could also be considered in the accounting of the overall costs related to exposure to HABs. Time spent interviewing patients, epidemiological analysis of data, communication with other services and writing reports for a total estimated at $697 per case of illness, and laboratory examination costs ranged from $278 to $556 (Todd 1995).

Impact on health-related quality of life

In this section, we show data on health-related quality of life for the illnesses reported in Table 4. The aim was to give an insight into how much well-being one (or a society) could lose when facing these illnesses, which may be caused by HABs. We found that breathing difficulty appeared to be the sickness which caused the most loss of QALYs in children, with a loss ranging between 0.16 and 0.771 per child (Craig *et al.* 2016), followed by angina, with 149.72 QALYs lost per 1,000 adults (Ock *et al.* 2015). Gastroenteritis could cause a loss of between 2.2 and 7.1 QALYs for 1,000 children and around 1.8–3.1 for parents who care for these sick children (Brisson *et al.* 2010). Visual disturbance may also cause loss of QALYs by 8.3 per 1,000 people, as Wittenborn *et al.* (2013) found. Marlow *et al.* (2015) found results in the same way, as sick children would lose between 3.1 and 3.5 QALYs and a loss of between 7.7 and 8.7 QALYs for the 1,000 family units of the sick children. For influenza-like illness such as nasal congestion and flu, the loss may be 7.5 QALYs per 1,000 people. Thus, if we suppose a specific cost of $50 K per QALY, we can find the health-related quality of life-associated cost of each disease (Poder 2018).

Overall cost

Having a general insight into potential health costs following exposure to HAB is important because it could help policy planning and decision-making. At the national level, the effect on public health represents the largest share of the impact of algae and is estimated to be about 42% of the total impact (Anderson *et al.* 2000; Hoagland *et al.* 2002). Knowing the source and type of contamination could help authorities in planning an effective fight against HABs. Studies have shown that the main source of contamination is drinking water (domestic use) and recreational activities (Hoagland *et al.* 2009, 2014; Wood 2016). Focusing on animals revealed that dogs and livestock are the most affected by drinking water contamination (Wood 2016).

We carried out calculations to assess the overall burden of diseases caused by HABs. We retained two illnesses (respiratory and digestive) and death, three levels of severity (mild, moderate and severe) and 3 days of the disease, 1 for treatment and 2 for recuperation (Hoagland *et al.* 2009, 2014; Ralston *et al.* 2011). We used treatment cost at $50 for mild illness, $500 for moderate, and $10,000 for severe illness (Ralston *et al.* 2011). We used the same prices for digestive and respiratory illness since we do not have evidence that one treatment is more expensive than the other. For severe disease requiring hospitalization, we used 5 days' hospitalization and 15 days' recuperation (Hoagland *et al.* 2014). Presenteeism may be estimated to be between 10% and 13% of productivity loss (Nierenberg *et al.* 2010). We used a daily income of $120 (Hoagland *et al.* 2009, 2014). For QALYs losses, we combined adults' data from Table 6. Gastroenteritis QALYs' losses are used as a proxy for digestive illness and influenza-like illness as a proxy for respiratory illness. For a mild case, we supposed a zero QALY loss. A loss of life is valued at $3M dollars (Hoagland *et al.* 2002; Ralston *et al.* 2011). We did not assume a value for pain and suffering, but it can be approximated by presenteeism as discussed by Nierenberg *et al.* (2010). Since medical expenses vary depending on countries and residential areas, our costs estimate mainly reflects those in use in Canada and the United States in a societal perspective.

We determined that a moderate case of illness due to contamination by HAB costs around $1,000 and a mild case costs around $100 (Table 7). The major health cost is due to fatal cases, which could be estimated at $3M. Using a small figure of 1,000 people affected each year, with 75% mild cases, 24% moderate, and 1% death, this could lead to a global burden of $30.3M each year.

Table 6 | Potential QALYs lost following exposure to harmful algae

Symptoms/illness	QALYs lost	References
Gastroenteritis	2.2 [95% CI: 1.7; 2.7] using HUI2; 7.1 [95% CI: 5.1; 8.5] using VAS; per 1,000 cases of gastroenteritis in children	Brisson *et al.* (2010) (Canada)
	1.8 [95% CI: 1.0; 2.7] using HUI2; 3.1 [95% CI: 2.0; 4.1] using VAS; for caregivers per 1,000 cases of gastroenteritis in children	
	3.1–3.5 per 1,000 children; using HUI2; 7.7–8.7 per 1,000 family units; using EQ-5D-5 L	Marlow *et al.* (2015) (United Kingdom)
Visual disturbance or mild impairment[a]	8.3 per 1,000 cases in population younger than 40; using published articles' estimates	Wittenborn *et al.* (2013) (United States)
Influenza-like illness	7.5 [min–max, median: 0–44, 6] per 1,000 cases of influenza-like illness (adults and children); using EQ-5D	van Hoek *et al.* (2011) (United Kingdom)
Angina	149.72 per 1,000 adults; using EQ-5D	Ock *et al.* (2015) (South Korea)
Breathing difficulty	0.16 for little difficulty and 0.771 for a great deal of difficulty per child; using paired comparison responses (similar to time trade-off)	Craig *et al.* (2016) (United States)

[a]Authors' calculations: we combined population suffering from injury and burns and visual disturbance and assumed that their QALY lost was 5% of the total QALYs lost in the visual impairment category.

Table 7 | Overall cost by disease and severity

		A Treatment	B Income loss	C Presenteeism (10% loss of productivity)	D QALYs lost (1 QALY = $50 K)	Total (A + B + C + D)
Digestive illness	Mild	50	0	3*12	0	86
	Moderate	500	3*120	0	0.0031	1,015
	Severe	10,000	20*120	0	0.0041	12,605
Respiratory illness	Mild	50	0	3*12	0	86
	Moderate	500	3*120	0	0.0075	1,235
	Severe	10,000	20*120	0	0.044	14,600
Death						3M

Costs in $2016 (US dollars).
M, Million.

DISCUSSION

Overall, reviewing the literature to address the lack of health cost data and trying to put together all these studies which had potential interest for our review led to some concern.

Unreported illness could be, by far, the most important bias which may occur in estimating health costs due to harmful algae exposure. Most of the time, 'surveillance systems record only 1–10% of foodborne cases' (CDC 1988; Huss *et al.* 2004) as stated in Ralston *et al.* (2011). These unreported cases may be because people do not seek medical care since these cases are mild or familiar to local residents, and they know how to deal with it. This idea is supported by another author (Todd 1989c), who supposed that only 10% of illness are reported. To address these unreported illnesses, reported illnesses are often multiplied by 10 (Todd 1995; Hoagland *et al.* 2002). This rule of multiplying by 10 may be an effective approximation, but it may either underestimate or overestimate the real cases.

The misleading symptoms of illness following exposure to harmful algae are also a limit. Since having flu, headache, diarrhea or fatigue, and the like may not be caused only by exposure to harmful algae; it is difficult to establish a direct and causal relationship between observed symptoms and harmful algae exposure in the absence of a systematic test of patients. This situation can also lead to many cases which may not be recorded because they were not diagnosed as related to harmful algae.

Chronic long-term effects are more difficult to highlight (Belleville *et al.* 2009). No studies have included costs related to long-term effects of chronic exposure to harmful algae. This insufficiency in reporting long-term effects may be caused either by the misleading symptoms or by an absence of follow-up with people living near a water source or continuously exposed to contaminated water. Some authors (Lopez *et al.* 2008; Bláha *et al.* 2009; Cheung *et al.* 2013) have shown that health problems develop in the long term such as liver cancer, cardiac arrhythmia, or neurodegenerative diseases. Estimating the long-term effects of chronic exposure to harmful algae, especially cyanobacteria, is also difficult in the way that it is difficult to isolate the exact contribution of cyanobacteria in the occurrence of the disease in the long term.

For some premature deaths due to acute exposure, there is no consensus regarding the value to consider, since many authors in this review considered different price setups according to the methodologies (e.g., hedonic wage, willingness to pay, and human capital) and hypotheses used (Todd 1995; Hoagland *et al.* 2002). However, one can consider the results of meta-analysis in the work of Viscusi & Aldy (2003).

There is an incapacity to measure all the costs following exposure to harmful algae, e.g., the cost of pain and suffering. Most of the studies included in our review did not consider these kinds of cost. One study (Nierenberg *et al.* 2010) discussed it but did not include it, as the authors acknowledge that they cannot estimate these costs, even if the cost of pain and suffering could be included in the calculation of QALYs lost due to harmful algae exposure. Also, since the studies included in this review provided too little information about the different kinds of HABs, it was impossible for us to estimate specific costs by the type of toxins.

There are many other studies which present costs of waterborne illness or foodborne illness that could be interesting to discuss here since they have some similarity to those about harmful algae. For example, some authors (DeFlorio-Barker *et al.* 2018) estimated the costs related to a set of recreational waterborne illnesses (gastro, respiratory, skin, eye, and ear) in the United States. Using multiple cases of illness severity varying from benign to moderate to severe, the authors found that the costs were, respectively, $11, $270 and $350,370 per case of illness (in $2016). These authors define a benign illness as a case where the sick person did not meet a healthcare provider, while a moderate illness is defined as a situation where the patient received a medical consultation either externally or in emergencies. Severe illnesses are defined as those requiring hospitalization or resulting in death. These estimates were not made in the context of illness due to harmful algae but in the general case of waterborne illness. Since the illness source and symptoms are similar, these costs can easily be extrapolated to our context.

In another study (DeFlorio-Barker *et al.* 2017) focusing on gastrointestinal illness associated with water recreation in the United States, the authors found that costs of illness were $1,220 (95% CI: $338–1,681) for incidental contact and $1,676 for swimming/wading (95% CI: $425–2,743) per 1,000 recreational water users (in $2007). The authors highlight the fact that loss of productivity accounts for up to 90% of total costs. Furthermore, they found that the cost for marine recreational water users was higher than for freshwater recreational water users. Given *et al.* (2006) also estimated the public health cost of contaminated coastal water. They estimated between 628 K and 1.5M cases of gastrointestinal illness caused by swimming in contaminated water in California. This figure yields a total cost varying from $21M to $51M (in $2000). Dwight *et al.* (2005) found the same cost as Given and colleagues in estimating the economic burden of illness associated with recreational coastal water pollution in California. These last authors found a cost (in $2001) of $36.58 per gastrointestinal illness and $76.76 per acute respiratory disease. The costs for earache and eye ache were, respectively, $37.86 and $27.31. Even if these costs may be far from those used in Table 6, the authors cited some studies (Liddle *et al.* 1997; Carabin *et al.* 1999) which found the same costs as in Table 6.

All of these costs estimated to access the economic impact of HABs on human health should be considered when evaluating the monetary benefits of improving water quality (DeFlorio-Barker *et al.* 2017). In this area, Hunter *et al.* (2012) evaluated the WTP of the public to reduce health risks posed by toxic algal blooms in Scotland (United Kingdom). With 55% of respondents willing to pay to reduce health risks, the authors found a WTP between $16.93 and 20.73 per household and per year. An aggregation of this amount over a small city of 10,000 households could lead to a total benefit of $170 K per year. Nunes & van den Bergh (2004) also tried to estimate the value people give for protection against invasive marine species in the Netherlands. Using a combination of travel costs and contingent valuation methods, the authors found that the benefits per individual were, respectively, $83 and $115. The survey also revealed that 'respondents with relatively high travel costs have a relatively low WTP for the marine-protection program.' Evaluating the cost of water treatment benefits could also be difficult since it could be confusing to separate the cost of routine water treatment from those due to pollution by HABs (Dodds *et al.* 2009).

We included studies which met our inclusion criteria without considering their methodological rigor since most were of low quality. This may be kept in mind while considering the overall results of this review. While extracting and reporting the cost data from the studies, some did not report explicitly the years in which costs are expressed. So, for the studies that did not give the year of their costs, we assumed the cost for the year of publication. The QALYs reported in Table 6 were not measured with the same tool. We had no means to make the correspondence between them. However, this provides an idea of these costs. Overall, the quality of the studies included in this review is moderate, especially for primary studies, even if reviews and reports did not match all the criteria well. Some studies were based on a population which may be concerned about water pollution, and extrapolation of the results may be done with precaution.

Illness from shellfish presented by Todd (1995) concerned sporadic events across Canada; this is the case for Hoagland *et al.* (2002). Since it remains difficult to collect data over all the contamination cases, all studies included in this review collected data on the same population or in the same time period. This may be a concern which should be considered when it comes to generalizing the results. The fact that not all the studies are precise about the harmful algae considered creates uncertainty over to which algae one could attribute the illness. However, it would not be easy to isolate the effect or contribution of each algae species on the disease. Finally, we found no specific study about cyanobacteria, and little is known about their impact on health and related health expenses (Donohue *et al.* 2008).

Finally, the fact that some studies used survey and self-reported exposure and illness could create a bias in the data used for cost estimation. In fact, having contact with water did not necessary imply contamination by HA as well as having symptoms similar to those caused by algae. In the absence of a medical diagnostic, self-reported data should be considered with caution.

CONCLUSION

This review gave specific regard to the economic impact of harmful algae on human health. We found that harmful algae could cause many health problems and generate important expenses. Having more studies which focus on the health aspects and consequences of human health could help present a better understanding of these health problems. Although this study may have some weakness due to the quality of the selected studies, it remains methodologically rigorous and could help assess human health costs due to cyanobacteria and harmful algae in general.

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COMPETING FINANCIAL INTEREST DECLARATION

None to declare.

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