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Geographical modeling of exposure risk to cyanobacteria for epidemiological purposes

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ABSTRACT

The cyanobacteria-derived neurotoxin β-methylamino-L-alanine (BMAA) represents a plausible environmental trigger for amyotrophic lateral sclerosis (ALS), a debilitating and fatal neuromuscular disease. With the eutrophication of water bodies, cyanobacterial blooms and their toxins are becoming increasingly prevalent in France, especially in the Brittany region. Cyanobacteria are monitored at only a few recreational sites, preventing an estimation of exposure of the human population. By contrast, phosphorus, a limiting nutrient for cyanobacterial growth and thus considered a good proxy for cyanobacteria exposure, is monitored in many but not all surface water bodies.

Our goal was to develop a geographic exposure indicator that could be used in epidemiological research. We considered the total phosphorus (TP) concentration (mg/L) of samples collected between October 2007 and September 2012 at 179 monitoring stations distributed throughout the Brittany region. Using readily available spatial data, we computed environmental descriptors at the watershed level with a Geographic Information System. Then, these descriptors were introduced into a backward stepwise linear regression model to predict the median TP concentration in unmonitored surface water bodies.

TP concentrations in surface water follow an increasing gradient from West to East and inland to coast. The empirical concentration model included five predictor variables with a fair coefficient of determination ($R^2 = 0.51$). The specific total runoff and the watershed slope correlated negatively with the TP concentrations ($p = 0.01$ and $p < 10^{-9}$, respectively), whereas positive associations were found for the proportion of built-up area, the upstream presence of sewage treatment plants, and the algae volume as indicated by the Landsat red/green reflectance ratio ($p < 0.01$, $p < 10^{-6}$ and $p < 0.01$, respectively).

Complementing the monitoring networks, this geographical modeling can help estimate TP concentrations at the watershed level, delivering a proxy for cyanobacteria exposure that can be used along with other risk factors in further ALS epidemiologic case–control studies.

1. Introduction

Amyotrophic lateral sclerosis (ALS) is a debilitating and fatal neuromuscular disease with an average annual incidence worldwide of 2 to 2.5 per 100,000 inhabitants (Chiò et al., 2013). Approximately 90% of ALS cases occur sporadically and are of unknown cause (Banack et al., 2010). The existence of an environmental factor that triggers sporadic ALS is supported by reports of conjugal ALS and by spatial clusters of ALS described in many Western countries, including the USA, Italy, Sweden, Finland, the United Kingdom and France (Caller et al., 2012). Associations with pesticides, solvents, and heavy metals (lead, mercury, and aluminum) have been suggested, but the results from occupational or environmental exposure studies have so far proven inconclusive (Sutedja et al., 2009). Much attention has been focused on the high incidence of ALS reported in the western Pacific (island of Guam) suggesting that a cyanobacteria-derived neurotoxin (β-methylamino-L-alanine or BMAA) represents a plausible environmental trigger for ALS (Kurland and Mulder, 1954, 1955). The potential role of BMAA in the etiology of sporadic ALS is further supported by its ability to cause neurodegeneration in vitro and its ubiquitous nature (Banack et al., 2010).

With the eutrophication of water bodies worldwide, high concentrations of cyanobacteria ("blooms") and cyanobacterial toxins are becoming increasingly prevalent. These blooms occur under nutrient-rich and optimal environment conditions, usually encountered in summer, with the potential for humans to be exposed to cyanobacteria toxins (Bradley et al., 2013). There is, however, no evidence of a direct relation between cyanobacteria biomass and toxin concentration. In addition to cyanobacteria, diatoms could be an additional ubiquitous source for

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BMAA in an aquatic environment with a great potential impact for human exposure as diatoms represent a major bloom-forming phytoplankton that can be found throughout the year (Jiang et al., 2014).

Contamination pathways are not fully understood but could consist of ingestion of water; consumption of contaminated foods, such as fish, crustaceans, and mollusks (as BMAA bioaccumulates within the aquatic food-web); or inhalation following aerosolization (e.g., water-based recreational activities such as swimming and water-skiing, fishing, bathing or showering with surface water, and close proximity to dams). Some agricultural fields are irrigated from water bodies invaded by cyanobacterial blooms, raising the potential for the presence of BMAA in milk, meat, or vegetables. All available evidence shows that it is crucial and timely to more accurately assess the ALS risk posed by exposure to the cyanotoxin, BMAA (Bradley et al., 2013).

Although BMAA can now be measured in the human blood, the assessment of an individual's lifetime cumulative exposure to BMAA remains challenging and therefore exposure to ecosystems containing cyanobacteria is used as a surrogate for BMAA exposure. Unfortunately, cyanobacteria concentration data in surface waters are generally available for only a few locations (if ever), mainly in recreational waters. Instead, phosphorus (P), the limiting nutrient for the development of cyanobacteria blooms, can be used as a proxy for cyanobacteria exposure. P concentration is monitored at numerous locations in a given region, either by local authorities or water companies. Such monitoring networks provide sufficient data to calibrate statistical models linking P concentration to environmental descriptors and, then, to estimate P concentration in unmonitored watersheds.

P inputs to surface water bodies may originate from point-source emissions (domestic or industrial origin) and diffuse emissions (agricultural or pedogenetic origin) (Van Drecht et al., 2009; Grizzetti et al., 2012; Dupas et al., 2015a). In Western countries, P concentrations in rivers have decreased since the 1990s as a result of a general improvement in wastewater treatment (Bouraoui and Grizzetti, 2011; Grizzetti et al., 2012; European Environment Agency, 2014). As a consequence, management efforts have been redirected toward mitigation of diffuse emissions, mainly of agricultural origin (Gburek et al., 2000; Sharpley et al., 2001). Diffuse P sources include mineral and organic fertilizer spread over agricultural fields (Ringeval et al., 2014). Diffuse P emission can occur when the P source coincides in space and time with a possibility for land-to-river transport (Haygarth et al., 2005; Heathwaite et al., 2005). The main transport pathways for P primarily include erosion and overland flow but also subsurface flow and artificial drainage (Heathwaite and Dils, 2000; Van der Salm et al., 2011; Mellander et al., 2012; Dupas et al., 2015b). The transport of P to surface water is driven by many factors related to hydrology, topography, soils and land use. In-channel processes, including bank erosion, play a major role in P transfer (Kronvang et al., 2013).

A number of physically based P models have been developed for improving understanding of the spatial origin and transport pathways of diffuse P across agricultural landscapes and for predicting stream P concentration (Radcliffe and Cabrera, 2006). However, the comprehensive input data, expert skills and time required to apply such models prohibit their implementation at large scales. As an alternative, simplified risk indicators for P export from agricultural fields have been developed since the 1990s to improve agricultural practices and subsequently minimize environmental impacts. Such "phosphorus index" (PI) approaches account for source factors such as soil P contents or fertilizer additions and transport factors such as erosion, surface runoff, subsurface drainage and connectivity between fertilized fields and receiving water (Buczko and Kuchenbuch, 2007). PIs are qualitative, at best semi-quantitative, indicators and require field-scale data (Birr and Mulla, 2001). Hence, they do not fulfill expectations for the large-scale quantitative estimation of P concentrations that are required for epidemiological purposes.

Our goal was to estimate P concentrations in stream water at the watershed level, based on agricultural census data, hydrological characteristics, landscape descriptors, and remote-sensing data, to deliver an accurate proxy for cyanobacteria exposure that could be considered in further ALS epidemiological studies.

2. Materials and methods

2.1. Study area

The Brittany region is located in western France and covers 27,000 km^2 (5% of France). Its geology is dominated by crystalline bedrock overlain by superficial formations, such as Quaternary loess (aeolian silt) and alluvial and colluvial deposits. Brittany has a temperate oceanic climate, with a mean annual temperature of 11.2 °C. Annual rainfall ranges from 700 to 1200 mm. Due to the impervious substratum and wet climate, drainage density is high (approximately 1 km/km^2) (Dupas et al., 2013). Water systems that use surface water (and not groundwater) stored in dammed rivers and bank-side reservoirs spread throughout the territory serve 80% of the population (3.25 million inhabitants in 2012).

A large part of the agricultural sector is devoted to intensive animal production, representing 55%, 40%, and 25% of the national production of pigs, chickens, and cow's milk, respectively. Following the intensification of agriculture since the 1950s, the increasing transfer of excess nutrients has accelerated eutrophication in rivers, lakes, and reservoirs. As a result, cyanobacterial blooms have become more intense and frequent in the surface waters used for domestic purposes (including drinking water). In 2011, a survey of 36 recreational water bodies conducted by the Regional Health Agency found high levels of cyanobacteria (>100,000 cells/mL) in 21 water bodies, among which 17 were closed in the summertime to protect human health.

2.2. Total phosphorus water concentration data

In Brittany, total phosphorus (TP) concentration is regularly monitored in streams through a network of 378 surface-water stations. These stations are located in 218 of the 314 watersheds of Brittany, according to the smallest level of the French national hydrography dataset. The monitoring protocol consisted of manual sampling at a distance from rainfall events, i.e., mainly during base flow periods. Watersheds were available as a Geographical Information System (GIS) layer in the Carthage® database (National Institute of Geographic and Forest Information, 2013). Station geographical coordinates were downloaded from the SANDRE® database (SANDRE, 2013) and the corresponding TP concentrations (in mg/L) were downloaded from the OSUR® database (OSUR, 2013). To obtain a reliable picture of the TP concentration, we calculated the median value over a 5-year period (from 1 October 2007 to 30 September 2012) where at least 10 measurements were available from the monitoring station (316 monitoring stations located in 201 watersheds met this requirement). Finally, only monitoring stations close to the outlet of the watershed were retained for analyses (leaving 179 stations in 179 watersheds).

2.3. Environmental predictors of water quality

P concentration in rivers is determined by the intensity of P pressure and the physical characteristics of the associated watersheds. In this study, environmental descriptors consisted of lumped values computed from readily available spatial data and GIS tools (SavGIS v.9.07.004 and ArcGIS v.10.2). Our choice of environmental descriptors was restricted to those that could be developed for all of Brittany at an appropriate spatial resolution. For descriptors available at administrative levels, surface weighted means were considered. For raster databases, the mean value within each watershed was calculated. Table 1 provides details on the characteristics, spatial resolution, sources, references and data preparation of the various environmental descriptors considered in this study.