



Toxic alkaloids in *Lyngbya majuscula* and related tropical marine cyanobacteria

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ABSTRACT

The cyanobacterium *Lyngbya majuscula* is found in the littoral zone and to a depth of 30 m in tropical, subtropical and temperate regions across the globe, as well as being an important contributor to coral reef ecosystems. This cyanobacterium produces a range of chemicals that may contribute to a variety of negative health outcomes including skin, eye and respiratory irritation. The toxic compounds, lyngbyatoxin A and debromoaplysiatoxin, have been implicated in acute dermatologic reactions in human swimmers, and experiments involving these two toxins show the formation of acute dermal lesions. We explore the reported distribution and health implications of *L. majuscula*, with reference to factors affecting bloom frequency. The likely implications of climate change upon the distribution of the organism, and frequency of blooms are also described.

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1. Introduction

Lyngbya majuscula, is a benthic filamentous cyanobacterium that forms drab, olive-coloured, hairy, mats that grow to depths of 30 m. It occurs predominantly in the tropical and subtropical coastal waters, and in other more temperate areas to a lesser extent (Izumi and Moore, 1987) (Fig. 1). Blooms of *L. majuscula* are of concern because of their association with negative impacts upon human health and economic implications also arise as toxins from *L. majuscula* appear to harm commercially important fish species and other marine fauna, including some associated with tourism (Arthur et al., 2006; Harr et al., 2008; Magnino et al., 2009). Several attempts at taxonomic classification of *L. majuscula* have been performed (Rippka et al., 1979; Stanier and Cohen-Bazire, 1977), and until very recently this was accepted as Cyanophyceae, order Oscillatoriales, family Oscillatoriaceae, subfamily Oscillatorioideae, genus: *Lyngbya*.

However, with advances in phylogenetic analysis the classification of certain genera of cyanobacteria has been clarified, with

the genus previously known as *Lyngbya* now shown to be a polyphyletic group which includes diverse lineages (Engene et al., 2013). It is supposed that some samples previously attributed to species of the genus *Lyngbya* may in fact have belonged to a recently nominated genus *Moorea*. Of note to this review, the compounds curacin A and barbamide are proposed to be derived from morphologically similar cyanobacterial species of this new genus (Engene et al., 2012). The origins of several other compounds, including Lyngbyatoxin, have also been questioned, and it is likely that *Lyngbya* and several other subtropical and tropical marine cyanobacteria may be reclassified soon, as advances in phylogenetic methods allow more precise definitions to be applied in the taxonomy of such groups (Engene et al., 2013). This review deals with findings accumulated from the 1960s through to 2012, and without the facility retrospectively to test genetic markers of the samples described, it must be emphasised that we have followed the same nomenclature used by the authors of the papers cited in each instance.

1.1. Impact on human health

The skin is an organ commonly affected by exposure to cyanobacteria, especially during water-based recreational activities (Codd et al., 1999). Several harmful algal species, from both freshwater and marine environments, have been implicated in

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dermatological reactions, including *Lyngbya* spp., but also from the *Oscillatoria* and *Schizothrix* genera (Carmichael et al., 1990). These skin reactions have been proposed to be due exposure to cyanobacterial produced toxins; causing contact irritancy and/or immunologic reactions (Osborne et al., 2001; Stewart et al., 2006c). The dermatotoxic reaction to the marine cyanobacterium *L. majuscula* has been associated with dermatitis in humans over the last fifty years, and is the best-characterised cyanobacterium causing dermatitis, although experimental evidence is also accumulating on the dermatotoxic nature of *Cylindrospermopsis* and related cylindrospermopsin-producing species (McGregor et al., 2011; Stewart et al., 2006a).

1.2. Environmental influences: toxin production and bloom frequency

L. majuscula has a worldwide distribution, but is most commonly seen in the tropics and subtropics (Table 1 and Fig. 1). Early descriptions revealed spatial and temporal differences in toxicity for samples collected in the Hawaiian (Grauer and Arnold, 1961) and Marshall Islands (Mynderse et al., 1977). Samples collected on the seaward side of the Marshall Islands were more toxic than samples collected on the lagoon side (Mynderse et al., 1977). More recently differences in amounts of toxins in *L. majuscula* collected from Moreton Bay, Australia have been noted, with debromoaplysiatoxin (DAT) being produced exclusively on the landward side of the bay, and lyngbyatoxin A (LA) predominantly being produced on the seaward side, 30 km away (Osborne et al., 2002). Temporal changes in the concentrations of certain chemicals in near shore environments may be caused, for example, by fertiliser run off during weather events. Changes in the ratios of phosphorus, nitrogen and iron have been implicated in the formation of *L. majuscula* blooms (Albert et al., 2005), and the effects of enrichment can be seen further up the food chain as changes in the feeding behaviour of grazing species such as *Stylocheilus striatus* (Arthur et al., 2009).

Climate change has a number of implications for the biology of *Lyngbya* species. In addition to the increase in the viable range of the genus which would be predicted if waters become warmer globally (Hays et al., 2005), the warming of water bodies has generally been shown to increase the growth rate of cyanobacteria to a greater extent than phytoplankton (O'Neil et al., 2012). It has already been demonstrated that warmer months increase cyano-

bacterial cell density within *Lyngbya*'s existing geographical range (Hu et al., 2009). A number of other changes to the physical properties of water, such as temperature-induced stratification and altered CO₂ concentrations, may offer cyanobacteria such as *Lyngbya* a competitive advantage over other microorganisms, and have been discussed in detail elsewhere (O'Neil et al., 2012). Modern technology allows the prediction of conditions likely to lead to algal blooms, for example machine learning algorithms based on previously collected datasets can predict *L. majuscula* blooms based on in climate-influenced factors such as wind speed and direction, and light intensity in shallow waters (Kehoe et al., 2012). The warming of the climate, including air temperatures and water bodies, might also be expected to increase the number of people using near-littoral sea areas for recreation, hence increasing the possibility of exposure to cyanobacterial toxins, although the way in which changes in seas level and temperature affect people's recreational preferences may be complex (Hipp and Ogunseitan, 2011).

The biochemical properties of near-shore waters could also be impacted by climate change. Eutrophication of near-shore waters may be made more likely by the sudden or extreme precipitation events predicted to be a component of climate change, which can result in the run off of Phosphorous and/or Nitrogen from agricultural land to the sea (Boxall et al., 2008). Additionally extreme precipitation events are likely to lead to more direct discharge of untreated sewerage via combined sewer overflows in populated areas, therefore increasing nutrient loading to the marine environment further. There is already evidence of an increase in frequency of *Lyngbya* blooms, and nutrient enrichment has been implicated (Arthur et al., 2009). Some authors suggest that the consequences of such nutrient enrichment, in favouring the growth of a number of species of harmful cyanobacteria, may be severe, and propose restricting the use of fertilisers in order to mitigate this (Paerl and Paul, 2012).

Although the impacts of climate change on cyanobacterial ecology are difficult to predict in detail, it is likely that changes in bloom frequency and distribution will occur. Factors such as higher water temperatures may result in range expansion or range shift into regions in which are not currently familiar with, or prepared for, *L. majuscula* bloom events. The combination of higher nutrient inputs and salt-water intrusion may also increase the exposure risk for humans, by increasing bloom frequency and

Table 1
Worldwide observations of *L. majuscula* blooms.

Territory	Location	Ocean/Sea	Authors
Australia	Moreton Bay, Queensland	Pacific/Coral Sea	Albert et al. (2005); Dennison et al. (1999)
Curacao	Carmabi Beach	Caribbean	Gerwick et al. (1994)
Fiji	Yacuna Island	Pacific	Williamson et al. (2000)
France	Le Brusch	Mediterranean	Milligan et al. (2000)
Grenada	Grand Anse Beach	Caribbean	Sitachitta and Gerwick (1998)
Guam	Piti Bomb Holes	Pacific	Nagle et al. (1997)
Hawaii	Oahu	Pacific	Banner (1959)
Madagascar	Tanikeli Island	Indian	Singh et al. (1999)
Marshall Islands	Enewetak Atoll	Pacific	Mynderse et al. (1977)
Mozambique	Inhaca Island	Indian	Silva and Pienaar (1999)
Okinawa	Ryukyus Islands	Pacific	Hashimoto et al. (1976)
Palau	Big Goby Marine Lake	Pacific	Mitchell et al. (2000)
Palmyra Island		Pacific	Habekost et al. (1955)
Papua New Guinea	Hermit Island	Pacific	Tan et al. (2000)
Philippines	Batan Island	Pacific	Beutler et al. (1990)
Puerto Rico	Mayaguez	Caribbean	Ainslie et al. (1986)
Sri Lanka		Indian	Grauer and Arnold (1961)
Taiwan	Tapong Bay	Pacific	Lin and Hung (2004)
United States of America	Florida	Atlantic	Albert et al. (2005)
Venezuela	La Blanquilla	Caribbean	Koehn et al. (1992)
Virgin Islands	St. Croix	Pacific	Márquez et al. (1998)

Adapted from Osborne (2004).

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