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A review of the incidence of cyanobacteria (blue-green algae) in surface waters in Scotland including potential effects of climate change, with a list of the common species and new records from the Scottish Environment Protection Agency

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ABSTRACT

Cyanobacteria, commonly known as blue-green algae, are a ubiquitous component of the freshwater microflora. Cyanobacteria are capable of producing toxic compounds that pose a risk to water-users, pets and livestock, with increased risk when they form dense growths, termed blooms, which may accumulate at the leeward shores of water bodies, often forming visible scums. The Scottish Environment Protection Agency receives numerous water samples annually for algal analyses, including determining the presence or absence of cyanobacteria, which are used in the management of risk to water users by water owners, local Councils and Health Authorities. The commonest cyanobacterial taxa recorded over the period 2008-2010 are detailed, along with new cyanobacterial records for Scotland. The current scenarios of climate change predict an overall increase in phytoplankton biomass, with potential increased dominance of cyanobacteria including increased intensity and frequency of blooms.

INTRODUCTION

Cyanobacteria are ubiquitous and contribute to the natural community of photosynthetic microscopic algae living in fresh waters. Cyanobacteria are more commonly referred to as blue-green algae due to the colour of the cells, which contain a mixture of photosynthetic pigments including chlorophyll (green), phycocyanin (blue) and sometimes phycoerythrin (red).

Excessive growths of cyanobacteria, termed blooms, have been related to the elevated nutrient status of water bodies (Reynolds and Petersen, 2000), to a number of seasonal factors (warmer temperatures, intensity of water thermal stratification) (Reynolds, 2006), to high alkalinities and pH (Shapiro, 1984), and to a number of physiological adaptations and mechanisms (Fogg, 1969; Reynolds, 1987; Shapiro, 1990). Carvalho *et al.* (2011) found that low water colour and neutral-alkaline conditions were the significant explanatory variables in determining which water bodies in the UK were vulnerable to cyanobacterial blooms, with increasing retention time and total phosphorus concentrations being borderline significant explanatory variables.

Certain cyanobacteria are able to form surface blooms through the regulation of their buoyancy by the use of gas vesicles, and such blooms may be restricted to the surface layers of the water. Light winds may concentrate the blooms to further accumulate and form scums, which may be extremely dense at leeward shores, bays and inlets, often where members of the public identify the problem, though when wind speeds increase the blooms disperse within the deeper water layers. Consequently blooms may form and disappear rapidly, within hours, due to variable weather conditions. Blooms are commonest during the summer, persisting into late-autumn, and are of concern to many water users as well as a danger to pets and livestock when the excessive growths and concentrations of cyanobacteria result in dense surface and shore-line scums. This is because cyanobacteria have the potential to produce toxins, and cyanotoxin production is much greater where cyanobacteria accumulate and form surface blooms and scums.

The different types of cyanotoxins produced by cyanobacteria and their mode of action have been widely documented (Chorus and Bartram, 1999). Cyanotoxins include neurotoxins, hepatotoxins, lipopolysaccharides, and a wide range of other products leading to enzyme inhibition and skin and gastrointestinal irritations (Chorus and Bartram, 1999). The exposure routes of cyanotoxins are diverse, mainly through ingestion, inhalation and skin contact. Exposure to cyanotoxins is therefore greatest during participation in water-based recreational activities. However, cyanotoxins may also be taken up directly through food consumption (Funari and Testai, 2008; Murch *et al.*, 2004). Symptoms produced by cyanotoxins can be mild (skin irritations and gastrointestinal illness), serious (acute poisoning and potential long-term illness) or terminal (death) (Chorus and Bartram, 1999). Cyanotoxins may also pose an additional threat due to their carcinogenic properties (Falconer, 2005). Furthermore, the issue of toxicity is complicated by the occurrence of both toxic and nontoxic strains within the same species of cyanobacteria. However, a high percentage (59%) of all samples are toxic (Chorus and Bartram, 1999).

Cyanobacterial blooms and associated toxicity have been reported worldwide over the years (Francis, 1878; Metcalf and Codd, 2004) and although previously limited in frequency, in recent decades the frequency, intensity and reporting of cyanobacterial blooms has become widespread (Krokowski and Jamieson, 2002; Carmichael, 2008). There continue to be reports of animal deaths and skin irritation in humans associated with algal and cyanobacterial blooms and scums throughout Scotland (Scottish Government, 2007; Krokowski, 2009), although objective evidence is difficult to obtain to confirm an association with cyanotoxin exposure. A number of Scottish freshwater bodies, however, continue to be perennial 'hot spots' containing high concentrations of cyanobacteria throughout summer and into autumn.

Cyanobacteria are therefore arguably the most visible symptoms of eutrophication (nutrient enrichment) of surface waters, and there is growing concern about the likely increase in the frequency and intensity of cyanobacterial blooms associated with global warming (Mooij *et al.*, 2005).

ASSESSMENT OF CYANOBACTERIA-RELATED BLOOMS AND SCUMS IN SCOTTISH FRESHWATER BODIES

Background

A comprehensive inventory of standing freshwaters derived from Ordnance Survey digital map data in Great Britain identified 25,615 water bodies in Scotland with surface area larger than $0.01km^2$ (Hughes *et al.*, 2004). The majority of these are in north-west Scotland. The data set contains no water bodies $<0.0002\ km^2$, with the numbers between $0.0002\ km^2$ and $0.002\ km^2$ almost certainly under-represented so numbers may be closer to 31,460 standing water bodies as identified earlier (Lyle and Smith, 1994). It is therefore impossible to accurately assess the extent of cyanobacterial blooms and scums in Scottish freshwater bodies, as there is no comprehensive survey of all freshwaters. Moreover, a reactive monitoring strategy has been adopted where samples are received for analysis from external sources from sites with a perceived visual algal problem.

In 1997, the Scottish Environment Protection Agency (SEPA) carried out an assessment of a selected number of lochs (based on size, amenity value and recreational potential) to assess the degree of eutrophication through the prevalence of cyanobacterial blooms (SEPA, 1999). The results are not representative of the total incidence of blooms across water bodies in Scotland, but of the 77 lochs monitored, 38 had a cyanobacterial scum present and an additional 20 lochs had cyanobacteria present at sufficient levels for bloom formation (this level is taken to be equivalent to more than 20,000 cyanobacterial cells/ml). A subsequent assessment of eutrophication in 2005, carried out as part of statutory review of eutrophication under the Urban Waste Water Treatment Directive, identified 17 lochs with excessive nutrient levels (primarily phosphorus) (SEPA, 2005). Although cyanobacteria were not monitored directly during the 2005 assessment, criteria selected were based on the exceeding of set thresholds of total phytoplankton biomass measured as chlorophyll *a*, as well as the exceeding of set thresholds for nutrient concentrations (nitrogen and phosphorus) and other selected attributes and biota (dissolved oxygen, macrophytes).

Algal and cyanobacterial assessment during 2008-2010

SEPA, amongst its other duties, continues to carry out surveillance monitoring in response to environmental legislation and is able to provide an analytical service for the analysis of algae and cyanobacteria. SEPA, however, does not carry out targeted monitoring and assessment for frequency and intensity of cyanobacteria, but relies on others to provide samples from affected waters that are perceived to pose a risk to water users.

Samples received by SEPA are normally collected from a point on the downwind shore of the water body where the concentration of cyanobacteria is greatest. If the downwind site is inaccessible, the water body is sampled at the nearest accessible point to the downwind shore. Details of sampling and location are provided to SEPA. Algae are sampled at or just below the water surface, and benthic algae are occasionally also collected. A full sampling protocol is detailed in the Scottish Government guidance (Scottish Government, 2007). Live samples are sent as quickly as possible to local SEPA laboratories for analysis (Aberdeen, Dingwall, Perth, Edinburgh, Galashiels, East Kilbride and Dumfries). Standard operating procedures are used by SEPA to quantify the type of cyanobacteria present, and their abundance is reported against the World Health Organisation guidance levels (Scottish Government, 2007). Microscopic analysis is carried out with identification to species level where possible, and algae and cyanobacteria are identified with the aid of taxonomic guides and keys (John *et al.*, 2011; Komarek and Anagnostidis, 1999, 2005). Results are generally reported the same day.

Information on cyanobacteria samples received from such assessment over the period 2008-2010 is summarised in Table 1, with a list of the common cyanobacteria and new records from Scottish freshwater bodies detailed in Table 2.

In the period 2008-2010, a total of 422 samples was received by SEPA and analysed for the type of algae present and their abundance (Table 1). No clear trend

	2008		2009		2010	
SEPA Ecology laboratory	**Total number of samples received**	**Number exceeding cyanobacterial threshold, expressed as % of the total**	**Total number of samples received**	**Number exceeding cyanobacterial threshold, expressed as % of the total**	**Total number of samples received**	**Number exceeding cyanobacterial threshold, expressed as % of the total**
Aberdeen	23	5 (22%)	29	12 (41%)	27	14 (52%)
Dingwall	8	4 (50%)	5	2 (40%)	8	4 (50%)
Perth	66	37 (56%)	36	11 (31%)	24	10 (42%)
East Kilbride	83	17 (20%)	63	13 (21%)	45	31 (69%)
Edinburgh and Galashiels	1	1 (100%)	5	5 (100%)	6	4 (67%)
Dumfries	0	0	9	4 (44%)	20	7 (35%)
All combined	**181**	**64 (35%)**	**147**	**47 (32%)**	**130**	**70 (54%)**

Table 1. Summary of the annual number of samples received by each SEPA Ecology laboratory for algal analysis from the reactive monitoring programme. Detailed are number of samples exceeding the cyanobacterial concentrations of 20,000 cells/ml (representing a relatively low probability of adverse health effects) and expressed as a percentage of the total number of samples received.

Order	**Cyanobacteria taxon**	**Frequency**
Chroococcales	*Aphanocapsa* Nageli 1849	F
	Aphanothece Nageli 1849	F
	A. minutissima (W.West) Komarkova-Legnerova et Cronberg 1994	R
	Chroococcus limneticus Lemmermann 1898	O
	Coelosphaerium kuetzingianum Nageli 1849	O
	Gomphosphaeria aponina Kutzing 1836	O
	Merismopedia Meyen 1839	O
	M. warmingiana Lagerheim 1883	R
	Microcystis Kutzing 1833 ex Lemmermann 1907 nom.cons	F
	M. wesenbergii (Komarek) Komarek in Kondrateva 1968	O
	Radiocystis geminata Skuja 1948	R
	Snowella Elenkin 1938	O
	S. atomus Komarek et Hindak 1988	N
	S. septentrionalis Komarek et Hindak 1988	N
	Synechococcus Nageli 1849	O
	Woronichinia naegeliana (Unger) Elenkin 1933	F
	W. karelica Komarek et Komarkova-Legnerova 1992	N
Oscillatoriales	*Oscillatoria* (Vaucher 1803) Gomont 1892	F
	O. tenuis (C.Agardh 1813) Gomont 1892	O
	Planktothrix agardhii (Gomont) Anagnostidid et Komarek 1988	F
	P. isothrix (Skuja) Komarek et Komarkova 2004	O
	Pseudanabaena Lauterborn 1914-17	F
	P. limnetica (Lemmermann) Komarek 1974	O
Nostocales	*Anabaena* (Bory 1822) Bornet et Flahault 1886	F
	A. affinis Lemmermann 1897	O
	A. catenula (Kutzing 1849) Bornet et Flahault 1886	O
	A. circinalis (Rabenhorst 1852) Bornet et Flahault 1886	F
	A. flos-aquae ((Lyngbye) Brebisson 1835) Bornet et Flahault 1886	F
	A. spiroides (Klebahn 1895)	F
	Aphanizomenon flos-aquae ((Linnaeus 1753) Ralfs 1850) Bornet et Flahault 1886	F
	A. gracile Lemmerman 1910	O
	Gloeotrichia (J.Agardh 1842) Bornet et Flahault 1886	F
	G. echinulata (J.E.Smith) P.G.Richter 1894	F

Table 2. Cyanobacterial taxa recorded from Scottish freshwaters as part of SEPA's algal analysis, indicating frequency – F (frequent), O (occasional), R (rare) and N (new – requiring further verification).

was evident in the incidence and frequency of cyanobacteria over the three-year period. The highest numbers of samples were received by East Kilbride and Perth laboratories, whereas the lowest numbers of samples were received by laboratories in Edinburgh and Galashiels. No samples were received by Dumfries laboratory in 2008.

The proportion of samples analysed and found to contain cyanobacteria exceeding the threshold concentration of 20,000 cells/ml also varied between the laboratories and over the years, but in general over one third of samples analysed contained cyanobacteria at concentrations above the threshold value.

In total, 33 cyanobacteria taxa from 17 genera were recorded from Scottish fresh waters (Table 2), with the most frequent toxin-producing cyanobacteria genera recorded as *Aphanocapsa*, *Aphanothece*, *Microcystis*, *Woronichinia*, *Oscillatoria* (*Planktothrix*), *Anabaena*, *Aphanizomenon* and *Gloeotrichia* (Table 2.). Cyanobacteria species not previously recorded from Scotland are also detailed, and include records from SEPA's phytoplankton monitoring carried at a number of lochs (>1km^2) across Scotland over the summer months (July to September) as required under the Water Framework Directive (European Commission, 2000). The WFD-related monitoring results are not detailed here in full, but of note are new records for *Snowella atomus*, *S. septetrionalis* and *Woronichinia karelica*. A number of these records require confirmation, if possible from live material, due to the very small dimensions of the cells and colonies and difficulties in correctly identifying the taxa from Lugol's iodine preserved material.

DISCUSSION

The 2008-2010 assessment

It is difficult to identify trends in the frequency and intensity of cyanobacteria across Scottish freshwaters based on the results presented here, mainly because they are based on subjective monitoring, since only sites that have a perceived algal problem are investigated. Furthermore, sites that have perennial cyanobacterial problems may not have been monitored in subsequent years. It is likely that visible warning signs of the presence of high concentrations of cyanobacteria in the water may be a deterrent in itself, and avoid the need to provide samples for analysis. However, the service provided by SEPA for the assessment of algae and cyanobacteria is crucial in providing an early detection system for the presence of potentially toxic species enabling appropriate monitoring and remedial action to be taken, not only for cyanobacteria (local algal action plan), but also for other algal groups (*Chrysochromulina*, Krokowski, 2009).

Empirical evidence indicates a direct positive relationship between increasing external load of nutrients and algal biomass, although each water body is unique (Vollenweider and Kerekes, 1982). In attempts to control eutrophication and its symptoms (such as excessive algal and cyanobacterial biomass) the most widely accepted and employed option is to reduce nutrient inputs, which has to be part of a long-term restoration and management strategy (Sas, 1989). The long-term restoration may also include methods aimed at reducing in-lake nutrient concentrations, controlling nutrient sources from sediments, and controlling in-lake levels of algae and cyanobacteria. Any future management options to control eutrophication, and the abundance of potentially toxic cyanobacteria, should be carefully assessed with a detailed restoration and management action plan.

Management of the health risks posed by cyanobacteria

To help provide effective management of the health risks associated with the exposure of humans and animals to cyanotoxins, the Scottish Government has produced guidance for the assessment and minimisation of risks to public health in inland and inshore waters (Scottish Government, 2007). Guidance adopted following equivalent guidance provided by the World Health Organisation (Chorus and Bartram, 1999) produced guideline values based on cyanobacterial abundance for recreational waters, relating them to a relatively low probability of adverse health effects (cyanobacterial concentrations of 20,000 cells/ml), moderate probability of adverse health effects (cyanobacterial concentrations of 100,000 cells/ml), and high probability of adverse health effects (where cyanobacterial scum is present). As an additional precaution, the guidance adopted in Scotland is at the lower level of risk, at the limit of 20,000 total cyanobacterial cells/ml at which bathing should be discouraged and the hazard investigated further, on-site risk advisory signs posted, relevant authorities informed, and mindful watch kept out for scum conducive conditions.

The Scottish Government guidance includes the development, implementation and coordination of local blue-green algae monitoring and action plans involving a number of organisations and stakeholders, aimed at identifying, inspecting and monitoring those water bodies most at risk of cyanobacteria, and providing remedial and preventative measures as well as providing information to the public. SEPA is one such organisation involved in helping to develop local action plans and able to provide an analytical service to identify and quantify algae and cyanobacteria from water samples. SEPA also contributes to the surveillance of environmental incidents as recorded via the Scottish Environmental Incident Surveillance System.

Potential effects of climate change

Climate change may pose significant and extreme threats to the phytoplankton community structure and hence to the ecological status of Scottish freshwater bodies. Modelled increases in annual air temperatures (IPCC, 2007) would give rise to increased water temperatures, and with high summer temperatures predicted there could be prolonged periods of thermal stratification of relatively deep water bodies. Predicted increases in rainfall would also increase nutrient run-off. Consequently, modelling predicts an increase in phytoplankton biomass, potentially increased dominance of cyanobacteria, and increased intensity and frequency of cyanobacterial blooms (Wagner and Adrian, 2009). The effects of warming on increasing cyanobacterial biomass, and frequency and intensity of blooms may however be more pronounced in relatively deeper, stratified water bodies, where there are relatively fewer macrophytes and where phytoplankton dominance is established (Moss *et al.*, 2003).

There are also likely to be expansions of warm-water species at the expense of cold-water species, with potential expansion of invasive cyanobacteria such as *Cylindrospermopsis raciborskii* (Wiedner *et al.*, 2007). *C. raciborskii* has spread from the tropics to temperate zones over recent decades and is now found in most northern European water bodies. *C. raciborskii* has the potential to produce toxins harmful to animals and humans (a neurotoxin saxitoxin and hepatotoxin cylindrospermopsin). There are currently no known records *of C. raciborskii* in Scotland, but if the succession of warmer summers continues it is likely that it may be recorded in the British Isles. The new phytoplankton taxa already recorded in the British Isles may reflect climate change or the increased sampling frequency across Scotland that is a consequence of the statutory WFD monitoring.

In order to be able to understand these complex water body-specific responses to climate change and to be able to predict response patterns, understanding of freshwater ecosystems will be required on a case by case basis. We therefore need to continue to monitor the aquatic environment to provide information for rapid and effective management of algal incidents, and to develop novel techniques for effective monitoring and remediation of freshwaters. We also need to acknowledge that current remedial measures may need to be considerably adjusted to take into account the effects of climate change, and that current restoration techniques may become less effective due to exacerbated effects of eutrophication brought on by climate change. It may be that green is the colour of environmental acceptability, unless it refers to the colour of water bodies (Reynolds 1997).

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