Desert Dust as a Vector for Cyanobacterial Toxins

J. S. Metcalf, A. D. Chatziefthimiou, N. R. Souza, and P. A. Cox

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1 Background: Brief Description of Deserts and Dust Storm Fronts

Drylands, which make up 41–45% of the Earth's land area, are inhabited by 31% of the world's human population and are characterized by climatic forces which shape the physical environment and its biological life (UNCCD 2012; Prăvălie 2016; IPCC 2017; Maliva and Missimer, 2012). Although deserts were conceptualized singularly in the context of temperature maxima or lack of precipitation, aridity indices (AI) which take into consideration annual precipitation (P) and evapotranspiration (ET) potential are more accurate and efficient in describing deserts (UNESCO 1979; IPCC 2007, 2017). This is because ET has an inherent co-linearity with additional climatic forces including temperature, wind speed, and Global Horizontal Irradiation (GHI). The water cycle, which influences soil type, vegetation cover and species abundance is factored in as well through incorporation of P in the aridity index (UNESCO 1979; IPCC 2007, 2017).

The Arabian Seas are surrounded by deserts in the hyper-arid ($AI < 0.0$) to arid ($0.03 < AI < 0.20$) continuum (MEA 2005; UNESCO 1979; UNCCD 2012), of yearly sums of GHI levels (2118–2775 kWh/m^2) comparable only to the Atacama (Chile and Peru), the driest hot desert in the world (Knight 2016; SSE 2017). These deserts also experience irregular rainfall of up to 80 mm on average per annum (hyper-arid) and between 80 and 350 mm on average per annum (arid), mainly occurring during the winter months when temperatures are low, with the exception

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J. S. Metcalf (✉) · N. R. Souza · P. A. Cox
Brain Chemistry Labs, Jackson, WY, USA
e-mail: james@ethnomedicine.org

A. D. Chatziefthimiou
Weill Cornell Medicine – Qatar, Education City, Doha, Qatar

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of those areas in the Southern Arabian Peninsula that are affected by the Monsoon season over India and receive precipitation in the summer months (Houseman 1961; IPCC 2007).

Seasonality is also exhibited in the frequency of desert dust storms in this geographic area, with dust sources originating in the Eastern and Southern Sahara, Northern and Eastern Sahel, and Northern and Southern Arabian deserts (Goudie and Middleton 2001; Al-Dousari et al. 2013). The Monsoon low over India generates the dust-bearing wind Al Shamal (called Simoon in Kuwait), a northwesterly wind that raises dust from the alluvial plains in the Tigris-Euphrates basin and deposits considerable dust over the Middle East and the Arabian Gulf in the dry summer months (Houseman 1961; Goudie 1983), while in the spring, dust originating from the Saharan desert transverses to the Northern Arabian Peninsula with the Sharav cyclones (cold front; Middleton 1986; Goudie and Middleton 2001; Notaro et al. 2013; Yu et al. 2015a).

The aforementioned deserts, together with the Gobi Desert in China, are the world's most important sources of dust, and their collective input of dust and particles into the atmosphere is 1133–1293 tons/km^2/year (Goudie and Middleton 2001; Al-Dousari et al. 2013). Particularly, in the Middle East, these natural sources of dust contribute 52% of the urban air pollution from particulate matter with an aerodynamic diameter of 2.5 μm (PM2.5), the highest percentage on a global scale where contributions range from 5% in Western Europe to 42% in Japan (Dayan et al. 1991; Karagulian et al. 2015 and references therein).

2 Overview of Components of Air That May Pose Risks to Human Health

A characteristic morphological feature of the soil surface in some deserts is biogenic crusts (biocrusts), also known as cryptobiotic, microfloral, microphytic, and organogenic crusts (Warren 2014). Biocrusts are comprised of microorganisms including cyanobacteria, autotrophic and heterotrophic bacteria, algae, fungi, and bryophytes (Belnap et al. 2001). Filaments and mycelia of these organisms fasten and bind soil particles and secretion of extracellular polysaccharides further cement this framework (Beraldi-Campesi 2013). Well-developed biocrusts aid in the retention of moisture and decrease wind erosion, exhibiting wind speed thresholds against erosion as high as 64.4 Km/h compared to wind thresholds of 16 Km/h observed in sandy areas (Belnap et al. 2001; UCAR/COMET 2010; Warren 2014; Powell et al. 2015). Depending on the species composition of microorganisms in biocrusts, nutrients can also be made available through photosynthesis and nitrogen fixation, which is particularly important in arid regions and other terrestrial environments, since readily bioavailable nitrogen is a limiting resource (Hooper and Johnson 1999). Fossil records suggest that organisms similar to extant cyanobacterial soil and rock crusts formed one of the earliest terrestrial ecosystems in Earth's history between 2.9 and 2.7 billion years ago (Watanabe et al. 2000; Beraldi-Campesi 2013).

Damage or destruction of biocrusts, through industrial development and engineering, grading of pristine soil surfaces for construction, disruption from military vehicles and munitions, off-road vehicles, and livestock trampling, reduces their ability to impede water and wind erosion (Warren 2014). Consequently, should winds impact such environments, then there is a greater likelihood that particles can become airborne, disperse, and exacerbate the intensity of dust storms. Airborne particulate matter, especially its smaller fractions, can have adverse effects on both human well-being, causing pathologies and neurodegeneration, and environmental health since they can trigger harmful algal blooms (HAB) and cyanobacterial blooms (CyanoHAB) and cause and contribute to soil erosion, ocean sedimentation, and climate change (Goudie 1983; Subba Rao and Al-Yamani 1999; Walsh and Steidingler 2001; Calderón-Garcidueñas et al. 2015).

The biological components of aerosols (bioaerosols) are considered to be detrimental to human health, and although 1 g of desert dust can contain up to 109 bacterial taxa, bioaerosols and airborne particulate matter are under-studied. Further research on how they affect human and animal health is required (Whitman et al. 1998). So far, studies have shown that disrupting the equilibrium of communities that make up the normal human microbiome results in overgrowth and dominance of opportunistic members (Shen et al. 2013). For example, disruption of the lung microbiome increases susceptibility to allergies (Gollwitzer and Marsland 2014). If one can think of bioaerosols then as the atmospheric microbiome, industrialization and dust storms disrupt the ambient equilibrium with observable increases in the abundance of airborne pathogens of up to 50% (Griffin et al. 2003). Advances in metagenomics and bioinformatics have facilitated a more resolved picture of the ratio of beneficial to pathogenic populations of bioaerosols than conventional culturing methods and have delineated how that ratio is altered during dust storms. Pathogenic bacteria of the genera *Mycobacterium*, *Clostridium*, and *Bacillus* as well as intracellular parasites *Brucella* and *Coxiella* were detected during dust storms in Iraq and Kuwait, and *Streptomyces*, *Micrococcus*, and *Nocardia* were detected in dust storms in Iran (Leski et al. 2011; Soleimani et al. 2014). Cyanobacteria are important components of bioaerosols, and the secondary metabolites that they produce may have severe impacts on human, animal, and ecosystem health, as discussed extensively in Sect. 3.

Similarly, many fungal genera have been identified that are known to cause allergies and infections such as *Cryptococcus*, *Acremonium*, *Alternaria*, *Aspergillus*, and *Ulocladium* (Kurup et al. 2000). Viruses are also able to be transported with windborne currents, with avian influenza (Chen et al. 2010) and coronaviruses (Owusu et al. 2014) having been detected, the latter linked to human disease such as severe acute respiratory syndrome coronavirus (SARS-CoV) and Middle East respiratory syndrome coronavirus (MERS-CoV) (de Wit et al. 2016). The transportation of viruses can be further exacerbated through the action of wind, as evidenced by periodic outbreaks of hantavirus (Taylor 2002). As the virus has a reservoir in small mammal populations in desert environments, when conditions allow, the virus can be present within the dried feces of these animals which can then become windborne by desert winds, potentially resulting in outbreaks of this hemorrhagic disease (Abbott et al. 1999).

Representatives of the chlorophytes, xanthophytes, and diatoms have also been detected within air samples and again contain genera that may be related to allergenic responses and human illness (Genitsaris et al. 2011; Sharma et al. 2007). In countries surrounding the Arabian Seas, where desert environments account for significant land cover, medical issues connected with respiratory disease have been shown to peak during dust storm events, and the prevalence of asthma across populations in the neighboring countries ranges from 10% in Oman to as high as 24% in Saudi Arabia (Al Ghobain et al. 2012; Al-Rawas et al. 2008). In Qatar, hospitalizations related to respiratory disease including the “Shamal flu” peak in December, are often associated with Al Shamal events, and incur a mortality rate of 1.7 per 100,000 (Al Marri 2006; Cox et al. 2009; Yu et al. 2015b). An increase in absenteeism and inferior performance has also been observed in school populations, especially during the dust storms (Al Marri 2006; Bener 2011), while for the construction sector, the average loss of productivity base has been reported to reach 10% in countries of the Middle East (Rashid 2014).

Furthermore, different dust sources harbor unique bioaerosol communities and have global reach, with reports of Saharan dust found in the European Alps and the Caribbean, or Asian dust found in the Mediterranean, and Gobi Desert dust throughout China and the western Pacific Ocean (Griffin et al. 2003; An et al. 2015; Weil et al. 2017; Roney et al. 2009). Since the atmosphere is an extreme environment, the populations of bioaerosols that survive these trans-boundary dispersal ranges are some of the most stress-resistant organisms known. They contain pathogens and can upset the local community equilibrium and become invasive (Subba Rao and Al-Yamani 1999; Schlesinger et al. 2006; Gat et al. 2017; Weil et al. 2017).

3 Cyanobacterial Toxins and Exposure Routes for Humans and Animals Within Deserts

Cyanobacteria, previously called blue green algae due to their pigmentation, are prokaryotes capable of producing a wide range of low molecular weight toxic compounds, which have been identified through poisoning incidents, screening of bloom material, and strain isolation from environments which they inhabit (Metcalf and Codd 2012). These toxic compounds, often termed cyanotoxins, can have both acute and chronic effects, depending on the type, dose, and mode of exposure (Metcalf and Codd 2012). In general, they are broadly split into categories, according to their mode of action and the organs that they target, and can be classified as hepatotoxic, cytotoxic, neurotoxic, endotoxic, and dermatotoxic.

Hepatotoxins

The best understood cyanotoxins are the cyclic peptide microcystins and nodularins, potent protein phosphatase inhibitors (Metcalf and Codd 2012). In acute doses, liver failure and death can occur, whereas low-dose chronic exposure has been implicated in cases of primary liver cancer in areas such as China and Eastern Europe (Carmichael 1994; Ohta et al. 1994; Ueno et al. 1996; Metcalf et al. 2000; Svircev et al. 2013).

Cytotoxins

Also considered to have hepatotoxicity, the cylindrospermopsins were identified after an outbreak of hepatic enteritis in Australia. Subsequent investigations identified that the human drinking water source correlated with the disease outbreak and ultimately a strain of *Cylindrospermopsis raciborskii* was isolated which produced a novel toxic guanidine alkaloid, cylindrospermopsin (Hawkins et al. 1985). Although acutely toxic in high doses, this cyanotoxin is also suspected to act as a carcinogen (Falconer and Humpage 2001).

Neurotoxins

These include the acetylcholine mimic, anatoxin-a, a potent postsynaptic depolarizing neuromuscular blocking agent which, in high doses, may lead to paralysis, asphyxiation, and death (Devlin et al. 1977; Carmichael et al. 1979; Carmichael 1994). Anatoxin-a(*S*) is a naturally occurring organophosphate, able to inhibit acetylcholine esterases (Mahmood and Carmichael 1986). Saxitoxins and analogues, more commonly known for their production in marine dinoflagellate blooms, can similarly be produced by cyanobacteria in freshwaters (Metcalf and Codd 2012). These sodium channel inhibiting compounds are extremely potent neurotoxins and have resulted in the deaths of animals and humans, largely through the consumption of contaminated shellfish (Carmichael 1994; Ballot et al. 2017). β-N-Methylamino-L-alanine (BMAA), a more recently studied non-proteinogenic neurotoxic amino acid, has been shown to cause the production of neuropathologies of the Guamanian ALS/PDC, including neurofibrillary tangles and amyloid plaques. These neuropathologies suggest perhaps a broader role for BMAA in human neurodegenerative disease worldwide (Cox et al. 2016).

Endotoxins

Although photosynthetic like algae and plants, cyanobacteria are Gram-negative bacteria. As a result, they contain lipopolysaccharides (LPS) in their cell wall (Drews and Weckesser 1982), and subsequently, these endotoxins have the potential to cause gastroenteritis (Codd et al. 2005; Metcalf and Codd 2012; Monteiro et al. 2017).

Dermatotoxins

Dermatotoxins such as aplysiatoxins and lyngbyatoxins are known to cause dermatitis and allergy-like symptoms, while they are also considered to be skin tumor promoters (Mynderse et al. 1977; Cardellina et al. 1979; Aimi et al. 1990; Fujiki et al. 1981, 1983; Osborne et al. 2008).

The geographical range of cyanobacteria and their toxins is expected to expand, partially due to climate change (Paerl and Paul 2012; IPCC 2018). Although there is a lack of aquatic/freshwater environments within deserts, the countries of the Middle East are surrounded by the Arabian Seas. This marine environment has historically harbored CyanoHABS and HABs (Al-Azri et al. 2007; Al Gheilani et al. 2011), with a variety of exposure routes to toxic compounds for people within these areas. Of the exposure routes possible, the three main routes are discussed below.

3.1 Water

With respect to desert environments, in Gulf countries such as Qatar, biocrusts can sometimes account for up to 87% of terrestrial land areas (Richer et al. 2012). As the name suggests, depressions, locally called *Rawdat*, are low-lying areas where runoff rainwater and soil nutrients accumulate, enriching the soil and supporting plant growth. Biocrusts are ecosystem pioneers in these depressions ensuring resource availability to higher plants through carbon and nitrogen fixation and surface soil stability through the excretion of polysaccharides and adhesion of soil particles with their filaments (Belnap et al. 2001; Richer et al. 2012). Analysis of surface biocrusts has revealed the presence and persistence of BMAA and its isomers, AEG and DAB (Cox et al. 2009; Metcalf et al. 2015; Richer et al. 2015), in addition to microcystins and anatoxin-a(*S*), whose production was inferred from assessment by acetylcholine esterase inhibition assays (Metcalf et al. 2012).

Furthermore, detection of cyanotoxins throughout the entirety of the desert soil horizon (95 – 1.05 cm), i.e., not just in surface biocrusts considered to be their origin, which may persist for years, may provide evidence that leaching is one constant source of cyanotoxins found in groundwaters, aquifers, and wells (Mohamed and Al Shehri 2009; Richer et al. 2015; Chatziefthimiou et al. 2016; 2020). During the winter rain season in desert regions, although accumulation is small by comparison to other parts of the world, ephemeral rainwater pools are observed in depressions (Richer et al. 2012) and initiate the life cycle of many desiccated and dormant organisms. Biocrust communities including cyanobacteria also proliferate at that time, and cyanotoxins can accumulate in the pools. In desert environments, this standing rainwater is available for animals to drink, and associated intoxications can result, as evidenced by dog poisoning cases in Qatar after consumption of such waters (Chatziefthimiou et al. 2014).

The increase in the human population of arid lands has necessitated the development and introduction of desalination plants, which since the 1960s provides the only source of drinking water in the Arabian Peninsula (Subramani and Jacangelo 2015). Post desalination, the water is transported through pipes in urban cities or in trucks to rural areas and is subsequently stored in tanks at homes and businesses alike (Chatziefthimiou et al. 2016). Often, water tanks are equipped with an overflow control opening, which allows the transmission of light, and, in some cases, air circulation and associated particulate matter (Chatziefthimiou et al. 2016).

Subsequently, there is a potential for inoculation and growth of cyanobacteria within water tanks, often resulting in accumulation of cyanotoxins, such as microcystins, that can be found at concentrations greater than the WHO Guideline Values for microcystin-LR in drinking water (Mohamed and Al Shehri 2007; Chatziefthimiou et al. 2016).

3.2 Food

Although exposure to cyanobacteria and their toxins is largely considered to occur through drinking water, other exposure routes are viable and, potentially, significant. One obvious source of exposure can be through the consumption of contaminated food (see Testai et al. 2016 for an extensive review on cyanotoxins in food). In the UK, analysis of salad lettuce crops spray-irrigated with water from a *Microcystis aeruginosa*-bloom-infested artificial pond identified the presence of microcystins. These adsorbed to the surface of this salad crop and were deemed to be at a concentration which would constitute a human health risk if consumed (Codd et al. 1999). Furthermore, there is increasing evidence showing that cyanobacterial toxins can be taken up into crop plants, such as rice and tomato among others, largely through the roots, and get incorporated into plant tissues. This type of contamination has been shown with cyanotoxins including microcystins and BMAA (Corbel et al. 2014, 2016; Liang and Wang 2015), highlighting the need to monitor water sources that are used for the irrigation of crops.

Within countries surrounding the Arabian Gulf, irrigation of lands to grow food crops is employed, significantly increasing domestic food supplies and self-sufficiency (Lampietti et al. 2011). As cyanobacteria can be prevalent organisms within surface biocrusts, and their toxins can leach into the soil horizon, contamination of groundwater wells may ensue. Ponds or other structures used to hold water may also become contaminated with cyanobacteria and could, potentially, contaminate any crops that are grown using such water (Mohamed and Al Shehri 2009). The neurotoxin BMAA has been found to bioaccumulate and biomagnify in terrestrial food chains in Guam (Cox et al. 2003), although studies have not yet been conducted in the terrestrial desert climate to determine whether they exhibit the same patterns.

Fish and molluscs have also been shown to contain cyanotoxins and/or cyanobacteria (Sipia et al. 2007; Magalhaes et al. 2001). Due to the proximity of countries to the marine environment of the Arabian Seas, seafood is a significant component of the human diet. The finding of marine blooms of diatoms and dinoflagellates in the Gulf has been correlated with the occurrence of large fish kills (Sheppard et al. 2010). Contamination of seafood may also occur by the isomers of BMAA, AEG and DAB, detected in tissues and organs of a range of fish and shellfish species that are commonly consumed by the local population in the Gulf (Banack et al. 2014; Chatziefthimiou et al. 2018).

3.3 Aerosols/Airborne Particles

Dust storms are common phenomena in deserts, and the presence of microorganisms and other biological elements in air samples comprising algae, cyanobacteria, autotrophic and heterotrophic bacteria, fungi, and viruses is all known to occur (Genitsaris et al. 2011; Wood and Dietrich 2011). Storm events can have implications for the economy, in addition to negatively impacting the environmental and human health of the surrounding areas (Gomez-Mejiba et al. 2009). For example, plant pathogens that spread with storm events could place crops at risk, especially ones with limited genetic diversity, i.e., mono-cultures (Brown and Hovmøller 2002), while bioaerosols may cause fish kills and fisheries closures, both incurring economic impacts (Al Gheilani et al. 2011; Zhao and Ghedira 2014). Seasonal Al Shamal northern winds within the Gulf environment transporting dust across the region also impact the economy. Al Shamal winds are associated with respiratory and flu-like symptoms, allergic asthma, rhinitis, and eczema leading to increased absenteeism of school children and workers (Bener 2011). Increased hospital admittance rates and loss of productivity base in companies during peak events increase the cost associated with this health burden (Larsen 2014).

The transmission of the foot-and-mouth disease virus (FMDV) through aerosols from Germany to Scandinavia, and from France to England, has been reported (Donaldson et al. 1982; Gloster 1982). In air samples, Genitsaris et al. (2011) found 38 algal and cyanobacterial taxa that have been linked with allergy-like symptoms, respiratory diseases, and dermatitis in humans resulting from inhalation exposure to these organisms and/or their toxins. Airborne algae and cyanobacteria have also been reported in Malaysia and Egypt with cyanobacteria (e.g., *Phormidium*, *Nostoc*) being the dominant group (EL-Gamal 2008; Ng et al. 2011). Both studies found species seasonality in their samples, with most species found in areas where human populations were higher. According to Nezlin et al. (2010), aeolian (windborne) dust can play a major role regulating the phytoplankton community in the Arabian Gulf, and it can also account for the dominant external source of iron at the open ocean surface (Jickells et al. 2005). Iron deposition in the marine environment can result in the production of cyanobacterial blooms, otherwise kept in check by iron limitation, and in some cases these blooms can be toxic (Ramos et al. 2005). Transmission of microcystins by air has been shown to occur (Backer et al. 2008, 2010). Experiments examining the inhalation of cyanobacterial toxins have shown this to be a viable exposure route, and the toxicity of these compounds by this exposure route can be significant (Fitzgeorge et al. 1994; Cheng et al. 2007; Backer et al. 2008, 2010; Wood and Dietrich 2011). According to Caller et al. (2009), the risk of developing Amyotrophic Lateral Sclerosis (ALS) seems to increase in populations living near lakes infested with cyanobacterial blooms, possibly due to exposure to aerosolized toxins contained in water droplets.

With respect to US military veterans of Operation Desert Storm in 1991, the incidence of ALS among deployed personnel was threefold higher than among individuals with similar training who were not deployed to the Gulf. The ALS cases appeared as a time-limited spike a decade after deployment (Horner et al. 2003; Cox et al. 2009). Military activities, including tank and truck traffic as well as the take-off and landing of helicopters, can disrupt biocrusts. In the soil horizon in countries such as Qatar, cyanobacterial toxins can be found throughout the entire soil horizon (Chatziefthimiou et al. 2016; 2020) suggesting that large pools of toxins may be released by disturbance of the surface biocrusts in these arid environments for subsequent windborne transportation. Determination of the amounts of cyanobacterial toxins that were present within desert biocrusts was used as a basis to determine whether there was a human health risk through inhalation of this material as dust (Metcalf et al. 2012). Based on breathing rates for an average human adult, the potential dose of microcystins received was considered to be of sufficient risk to humans, especially during long dust storms, which are common in the Gulf region (Metcalf et al. 2012). Even though the concentrations of individual toxins, such as the microcystins, were sufficient to potentially cause illness, the fact that BMAA and neurotoxic isomers (Cox et al. 2009) have been found in this dust material, in the same pool as microcystins and anatoxin-a(*S*) (Metcalf et al. 2012), suggests a potential for co-exposure and synergistic effects among toxins, as previously noted for BMAA and the neurotoxic methylmercury (Rush et al. 2012), and more recently for these actual isomers in neuronal cells (Martin et al. 2019).

The risk of exposure to cyanobacterial and algal toxins through aerosols, which are largely present as water droplets, is one that requires further research to assess the potential effects and health risks for the population living near such environments. In addition to the possibility of inhalation of dust, people in desert environments often live near coasts. Therefore, the potential for exposure to water droplets containing bacteria or toxins associated with marine blooms, including brevetoxins (Pierce et al. 2003), may affect human health.

4 Remediation

4.1 Water

There are many ways to remediate cyanobacteria and their toxins when present in freshwaters. For the preparation of drinking water, various water treatment options are available to remove cyanobacteria and their toxins (Westrick 2008; Westrick et al. 2010; He et al. 2016).

With regard to desert environments, where the practice of desalination appears to be effective for the removal of a wide range of cyanobacterial toxins (Laycock et al. 2012; Villacorte et al. 2015), research is needed to better understand whether this particular means of water treatment through reverse osmosis is effective for the removal of all cyanobacterial toxins. Insufficient post-production treatment and the nature of water storage on the type of tanks used in arid regions may lead to seeding and contamination with cyanobacteria and cyanotoxins. This is especially important, as in the case of the high amount of cyanobacteria present as bio crusts in the State of

Qatar, such organisms may be distributed by winds such as Al Shamal winds and enter water storage tanks (Chatziefthimiou et al. 2016).

Consequently, any potable water stored at sites that are at risk of contamination and receiving sufficient light should be carefully examined. This may include periodic monitoring of the tanks, along with visual inspections and possible cyanotoxin analysis to determine the cyanobacterial toxin load within the drinking water system. In addition, better education and public outreach campaigns can inform the public as to the potential risks posed through exposure to drinking water in desert environments. Although the WHO has Guideline Values concerning the permissible concentration of microcystin-LR in drinking water of 1 μg/l, this is based on a 60-kg adult drinking 2 l of water per day. Such Guidelines may not be amenable to persons living in desert environments. Due to the environmental conditions encountered, such as with high daytime temperatures (up to 50 °C), it is likely that people living in these environments are drinking in excess of 2 liters of water to remain hydrated. Consequently, research is required to determine whether Guideline Values in desert environments should be altered to account for this increased consumption. Monitoring, routine inspection, and, if necessary, analysis of cyanotoxins can prevent intoxication and protect consumers.

4.2 Food

Frequent monitoring and subsequent toxin analysis, when possible or indicated, should be implemented in areas where food sources are harvested (e.g., crops). In China, over 6 million hectares of arid areas have been damaged by commercial collection of the cyanobacterium *Nostoc flagelliforme*, resulting in increased dust throughout China, as well as dietary ingestion of BMAA from the cyanobacterium itself (Roney et al. 2009). In the case of seafood, such as shellfish (Banack et al. 2014), if cyanobacterial toxins are considered to be present, then depuration of living shellfish can often result in seafood that is considered to be safe for human consumption. In the event that the seafood cannot be consumed, then closure of fisheries can often prevent contaminated food from entering the food chain until the bloom subsides and the risk passes.

4.3 Airborne/Aerosol

Many countries in the Gulf region are experiencing a construction boom. In many cases, construction materials are sourced locally, and as such, in some Gulf countries, necessary fill materials may include biocrusts depending on where they are sourced. Excavation of these biocrusts can lead to dusts becoming airborne and, based on the fact that cyanotoxins have been found to occur deep and throughout the soil horizon in desert environments (Chatziefthimiou et al. 2016; 2020), suggests that inhalation exposure may be a risk. Therefore, workers involved with the removal of construction materials should be provided with protective work-wear to minimize inhalation exposure, and techniques should also be implemented such as wetting of the soil in construction sites to minimize dust formation (Ivanov and Stabnikov 2017). Kellogg and Griffin (2006) suggest the use of remote sensing as a possible tool that could be adapted to monitor aerosolized microbes. By understanding the range and movement of microbes in the air column, early warning systems can be instated, something that could further protect workers and the general public.

5 Steps That Need to Be Taken to Seal the Gaps of Our Understanding

Ultimately, policy and regulations based upon sound science need to be implemented. These can be used for the testing of toxins in water and food and for the creation of monitoring and alert systems for toxins in dust and seawater. Furthermore, depending on the risk, this could ultimately be part of the meteorological updates for each country. Kuwait does have this as part of Regional Organization for the Protection of the Marine Environment (ROPME) Programme, but these results are not necessarily shared among member countries and sometimes are unevenly shared with the general population (ROPME 2017). This is problematic because the Gulf is a trans-boundary body of water, thus requiring a multi-lateral environmental management for efficient prevention of outbreaks.

6 Future Issues with Respect to Climate Change

Ultimately, the growth in the human population will further increase the demand for food and water. Along with climate change, the potential for cyanobacterial blooms to increase in freshwaters is well known. However, with respect to desert environments, the likelihood of (a) increasing desertification and (b) increasing human populations in desert environments indicates an increased demand for water supplies. Furthermore, in desert environments near marine waters, desalination is likely to be relied upon even more heavily.

In the future, in desert environments, increased monitoring is likely to be required by a number of agencies with corresponding co-operation between nations where necessary. Furthermore, the potential for toxins to be airborne should be recognized, especially for cyanotoxins deep within soil horizons. Understanding the risks posed by exposure to cyanobacterial toxins will depend upon the likely nearby sources and the correct legislation to protect human health. Although a nascent science, airborne cyanobacteria and their toxins require further research and assessment to determine the risks involved.

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