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Climate change and cyanobacteria harmful algae blooms: adaptation practices for developing countries

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Abstract. Cyanobacterial harmful algal blooms (CyanoHABs) are increasingly being reported worldwide owing to several reasons, including widespread eutrophication and enhanced scientific monitoring. Catchment and water management, organisations, industry, farmers and local governments are all confronting the effects of climate change, which stimulate the growth of cyanobacteria and affect the efficacy of adaptation measures in water systems. To tackle climate change and CyanoHABs growth, actors at different levels require both 'top-down' and 'bottom-up' assessments to help them in formulating and implementing adaptation measures. Potential solutions must also be assessed locally to limit associated adverse effects, in particular, negative effects on water quality. Thus, having a better understanding of the synergies, conflicts and trade-offs between adaptation practices and climate-change effects on CyanoHABs makes a valuable contribution to a more integrated climate policy and the effective climate-proofing of our water bodies. This article examines adaptation practices focused on tackling CyanoHABs occurrence in a changing climate. It fills an important gap between a major environmental problem and potential solutions. The practices and measures advanced as a result of the analysis can be used by persons with different expertise and skill levels for improving the relevant institutional frameworks and policies to protect their local water bodies.

Keywords: eutrophication, climate change, adaptation, cyanobacteria.

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Introduction

The vulnerability of water resources to the impacts of climate change, especially impacts on water quality for human consumption, is influenced by several factors. One of the most important is human behaviour, both in terms of water managers (governance bodies, water supply and distribution agencies) and consumers (for drinking, irrigation and industrial uses). Developing economies are especially vulnerable because of the lack of science-informed policy (Lahsen *et al.* 2010), low income and limited institutional capacity, poor access to information as well as their greater reliance on climate-sensitive sectors such as agriculture and forestry (Nath and Behera 2011). These factors place developing economies at a disadvantage and challenge their capabilities to absorb additional stresses caused by climate change and extreme weather events. Such complex vulnerabilities require specific adaptation practices to enhance the adaptive capacity of the developing countries and move them towards achieving sustainable development in this century. Properly assessed, the experience gained from efforts to develop adaptation practices in developed economies can provide useful pointers for adaptation in developing countries.

Observational records and climate projections provide a substantial amount of evidence that water resources are vulnerable to, and have the potential to be strongly affected by, climate change (Delpla *et al.* 2009; Kundzewicz *et al.* 2018; Natalia *et al.* 2020; Rivadeneira Vera *et al.* 2020; Tesfahunegn and Gebru 2020). Higher water temperatures and changing weather patterns can affect water quality and exacerbate many forms of water pollution. For instance, drought can decrease water quality by concentrating pollutants (such as nutrients) and intense rain can wash fertilisers from crops, which are then discharged in water systems (Allen *et al.* 2021). Such climatic events, and the associated accumulation of nutrients in water bodies, are contributing to global eutrophication and the expansion of cyanobacterial harmful algal blooms (CyanoHABs) across geographically diverse regions (Xia *et al.* 2016; Glibert 2020; Paerl *et al.* 2020).

Under such circumstances, one option available for developing countries to counter the negative effects of climate change is to develop specific actions, especially at local levels. Because of the usual lack of adequate financial and technological resources and scientific infrastructure, only a few developing countries can afford to conduct the required studies and design appropriate actions. Therefore, there is a need to understand the particularities and constraints of developing economies for informing and formulating specific adaptation practices to effectively and efficiently tackle water-quality issues (Nath and Behera 2011).

Water managers around the world have begun to directly address the implications of climate change as part of their water supply management practices, by using conventional water infrastructure solutions (as building more reservoirs) or developing unconventional solution such as atmospheric moisture harvesting (cloud seeding or fog water collection; Chadwick *et al.* 2020; Loudière and Gourbesville 2020; United Nations Educational, Scientific and Cultural Organization 2020). However, examples of concrete actions in the water sector to specifically (and solely) adapt to a changing climate are rare (Dokulil and Teubner 2010; Moss *et al.* 2011; United Nations Educational, Scientific and Cultural Organization 2020). This is partly due to climate change often being one of many drivers considered in adaptation strategies and investment plans, and partly attributable to uncertainty in projections of future hydrological changes.

The present paper reviews and uses valuable information from the specialised scientific literature on climate change and its impacts on CyanoHABs and specific adaptation practices to tackle the impacts, thereby making the available evidence more accessible to decision makers. It seeks to focus on several aspects not sufficiently emphasised in previous studies, or mentioned separately, allowing a better understanding of the synergies, conflicts and trade-offs. It begins with an exploration of the effect of climate change on CyanoHABs, which gives a snapshot of the complex confluence of factors at the nexus of CyanoHABs and climate change. It is providing an overview on the complexities of the vulnerability of developing economies in the context of climate change and CyanoHABs, and helping target and advance adaptation practices to tackle climate-change impacts on CyanoHABs that can be potentially applied in such developing contexts.

The information is presented in a form that can guide the multiple stakeholders concerned, including catchment and water managers, organisations supplying drinking water, farmers, and local governments. It, hence, fills an important gap between research about the problems and effective and efficient implementable solutions.

Approach to defined potential adaptation practices in developing countries

In the context of the quality of water resources, adaptation specifically means anticipating the effects of climate change and taking appropriate action to prevent or minimise the damage CyanoHABs can cause, or exploit opportunities they may present (adapted from United Nations Framework Convention on Climate Change 2007).

The extent to which climate change is intensifying CyanoHABs is not fully clear yet (Burford *et al.* 2020). The United Nations' Intergovernmental Panel on Climate Change's (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), approved in September 2019, was the first IPCC report to directly link CyanoHABs to climate change with

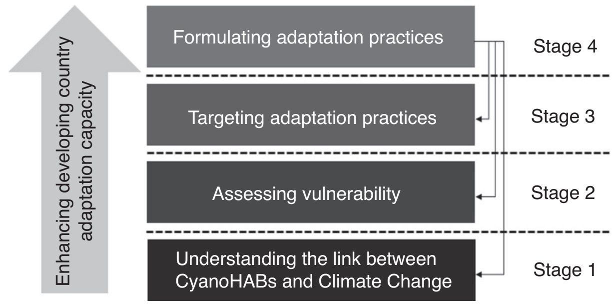

Fig. 1. Methodology applied to identify potential adaptation practices. Source: developed by the authors.

a 'high degree of confidence'. Therefore, adaptation practices to improve and maintain water quality must clearly be based on understanding the interaction between climate change and CyanoHABs.

Several barriers and constraints must be considered when adaptation practices are designed in a developing country context. Adaptation actions can range from short-term coping measures to longer-term and deeper transformations aimed at achieving more than climate-change goals alone. Although attention to flexibility and safety margins is common in selecting adaptation options, developing countries may see the need for more transformative changes such as making ecological sustainability its first priority (Laininen 2018). In terms of CyanoHABs, measures should be designed on the basis of avoiding or minimising the risk, the negative effects, and taking advantage of opportunities. Thus, adaptation requires participation by most economic sectors and involves many levels of decision-making.

So as to define and prioritise climate-change adaptation practices focusing on CyanoHABs, the methodology used in this paper consists of four stages (Fig. 1), which are discussed in turn.

Stage 1. Impacts of climate change on CyanoHABs

Recent studies have shown that global and regional climatic changes benefit various species of harmful cyanobacteria by increasing their growth rates, dominance, persistence, geographic distributions and activity (Paerl and Huisman 2009; Jeppesen *et al.* 2010; Moss *et al.* 2011).

This section specifically focuses on pelagic HABs species, which affect drinking water supplies (such as *Microcystis*). It should be noted that toxic benthic CyanoHABs appear to be increasing as a result of climate change. However, they have received less attention in the specialised literature (Burford *et al.* 2020) probably because researchers have been focusing on species that affect drinking water production. Further research of climate change effects on individual species is hence required to develop specific adaptation practices; this issue is not covered in this paper.

According to the report by Berg and Sutula (2015), harmful algae can reproduce quickly in favourable conditions where there are (i) high concentrations of nutrients (especially nitrogen and phosphorus), (ii) high irradiance, (iii) low salinity, (iv) warm temperature and (v) high residence time (stratified conditions). It is also widely accepted that climate change will affect surface water temperatures, and modify rainfall patterns and wind characteristics (Moss *et al.* 2011; Paerl 2014; Chen *et al.* 2016; Giupponi and Gain 2017; Haakonsson *et al.* 2017). All these factors are analysed below to understand the climate-change effects on CyanoHABs.

Temperature effects

The effect of the factors that influence the growth of cyanobacteria is likely to worsen with increased water temperatures caused by climate change. The general consensus is that the optimum growth temperature for cyanobacteria is higher than that for most algae (Butterwick *et al.* 2005).

Many species of cyanobacteria possess gas vesicles that enable buoyancy regulation. Their function is to give cyanobacteria an ecologically important mechanism, enabling them to adjust their vertical position in the water column, such as, for instance, looking for zones with higher nutrient concentrations (Reynolds *et al.* 1987). Rising temperatures decrease the resistance of water to vertical migration of phytoplankton. When the water is turbulent, cyanobacteria are evenly distributed over the water column. However, when temperatures increase and there is little wind mixing, the water column becomes stagnant, allowing buoyant cyanobacteria to float upward, forming dense scums at the water surface. Some harmful cyanobacteria contain pigments that help them to survive in high-irradiance conditions of the surface water (Paerl *et al.* 1983). In addition, surface blooms reduce the penetration of sunlight to deeper sections of the water column, thereby suppressing their non-buoyant eukaryotic phytoplankton competitors (Jöhnk *et al.* 2008; Huisman *et al.* 2018). Moreover, many cyanobacterial species can uniquely exploit stratified conditions and this indirectly enhances HABs. Lakes in temperate zones tend to stratify in spring but rising temperature would cause an earlier appearance of this phenomenon and probably extend it to later into the autumn (Paerl and Huisman 2009; Monchamp *et al.* 2018).

Another indirect effect of the water resistance to vertical migration of phytoplankton is the availability of carbon dioxide (CO_2). The research conducted by Xing Ji showed that some bloom-forming cyanobacteria, such as *Microcystis aeruginosa*, will benefit from elevated CO_2 concentrations (Ji *et al.* 2017). A high incidence of photosynthetic organisms restricts the CO_2 availability (Enríquez *et al.* 1996). Considering that the cyanobacteria can adapt better to live in the surface stratus, they can directly intercept CO_2 from the atmosphere, taking advantage of the conditions (Paerl and Ustach 1982).

As a result of the photosynthetic activity of blooms, the CO_2 concentration in eutrophic lakes can vary from supersaturation in winter to undersaturation in summer. Bloom-forming cyanobacteria display an unexpected diversity in CO_2 responses, because different strains combine their uptake systems for CO_2 and bicarbonate in different ways to adapt (Visser *et al.* 2016). However, increases in atmospheric concentrations of CO_2 could have a more beneficial effect on cyanobacteria's competitors, such as eukaryotic algae (Fu *et al.* 2007). Although this might suggest that globally rising CO_2 could diminish the intensity of CyanoHABs, little is known regarding how increases in the concentration of this gas will affect other aspects such as cell physiology and growth rates of individual cyanobacteria genera (O'Neil *et al.* 2012). It is important to highlight that some research has demonstrated, both in theory and in experiments, that rising CO_2 concentrations can alter the community composition and toxicity of *Microcystis aeruginosa* blooms (Van de Waal *et al.* 2011). However, it is not clear whether the results are the same for other cyanobacterial taxa in general.

Fish communities in warm waters have lower numbers of strictly piscivorous fish but higher numbers of omnivorous fish (Moss *et al.* 2011). Omnivores, the fish species that eat zooplankton, which are microscopic animals that can feed on and control cyanobacteria (Ger *et al.* 2014), may increase in density in warmer water. In particular, the zooplankton called *Daphnia* is very effective in controlling algae; however, its density is governed partly by the seasonal temperature cycle (George *et al.* 1990; Havens and Paerl 2015). How climate change will affect *Daphnia* populations is not totally clear yet (George *et al.* 1990; Hiltunen *et al.* 2021). Furthermore, cyanobacteria are harder to digest by zooplankton. So, if this species dominates water systems (coastal and inland waters, including rivers, lakes and reservoirs), the natural capacity to control the blooms decreases (Jeppesen *et al.* 2010).

Unfolding climatic changes can potentially weaken marine food webs, leading to food-web simplification. This phenomenon alters the producer–consumer dynamics, both of which have important implications for the structuring of cyanobacteria (Ullah *et al.* 2018). Climate change can potentially reduce energy flow to higher trophic levels and cause a shift towards a more detritus-based system, leading to food-web simplification and altered producer–consumer dynamics. Furthermore, the research conducted by du Pontavice *et al.* (2020) detected and projected alterations as a result of climate change in mean trophic transfer efficiency and the biomass residence time in the food web that may undermine food-web functioning (du Pontavice *et al.* 2020).

Another important factor is the behaviour of submerged vegetation. Submerged aquatic plants provide buffers in temperate zones against increasing external nutrient load. They, therefore, play an important role in water ecosystems. Nutrient availability increases competition between macrophytes and phytoplankton (Lacoul and Freedman 2006). This results in phytoplankton dominance and the disappearance of macrophytes (Declerck *et al.* 2005). The main reason for that is that eutrophication promotes algal (benthic and planktonic) growth, which decreases the light reaching other plants (macrophytes), thus decreasing their growth, productivity and distribution. In addition, climate change can also influence macrophyte growth. Thus, macrophyte growth and distribution can be taken as a reliable bio-indicator to study the relationships between environmental disturbance and vegetation growth (Hossain *et al.* 2017).

Change in weather-pattern effects

Alterations in seasonal and internal weather patterns (including droughts, storms and floods) may influence the growth rates of cyanobacteria. In many inland waters of the world, salinity is rising because of droughts, rising sea levels and increasing use of freshwater for agricultural irrigation. This represents another advantage for some cyanobacteria because of their high salt tolerance (for example, species such as *Nodularia* spp. and *M. aeruginosa*; Tonk *et al.* 2007; Pade and Hagemann 2014). Moreover, salinity increases vertical density stratification, which favours buoyant cyanobacteria. Drought and reduced discharge into inland waters could, thus, have effects on eutrophication and water quality. These episodes will result in greater salinisation, exacerbated by increased evaporation and greater use of water for irrigation (Jeppesen *et al.* 2010).

Finally, an intensifying water (hydrological) cycle, alternating with warm dry periods, can lead to the proliferation of CyanoHABs in water bodies. A short period of intensive rain may substantially overload rivers, lakes and reservoirs, with excess nutrients via runoff, and increase the likelihood of CyanoHABs events that severely impair water quality (Paerl *et al.* 2016). Rainfall washes nitrogen and phosphorus from human activities, such as agriculture and fossil fuel combustion, into rivers, lakes and reservoirs (Pade and Hagemann 2014). In addition, the warm, dry periods allow stratification in lakes and reservoirs and the growth of planktonic cyanobacteria (Reichwaldt and Ghadouani 2012).

Wind effect

Although temperature and precipitation variables are getting most of the attention in discussions about climate change, wind is another climate-change impact on water systems directly related to CyanoHABs. Climate warming has produced stronger winds along some coasts, a result of growing differences in temperature and pressure between land and sea (Sydeman *et al.* 2014). When nutrient concentrations in water increase, wind may become a new CyanoHABs-limiting factor (Yang *et al.* 2008). The most significant effect of wind is the transportation and dynamics of CyanoHABs blooms (Wang *et al.* 2016; Zhang *et al.* 2016). Wind causes a drift of cyanobacteria, which often accumulate in one part of a lake such as a bay. Evenly distributed cyanobacteria can therefore accumulate to a bloom in a part of a stagnant water body when wind drifts them to one location.

Table 1 brings together the key concepts about climate change and HABs. The stressors and climate-change effects on CyanoHABs specified in this table confirm that an effective adaptation approach must take into account climate change as one of the fundamental pressures on water resources (United Nations 2010). Moreover, proper consideration of the likely climate-change impacts on water quality will ensure comprehensive coverage of the link between stressors and effects in climate-change adaptation strategies.

Stage 2. Vulnerabilities in developing countries to climate-change adaptation

Adaptation researchers have generally assumed lower vulnerability and greater adaptive capacity in developed countries than in developing countries, but have, however, tended to focus their research on the former (Adger *et al.* 2003; Mertz *et al.* 2009). Yet, climatic events such as snow storms, flooding and bushfire in Europe, the United States and Australia in recent years have also led to critical questioning of the richer nations' ability to adapt to climate change and, in turn, a greater focus on innovative approaches (Moser and Ekstrom 2010). In developing countries, there is, hence, an opportunity to develop science-informed actions (strategies, policies and measures), both good and bad, on the basis of developed nations' experiences.

In addition, it is necessary to build up scientific infrastructure. This includes both education and training. Even routine scientific tasks in developed countries, such as sampling and monitoring of water bodies, may be beyond the technological and financial resources of developing countries. In addition, a 'disconnection' between the knowledge generated by the scientific community and the specific needs of developing economies can be discerned.

Transferring knowledge and instrumentation must be tied to national and local needs to create trust and services for society in the long term (Harris 2004). More effective dialogue is certainly required between scientists and communities of practitioners, both to improve the dissemination and communication of scientific information as well as to learn from the experiences, knowledge and the needs of users' communities (Macleod *et al.* 2007). Large gaps in integration between policies and regulation can lead to conflicting and competing measures and uncertain outcomes.

Policies on knowledge and technology transfer are necessarily complex and cross-linked with a range of issues in the broader sustainable development agenda, especially in developing countries. Policy outcomes need to target increasing access to technology and improving the abilities of users to identify, acquire, adapt and use knowledge. Particularly in this point but also in many others related to sustainable development, research and innovation are essential. Developing countries need

Table 1. Climate-change effects on CyanoHABs
Source: developed by the authors

Stressor	Effects that may increase CyanoHABs
Increased temperature	Increased water temperature
	Biota alteration (particularly fish and plants)
	decrease the water resistance to vertical migration of phytoplankton
Changed in rainfall patterns	Increased salinity
	Enhanced stratified conditions
	Increased nutrient load
Changed wind patterns	CyanoHABs transportation and dissemination
	CyanoHABs spatial–temporal dynamics

national policies that support improving domestic absorptive capacities and stimulate local innovation. However, it is important to bear in mind that in developing-country context, innovation should create a triple impact, including social, environmental and financial returns.

Another discussion possible to arise in developing economies is the way that the government measures practice effectiveness. There are conflicting views concerning the choice of metrics and objectives, because governments, institutions, communities and individuals value needs and outcomes differently. In addition, in some cases, the values cannot be captured in a comparable way. Thus, the metrics that are most useful for policy learnings are those that track not just process and implementation, but also the extent to which expected outcomes are achieved considering local and national stakeholder points of view.

Metrics help support institutional and social learning, which is commonly considered necessary to deal with complex and uncertain problems (Moser and Ekstrom 2010). For effective adaptive management, mechanisms must be put in place to allow monitoring and periodic evaluation. A key aspect of CyanoHABs mitigation and adaptation practices thus involves the establishment of monitoring programmes and systems integrating both science and knowledge held by the users themselves, to facilitate the safe use of water sources (Ford *et al.* 2011).

There is usually uncertainty about how economic actors in developing countries may react to environmental regulations because of the economic, financial and social restrictions that many are already facing. It can be expected that any major structural change would affect most of the economic activities in a country or region. Furthermore, there will always be a degree of conflict among short-term economic and political goals, long-term environmental goals, and the different water users' interests. In this situation, collaborative governance through local stakeholder engagement may foster new ideas and pathways to support greater endorsement of future measures (Giupponi and Gain 2017). For instance, in the USA, research suggests that the level of collaborative activity between the local government and stakeholders is positively associated with higher policy outputs and outcomes (Kalesnikaite 2019).

In the context of CyanoHABs control, understanding and anticipating the actors' behaviour is key to manage nutrient-laden runoff, and hence to maintain or restore healthy natural ecosystems (Maye and Duncan 2017). A transition towards more sustainable land and water management alternatives will probably result from a transdisciplinary reflection on agricultural, social, economic and cultural (diet) practices (Herrero and Thornton 2013). On the basis of the experiences of developed countries, any significant achievement in that direction would include profound, structural changes in the human agro-food system and land uses (Desmit *et al.* 2018). These prefund structural changes can be difficult to achieve in developing countries, mainly because the sheer scale at which modified production methods would have to be adopted, the significant governance and market-structure challenges and the considerable difficulties involved in measuring, reporting and verifying the expected outcomes.

The uncertainties and complexity of climate change may lead to maladaptation. This means that a 'solution' can be worse than the problem itself, resulting in increased vulnerability to CyanoHABs or significantly undermining the capacities or opportunities for present and future adaptation.

Developed countries are building dams to assist with adaptation to climate change and help restore ecosystems (Watts *et al.* 2011). In addition, the building of water infrastructure is accompanied by strong monitoring and regulation systems to avoid maladaptation. However, farm dams could also be subjected to CyanoHABs and affect water storage downstream (Silvarrey Barruffa *et al.* 2021). Thus, the lack of complementary actions (such as setting strong water monitoring systems or nutrient pollution controls) leads in a high risk that the water storage in dams becomes useless for the irrigation of certain crops and for livestock (Bouaïcha and Corbel 2016). Developing countries have to think more long term about site-specific adaptation measures driven by current and future institutional capacity as well as local perspectives.

Barnett and O'Neill (2010) defined actions as maladaptive if they (1) increase emissions of green-house gases (GHGs), (2) disproportionately burden the most vulnerable, (3) have high opportunity costs, (4) reduce incentives and capacity to adapt, and (5) set paths that limit future choices. However, these are not totally applicable in developing economies. The first consideration implies that any action that increases GHG emissions is maladaptive; however, a judgment on the relative benefits or disadvantages must be made locally. The second consideration includes the word 'disproportionately', which is not easy to interpret (i.e. subjective) considering the general diversity of stakeholder viewpoints. Additionally, these factors do not consider that sustainable water resource management has historically, and often, been in conflict with the imperatives of economic growth; so, not all countries, especially developed ones, assess the opportunity costs and benefits in the same way.

In developing countries, there is substantial underinvestment in resilience-building efforts (International Monetary Fund 2019). The important concept of resilience owes much to the work of Holling (1973). According to Holling, ecological resilience determines the continuity of relationships within an ecosystem and is a measure of the ability of the system to absorb changes of its state variables, driving variables and parameters, and still persist (i.e. survive and growth). Ecological resilience is thus the capacity of a system to absorb disturbance and reorganise while undergoing change, so as still to retain essentially the same function, identity and feedbacks.

Adaptation assessments are often categorised into 'top-down' and 'bottom-up' assessments. Top-down assessments to determine the potential impacts of climate change generally employ a modelling-driven scenario approach. Bottom-up assessments begin at the local scale, address socio-economic responses to climate and tend to be location specific (Dessai and Hulme 2004; Noble *et al.* 2015). The necessary data inputs to develop top-down assessments, even using a modelling approach that requires few inputs, can be difficult to obtain and process in developing economies (Silvarrey Barruffa *et al.*

2021). By contrast, bottom-up approaches do not generally rely on model-generated climate data, but involve collecting valuable information from the specific location of concern (Hinkel 2011). The great majority of bottom-up assessments are found in developing countries, probably because vulnerability to present-day climatic variability is commonly perceived to be more of a threat than is long-term climate change. However, it is important that developing countries also include top-down approaches, as generally deployed in developed countries, to be resilient to climatic changes and extreme weather events.

Following the experiences of developed countries, the use of natural base solution (NbS) is arising as an opportunity to enhance the adaptation capacity of developing economies. NbS uses the multiple services provided by natural ecosystems to improve resilience and adaptation capacity. It can help protect us from climate-change impacts while slowing further warming, supporting biodiversity and securing ecosystem services offering attractive economic benefits (Organisation for Economic Co-operation and Development 2020). In some cases, these solutions represent substantial advantages in terms of reliability and cost-effectiveness compared with engineered alternatives, and their resilience to climate change.

However, trade-offs can arise if climate mitigation policy encourages NbS with a low biodiversity value, such as afforestation with non-native monocultures (Seddon *et al.* 2020). This can result in maladaptation, especially in a changing climate scenario. Thus, it is necessary for natural and social scientists to engage with policy makers. They must ensure that adaptation practices can achieve their potential to tackle both the climate and biodiversity crisis, while also contributing to sustainable development.

Many developing countries emphasise the importance of international assistance, whereas developed countries focus more on domestic financing and the private sector. Although upfront investments may seem high in absolute terms, financial feasibility is realistic when considering existing global financial stocks and flows and the expected benefits. Nevertheless, financial and intellectual support from outside is an important basis to tackle future climate change-based problems. It is not to be expected that most of the developing countries will be able to implement the suggested methods on their own.

Stage 3. Targeting adaptation practices

Another discussion plausible to arise about whether developing countries should prioritise some practices over others. First, most practices are themselves means, or intermediate goals, contributing to reduce CyanoHABs. The structure of the practices itself may blur the fact that different practices have different functions, such as providing resources or enabling environments. Greater focus on the interlinkages and synergies among practices could enhance the effectiveness of implementation and reduce costs.

The study conducted by Hallegatte (2009) examined the following five methods for climate-change adaptation: (i) selecting ‘no-regret’ strategies that yield benefits even in the absence of climate change; (ii) favouring reversible and flexible options; (iii) buying ‘safety margins’ in new investments; (iv) promoting soft adaptation strategies, including with a long-term perspective; and (v) reducing decision-time horizons. Briefly, then, adaptation measures designed and implemented in developing countries must be flexible and focused on improving their infrastructure and socio-economic systems, even in the absence of climatic changes, to achieve transformative changes. On account of uncertainties, reducing the decision-making time horizons and creating safety margins are essential in adaptation practices.

On the basis of former stages, CyanoHABs adaptation measures in a changing climate should consider at least the following decision criteria: (a) encourage and coordinate research on impacts and adaptation to comprehend the local context and synergies, (b) facilitate and strengthen the capacity for coordinated action on adaptation among all the stakeholders and support knowledge-sharing networks, and (c) encourage monitoring and evaluation programs capable of reflecting the stakeholder points of view. In an adaptation setting, these are the variables, or characteristics, that are important to the catchment or water manager setting the framework. They should help evaluate the practices from which decision-makers are choosing, without losing the focus on the main purpose of intervention for improving the situation.

In addition, the practices selected should holistically integrate the following three key perspectives (or dimensions): governance, socio-economic and CyanoHABs. Environmental changes in climatic and abiotic factors, interacting species (biotic), and direct human influences (anthropogenic) are all affecting CyanoHABs and, thus, biodiversity and ecosystem services. Determining whether the magnitudes of the impacts of abiotic, biotic and anthropogenic drivers differ, and accounting for their direct effects and effects mediated through other drivers, would allow us to better design adaptation practices. As was mentioned before, climate-change governance poses difficult challenges for political and administrative systems; the interaction of governance with other perspectives must hence be considered. In addition, there will always be a degree of conflict between practices and water user and stakeholder interests. These three dimensions play an important role in adaptation practices.

Stage 4. Identification of potential adaptation practices

Successful implementation of adaptation practices to ensure the safety and health of populations and security of assets in response to climate impacts depends, in particular, on the availability of information, and access to relevant technology and funding (Yohe and Tol 2002; Adger 2006).

Identifying needs, stemming from climate risks and vulnerabilities, provides a foundation for selecting adaptation options. Several adaptation options have been identified over the years (Noble *et al.* 2015). They include a wide range of practices that can be organised into two general categories, namely, ‘green’ and ‘soft’. Nevertheless, the demarcation of these categories is fuzzy and, in most cases, successful practices require both green and soft approaches.

Green practices refer to NbS, technological and engineering solutions to improve the adaptation of the territory (land-use considerations), infrastructures and people.

Soft practices include policy, legal, social, management and financial measures that can influence human behaviour and transform styles of governance, thus contributing to increased awareness on climate change water matters, enhancing adaptation capacity. Soft practices involve empowering local communities as well as building institutional capacity and community assets.

The practices discussed below focus on the impact of climate change on CyanoHABs. It is a guide for catchment and water managers to consider the relevant aspects mentioned in the specialised literature. They can be adjusted in accordance with the characteristics of the catchment and the local context, such as budget availability, local regulations, and measures being already applied, among others. Moreover, the list is not rigid; rather, it should be enhanced by new knowledge and research. Updating and enhancing measures should be considered in particular periods, associated with monitoring of catchment and water health and results of actions for improvement, defined by the catchment and water managers in consultation with the other organisations involved in water management.

Combined approach of green and soft practices

Tackling nutrient pollution

A scientific consensus exists that degraded water quality from increased nutrient pollution promotes the development and persistence of CyanoHABs (Heisler *et al.* 2008). In consequence, actions focused on reducing nutrient discharge on water bodies help reduce CyanoHABs. Actions for improvement include reducing fertiliser applications, improving the sewage systems in the settlement(s) located in the catchment and building wastewater treatment plants, and these are essential to reduce nutrients loads (Hamilton *et al.* 2016).

In terms of fertiliser management, rainfall-runoff nutrient loading can be reduced by controlling the timing, amount and type of fertiliser used in crops, as well as by considering the distance of spreading from a waterbody and rainfall forecast (Sharpley 2016). Precision agriculture is especially useful for efficient and effective crop fertilisation. According to the International Society for Precision Agriculture (ISPA), precision agriculture is a management strategy that combines temporal, spatial and individual data from different sources to support management decisions. This strategy is focused on improving resource-use efficiency, productivity, quality, profitability and sustainability of agricultural production. To implement precision agriculture, it is hence necessary to combine existing agriculture production measures with innovative, usually high-tech, technologies (Chen *et al.* 2014). Relevant technologies undoubtedly present an opportunity when they are able to leverage existing capabilities, and thereby provide a more direct and reliable path to adaptation. However, they often require complementary and costly investments. In this situation, governments should promote and encourage their acquisition because relevant innovative technologies can help reduce overfertilisation and thus lower the prices of agricultural commodities produced and, in turn, increase the financial returns to the farmers.

Contrary to 'uniform' fertiliser application, for example, variable-rate application permits an effective treatment by varying of the quantities of fertiliser used inside the land zone or parcel in production. Fertilisers should be applied only where and when they are essential and within the needed quantities for each zone or parcel. Precision agriculture can undoubtedly bring obvious benefits in terms of controlling CyanoHABs, but to accurately perform these actions, special software, global positioning system (GPS), sensors and machinery are necessary.

In this example, both green and soft practices can be identified. The technical and engineering solutions, including required infrastructure, to apply fertilisers at variable rates can be categorised as green practices, whereas the actions by governments to encourage and facilitate these practices in catchment can be classified as soft practices.

Total maximum daily loads

To be effective in controlling nutrient discharge, it is critical to establish a total maximum daily load (TMDL) for nutrients, a threshold below which CyanoHABs may be controlled. The objective of TMDL is to determine the loading capacity of the waterbody of concern and to distribute the total load permissible among different nutrient sources, so that the appropriate control actions can be taken and water quality standards achieved or maintained. The lack of TMDL may lead to the implementation of ineffective measures (Romo *et al.* 2005; Alex Elliott and May 2008). The TMDL setting process is important for improving water quality because it serves as a link in the chain between water quality standards and implementation of control actions designed to attain those standards. To calculate the TMDL in a particular catchment, computational models and monitoring stations are needed; this can be considered as a green practice. In contrast, the formulation of the policy framework to control nutrient discharge on the basis of TMDL, management and financial measures to implement this approach can be classified as a soft practice.

As in the examples mentioned above, in most cases, successful adaptation practices require a combination of green and soft approaches to be successful. However, to be more precise, examples of green and soft practices separately are explained below.

Green practice examples

Local factors and actions

To design and implement measures successfully, catchment and water managers must have a working understanding of the local factors (abiotic, biotic and anthropogenic) that control water quality, and the sensitivity of those factors to changes in climate and resource use (Murdoch *et al.* 2000). As mentioned, local biota plays an important role in water quality; so, they must be considered to implement ecosystem approaches (green practices). For example, preserving and restoring riparian habitat can trap nutrients moving across the surface or subsurface (Murdoch *et al.* 2000; Borin *et al.* 2005; Hefting *et al.* 2005; Lovell and Sullivan 2006; Aguiar *et al.* 2015). These permanent vegetation areas are located within and between agricultural fields and the watercourses that they drain. These buffers are intended to intercept and slow runoff, thereby providing water quality benefits, reducing the nutrients loads (Fischer and Fischenich 2000). In addition, in many settings, they are intended to intercept shallow groundwater moving through the root zone below the buffer. Wetlands also have a positive effect on reduced nitrogen transport to aquatic environments (Paludan *et al.* 2002). Therefore, the implementation of ecosystem approaches such as buffer strips, recovery and constructed wetlands, is highly recommended as an adaptation practice.

Physical, chemical and antibiotic approaches to CyanoHAB control in surface water have also been proposed, implemented and evaluated. For example, the combined use of adequate aquatic plant harvests and hydraulic management increases the efficiency of the system and, therefore, seems to be a useful tool for restoring small, shallow lakes (Rodríguez-Gallego *et al.* 2004). The use of geo-engineering techniques for phosphorus management also offers an alternative for ecological recovery. This can be effective when used with other restoration measures, but it should not be considered a panacea (Mackay *et al.* 2014), and must be implemented together with external nutrient discharge controls (Paerl *et al.* 2016; Jeppesen *et al.* 2017). Nevertheless, these techniques need to be assessed locally for inadvertent adverse effects, in particular, on water quality (Paerl and Otten 2013). However, there are examples of measured application during many years without negative effects (Gächter and Wehrli 1998), although practical applications should be closely monitored.

Catchment simulation models

The construction of relevant models should be a critical component of any mitigation and target-setting strategy. Models can help (i) simulate and analyse current and likely future situations, (ii) consider the effects of, and integrate and prioritise, actions that are cost-effective, including relevant timescales for cropping in intensively farmed lands, management and forms of nutrients. Otherwise, there is a likelihood of either underestimating or overestimating the real effect of the measures to be applied in the catchment of concern (Drewry *et al.* 2006).

Monitoring programs

As with many environmental issues, monitoring programs and systems that gather relevant information to track trends in water quality, hydrology and associated changes in ecosystem functions play an important role to analyse the impact of mitigation measures. To determine climate influences on water quality, a monitoring system for tracking trends in discharge, temperature and chemistry must be designed, built and maintained (Murdoch *et al.* 2000; Vaughan *et al.* 2001).

Among others, on the basis of the effect of climate change on fish community, measuring the stock and health condition of fish for water quality assessment can be an effective practice. There is also one important research in developing economies related to fish community and eutrophication (Chalar *et al.* 2013). Also, macrophytes can be taken as a reliable bioindicator to study climate-change effect on water bodies (Hossain *et al.* 2017). Even citizen monitoring is a promising approach that may complement the classical approach to sustainable monitoring of cyanobacteria in developing countries (Mitroi *et al.* 2020).

Soft practice examples

Territory – land use

There is an association between cyanobacteria and the characteristics of the territory (characterised by land use). Land-use types reflecting anthropogenic pressures could act as critical drivers explaining phytoplankton structure. Most water bodies are sensitive to the land-use types within their catchments; thus, landscape structure and configuration should be taken into account towards effective conservation and management plans (Katsiapi *et al.* 2012).

For example, trees have emerged as one of the most popular measures to curve climate change (Wilcock *et al.* 2008). Many governments and advocates have advanced plans to plant vast numbers of trees to absorb carbon dioxide from the atmosphere in an attempt to slow climate change. Nevertheless, recent research has indicated that changes in land use, land management and some type of forestry activities (and trees' species) can increase the nutrient-discharge water sources in catchments (Sinha *et al.* 2019; Silvarrey Barruffa *et al.* 2021).

Closing gaps

Closing the gap between research and practice in developing countries is essential to successfully tackle CyanoHABs. There are currently several theoretically informed frameworks available to researchers that can guide their planning and implementation (Bero *et al.* 1998); however, not all the frameworks consider the vulnerabilities of developing economies. In this situation, and given the current needs to enhance the uptake of knowledge about the effects of routine practice, funding organisations should encourage researchers to adopt a theoretically informed approach that is capable of being understood and implemented by individuals with different backgrounds.

Table 2 summarise the key aspects mentioned before through a set of potential soft and green adaptation practices, which, according to the literature review, are capable of reducing the impact of CyanoHABs under unfolding climatic changes, particularly in developing economies.

Conclusions

Climate change is extensively transforming Planet Earth and its aquatic ecosystems. There is now a scientific consensus that the public health, recreational, tourism, fishery and ecosystem impacts from CyanoHABs have increased over the past several decades as a result of unfolding climatic changes. The extent to which climate change is intensifying these impacts has not yet been fully determined, but the research on this topic has increased over the past years. However, there is certainty that CyanoHABs will occur more in climatically altered water bodies and that their future impacts will differ from what we know today.

Tackling widespread algal blooms in water bodies is based on the implementation of effective and efficient nutrient reduction programs, setting metrics and reliable monitoring systems on catchment and water health. In developing countries, several barriers exist for successful mitigation and adaptation actions, which tend to be exacerbated by difficulties related to the key actors' coordination. Experience has shown that to avoid inadvertent adverse effects, in particular on water quality, any proposed measure must be assessed locally. Consequently, to effectively respond to climate change and CyanoHABs, local actors at different levels require guidance, especially on the set of feasible adaptation measures, to assist them in the required decision-making process.

Table 2. Potential adaptation practices to cyanobacteria harmful algae blooms in unfolding climate change
Source: developed by the authors

Number	Practices
Soft adaptation practices	
(1)	Targeting funding, through increased or redistribution of national, state or local, budgetary allocations for settlement wastewater treatment in the locations where this action is deemed essential.[A]
(2)	Assisting primary producers to properly assess the commercial viability of best 'practice' fertiliser use.
	This action requires mobilisation, and encouragement to working together by industry, relevant international organisations, governments, scientists and researchers, academia and educators, farmers, non-governmental organisations (NGOs), and local communities (broadly termed 'civil society'). See also (5) below.
(3)	Informing producers about the economic and environmental benefits of less-nutrients usage.
	The most commonly acknowledged barrier is a lack of knowledge about the connection between land-care practices and the local watershed. See also (5) below.
(4)	Generating awareness among farmers about the risk of overfertilising and capacitate them about the implementation of alternative practices. See also Point 5 below.
(5)	Accelerating the introduction of research and innovative technology for precision agriculture and precision fertilisation, and related activities, to generate regional and community environmental social and economic benefits.
	Introducing new approaches that profoundly change the basic routines, resource and authority flow is a complex process. This requires industry to work in collaboration with research and academic institutions, public organisations, NGOs, and the community ('civil society') to jointly develop, test and scale up innovative ideas and solutions to tackle common problems.[A] An innovation is considered the introduction of a new idea, technology, practice, or procedure which is perceived as 'new' by the particular social system. Innovations may be based on ideas or prototypes that are invented, borrowed, imitated or adapted. Therefore, what is already established in a place (say a developed country or a developed region) may, by borrowing, imitation or adaptation, become an innovation in another place (say a developing country or a developing region).
	In the specialised literature on innovation, actions involving collaboration among multiple actors to accelerate the transfer of research and innovation is known as the 'Helices approach' (Cavallini *et al.* 2016).
(6)	Targeting funding through increased or redistribution of national, state or local, budgetary allocations and create innovative funding mechanisms for climate-change research and dissemination of relevant information.[A]
(7)	Providing information, policy briefs and other communication materials for policymakers, managers, decision-makers that have an influence on how water is used, as well as the public.[A]
	The framework to create and disseminate of these materials should be analysed in each context. For example, if not in existence, the creation a Catchment Management Commission (or Authority as termed in the State of Victoria, Australia) with the participation of industries, governments, farmers, scientists, researchers and local communities.
(8)	Promoting and encouraging by local governments interaction among policymakers, farmers, scientists and researchers to ensure proper consideration in relevant actions of unfolding climatic changes and their impact on water quality (see also Point 5 and 7).
(9)	Encouragement (by local governments) of the use of sewage trucks service for empty septic tanks in settlement without sewage system or domestic wastewater treatment systems.
Green adaptation practices	
(1)	Implementing precision agriculture and precision fertilisation, through Global Positions Systems and sensors and complementary technologies (e.g. crop water metering), which are appropriate to the conditions of the developing country and region(s) of concern.
(2)	Implementing ecosystem approaches, such as the recovery and construction of buffer strips and natural wetland and construction of wetlands.
(3)	Determining the impacts of current land uses in the catchment and water system of concern, and analysing alternative land uses that are likely to improve the health of the catchment and water (Silvarrey Barruffa *et al.* 2021).
(4)	Defining high-risk areas in terms of nutrients discharges in catchments to be regularly monitored and controlled by the responsible organisations, such as, for example, agricultural production areas without buffer strips or high fertiliser use.
	This can be undertaken by using a combination of computational modelling and monitoring programs.
(5)	Establishing total maximum daily loads for nutrients below which CyanoHABs may be controlled.
(6)	Building the knowledge base on water issues through efficient monitoring and reporting systems at different decision-making levels, and facilitating easy access to this knowledge through regular 'state of the system' reports and wide diffusion via the Internet.
(7)	Studying the effects of CyanoHABs in the waterbody of concern and the possible controls available to take actions for improvement by local authorities supported by academia and research institutions.
(8)	Establishing appropriate catchment and water resources modelling by local authorities supported by academia and research institutions.

[A]General note: adaptation measures can be difficult to finance but some ways include funds under the United Nations Framework Convention on Climate Change (2007), non-compliance fund, disaster relief and risk reduction, public expenditures, including public–private partnerships, insurance, or foreign direct investment (Ackerman 2009).

Therefore, in this context, some of the adaptation practices explained in this paper focus on, and encourage the implementation of, top-down and bottom-up approaches in developing countries as well as the urgent need to strengthening their knowledge and adaptation capacity. On the basis of the most relevant information in the specialised literature and the authors' interpretation and synthesis, this paper has highlighted several practices for tackling climate change and CyanoHABs in developing contexts. It, thus, fills important gaps between specialised scientific literature and specific adaptation practices, and there are no technological or other operational obstacles to implement them.

Data availability statement

Data sharing is not applicable as no new data were generated or analysed during this study.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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References

Ackerman, F. (2009). Financing the climate mitigation and adaptation measures in developing countries. G-24 Discussion Paper Series, number 57, UNCTAD/GDS/MDP/G24/2009/4. (United Nations.) Available at https://unctad.org/system/files/official-document/gdsmdpg2420094_en.pdf

Adger, W. N. (2006). Vulnerability. *Global Environmental Change* **16**(3), 268–281. doi:10.1016/J.GLOENVCHA.2006.02.006

Adger, W. N., Huq, S., Brown, K., Conway, D., and Hulme, M. (2003). Adaptation to climate change in the developing world. *Progress in Development Studies* **3**(3), 179–195. doi:10.1191/1464993403PS060OA

Aguiar, T. R., Rasera, K., Parron, L. M., Brito, A. G., and Ferreira, M. T. (2015). Nutrient removal effectiveness by riparian buffer zones in rural temperate watersheds: the impact of no-till crops practices. *Agricultural Water Management* **149**, 74–80. doi:10.1016/J.AGWAT.2014.10.031

Alex Elliott, J., and May, L. (2008). The sensitivity of phytoplankton in Loch Leven (UK) to changes in nutrient load and water temperature. *Freshwater Biology* **53**(1), 32–41. doi:10.1111/J.1365-2427.2007.01865.X

Allen, J., Gross, E. M., Courcoul, C., Bouletreau, S., Compin, A., Elger, A., Ferriol, J., Hilt, S., Jassey, V. E. J., Laviale, M., Polst, B. H., Schmitt-Jansen, M., Stibor, H., Vijayaraj, V., and Leflaive, J. (2021). Disentangling the direct and indirect effects of agricultural runoff on freshwater ecosystems subject to global warming: a microcosm study. *Water Research* **190**, 116713. doi:10.1016/J.WATRES.2020.116713

Barnett, J., and O'Neill, S. (2010). Maladaptation. *Global Environmental Change* **20**(2), 211–213. doi:10.1016/J.GLOENVCHA.2009.11.004

Berg, M., and Sutula, M. (2015). Factors affecting growth of Cyanobacteria with special emphasis on the Sacramento-San Joaquin Delta. Southern California Coastal Water Research Project Technical Report 86959, http://scholar.googleusercontent.com/scholar?q=cache:hdcnxcun-o4J:scholar.google.com/+Factors+Affecting+Growth+of+Cyanobacteria&hl=es&as_sdt=0,5&as_vis=1 [Verified 9 June 2020].

Bero, L. A., Grilli, R., Grimshaw, J. M., Harvey, E., Oxman, A. D., and Thomson, M. A. (1998). Closing the gap between research and practice: an overview of systematic reviews of interventions to promote the implementation of research findings. The Cochrane Effective Practice and Organization of Care Review Group. *BMJ* **317**(7156), 465–468. doi:10.1136/BMJ.317.7156.465

Borin, M., Vianello, M., Morari, F., and Zanin, G. (2005). Effectiveness of buffer strips in removing pollutants in runoff from a cultivated field in north-east Italy. *Agriculture, Ecosystems & Environment* **105**(1–2), 101–114. doi:10.1016/J.AGEE.2004.05.011

Bouaïcha, N., and Corbel, S. (2016). Cyanobacterial toxins emerging contaminants in soils: a review of sources, fate and impacts on ecosystems, plants and animal and human health. In 'Soil Contamination – Current Consequences and Further Solutions'. pp. 105–126. (InTech.) doi:10.5772/64940

Burford, M. A., Carey, C. C., Hamilton, D. P., Huisman, J., Paerl, H. W., Wood, S. A., and Wulff, A. (2020). Perspective: advancing the research agenda for improving understanding of cyanobacteria in a future of global change. *Harmful Algae* **91**, 101601. doi:10.1016/J.HAL.2019.04.004

Butterwick, C., Heaney, S. I., and Talling, J. F. (2005). Diversity in the influence of temperature on the growth rates of freshwater algae, and its ecological relevance. *Freshwater Biology* **50**(2), 291–300. doi:10.1111/J.1365-2427.2004.01317.X

Cavallini, S., Soldi, R., Frield, J., and Volpe, M. (2016). Using the quadruple helix approach to accelerate the transfer of research and innovation results to regional growth. (Committee of the Regions, European Union.) Available at https://op.europa.eu/en/publication-detail/-/publication/6e54c161-36a9-11e6-a825-01aa75ed71a1/language-en

Chadwick, C., Gironás, J., Barría, P., Vicuña, S., and Meza, F. (2020). Assessing reservoir performance under climate change. When is it going to be too late if current water management is not changed? *Water* **13**(1), 64. doi:10.3390/W13010064

Chalar, G., Delbene, L., González-Bergonzoni, I., and Arocena, R. (2013). Fish assemblage changes along a trophic gradient induced by agricultural activities (Santa Lucía, Uruguay). *Ecological Indicators* **24**, 582–588. doi:10.1016/J.ECOLIND.2012.08.010

Chen, C., Pan, J., and Lam, S. K. (2014). A review of precision fertilization research. *Environmental Earth Sciences* **71**(9), 4073–4080. doi:10.1007/S12665-013-2792-2

Chen, L., Yang, Z., and Liu, H. (2016). Assessing the eutrophication risk of the Danjiangkou Reservoir based on the EFDC model. *Ecological Engineering* **96**, 117–127. doi:10.1016/J.ECOLENG.2016.02.021

Declerck, S., Vandekerkhove, J., Johansson, L., Muylaert, K., Conde-Porcuna, J. M., Van Der Gucht, K., Pérez-Martínez, C., Lauridsen, T., Schwenk, K., Zwart, G., Rommens, W., López-Ramos, J., Jeppesen, E., Vyverman, W., Brendonck, L., and De Meester, L. (2005). Multi-group biodiversity in shallow lakes along gradients of phosphorus and water plant cover. *Ecology* **86**(7), 1905–1915. doi:10.1890/04-0373

Delpla, I., Jung, A. V., Baures, E., Clement, M., and Thomas, O. (2009). Impacts of climate change on surface water quality in relation to drinking water production. *Environment International* **35**(8), 1225–1233. doi:10.1016/J.ENVINT.2009.07.001

Desmit, X., Thieu, V., Billen, G., Campuzano, F., Dulière, V., Garnier, J., Lassaletta, L., Ménesguen, A., Neves, R., Pinto, L., Silvestre, M., Sobrinho, J. L., and Lacroix, G. (2018). Reducing marine eutrophication may require a paradigmatic change. *The Science of the Total Environment* **635**, 1444–1466. doi:10.1016/J.SCITOTENV.2018.04.181

Dessai, S., and Hulme, M. (2004). Does climate adaptation policy need probabilities? *Climate Policy* **4**(2), 107–128. doi:10.1080/14693062.2004.9685515

Dokulil, M. T., and Teubner, K. (2010). Eutrophication and climate change: present situation and future scenarios. In 'Eutrophication: Causes, Consequences and Control'. (Eds A. A. Ansari and S. S. Gill.) pp. 1–16. (Springer.) doi:10.1007/978-90-481-9625-8_1

Drewry, J. J., Newham, L. T. H., Greene, R. S. B., Jakeman, A. J., and Croke, B. F. W. (2006). A review of nitrogen and phosphorus export to waterways: context for catchment modelling. *Marine and Freshwater Research* **57**(8), 757–774. doi:10.1071/MF05166

du Pontavice, H., Gascuel, D., Reygondeau, G., Maureaud, A., and Cheung, W. W. L. (2020). Climate change undermines the global functioning of marine food webs. *Global Change Biology* **26**(3), 1306–1318. doi:10.1111/GCB.14944

Enríquez, S., Duarte, C. M., Sand-Jensen, K., and Nielsen, S. L. (1996). Broad-scale comparison of photosynthetic rates across phototrophic organisms. *Oecologia* **108**(2), 197–206. doi:10.1007/BF00334642

Fischer, R. A., and Fischenich, J. C. (2000). 'Design Recommendations for Riparian Corridors and Vegetated Buffer Strips.' (Engineer Research and Development Center.)

Ford, J. D., Berrang-Ford, L., and Paterson, J. (2011). A systematic review of observed climate change adaptation in developed nations. *Climatic Change* **106**(2), 327–336. doi:10.1007/S10584-011-0045-5

Fu, F. X., Warner, M. E., Zhang, Y., Feng, Y., and Hutchins, D. A. (2007). Effects of increased temperature and CO_2 on photosynthesis, growth, and elemental ratios in marine *Synechococcus* and *Prochlorococcus* (cyanobacteria). *Journal of Phycology* **43**(3), 485–496. doi:10.1111/J.1529-8817.2007.00355.X

Gächter, R., and Wehrli, B. (1998). Ten years of artificial mixing and oxygenation: no effect on the internal phosphorus loading of two eutrophic lakes. *Environmental Science & Technology* **32**(23), 3659–3665. doi:10.1021/ES980418L

George, D. G., Hewitt, D. P., Lund, J. W. G., and Smyly, W. J. P. (1990). The relative effects of enrichment and climate change on the long-term dynamics of *Daphnia* in Esthwaite Water, Cumbria. *Freshwater Biology* **23**(1), 55–70. doi:10.1111/J.1365-2427.1990.TB00253.X

Ger, K. A., Hansson, L. A., and Lürling, M. (2014). Understanding cyanobacteria–zooplankton interactions in a more eutrophic world. *Freshwater Biology* **59**(9), 1783–1798. doi:10.1111/FWB.12393

Giupponi, C., and Gain, A. K. (2017). Integrated water resources management (IWRM) for climate change adaptation. *Regional Environmental Change* **17**(7), 1865–1867. doi:10.1007/S10113-017-1173-X

Glibert, P. M. (2020). Harmful algae at the complex nexus of eutrophication and climate change. *Harmful Algae* **91**(June), 101583. doi:10.1016/J.HAL.2019.03.001

Haakonsson, S., Rodríguez Gallego, L., Somma, A., and Bonilla, S. (2017). Temperature and precipitation shape the distribution of harmful cyanobacteria in subtropical lotic and lentic ecosystems. *The Science of the Total Environment* **609**, 1132–1139. doi:10.1016/J.SCITOTENV.2017.07.067

Hallegatte, S. (2009). Strategies to adapt to an uncertain climate change. *Global Environmental Change* **19**(2), 240–247. doi:10.1016/J.GLOENVCHA.2008.12.003

Hamilton, D. P., Salmaso, N., and Paerl, H. (2016). Mitigating harmful cyanobacterial blooms: strategies for control of nitrogen and phosphorus loads. *Aquatic Ecology* **50**(3), 351–366. doi:10.1007/S10452-016-9594-Z

Harris, E. (2004). Building scientific capacity in developing countries. *EMBO Reports* **5**(1), 7–11. doi:10.1038/SJ.EMBOR.7400058

Havens, K. E., and Paerl, H. W. (2015). Climate change at a crossroad for control of harmful algal blooms. *Environmental Science & Technology* **49**(21), 12605–12606. doi:10.1021/ACS.EST.5B03990

Hefting, M. M., Clement, J.-C., Bienkowski, P., Dowrick, D., Guenat, C., Butturini, A., Topa, S., Pinay, G., and Verhoeven, J. T. A. (2005). The role of vegetation and litter in the nitrogen dynamics of riparian buffer zones in Europe. *Ecological Engineering* **24**(5), 465–482. doi:10.1016/J.ECOLENG.2005.01.003

Heisler, J., Glibert, P. M., Burkholder, J. M., Anderson, D. M., Cochlan, W., Dennison, W. C., Dortch, Q., Gobler, C. J., Heil, C. A., Humphries, E., Lewitus, A., Magnien, R., Marshall, H. G., Sellner, K., Stockwell, D. A., Stoecker, D. K., and Suddleson, M. (2008). Eutrophication and harmful algal blooms: a scientific consensus. *Harmful Algae* **8**(1), 3–13. doi:10.1016/J.HAL.2008.08.006

Herrero, M., and Thornton, P. K. (2013). Livestock and global change: emerging issues for sustainable food systems. *Proceedings of the National Academy of Sciences of the United States of America* **110**(52), 20878–20881. doi:10.1073/PNAS.1321844111

Hiltunen, M., Vehniäinen, E. R., and Kukkonen, J. V. K. (2021). Interacting effects of simulated eutrophication, temperature increase, and microplastic exposure on *Daphnia*. *Environmental Research* **192**, 110304. doi:10.1016/J.ENVRES.2020.110304

Hinkel, J. (2011). Indicators of vulnerability and adaptive capacity: towards a clarification of the science-policy interface. *Global Environmental Change* **21**(1), 198–208. doi:10.1016/J.GLOENVCHA.2010.08.002

Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics* **4**(1), 1–23. doi:10.1146/ANNUREV.ES.04.110173.000245

Hossain, K., Yadav, S., Quaik, S., Pant, G., Maruthi, A. Y., and Ismail, N. (2017). Vulnerabilities of macrophytes distribution due to climate change. *Theoretical and Applied Climatology* **129**(3–4), 1123–1132. doi:10.1007/S00704-016-1837-3

Huisman, J., Codd, G. A., Paerl, H. W., Ibelings, B. W., Verspagen, J. M. H., and Visser, P. M. (2018). Cyanobacterial blooms. *Nature Reviews. Microbiology* **16**(8), 471–483. doi:10.1038/S41579-018-0040-1

International Monetary Fund (2019). Building resilience in developing countries vulnerable to large natural disasters. *Policy Papers* **19**(020), 1. doi:10.5089/9781498321020.007

Jeppesen, E., Moss, B., Bennion, H., Carvalho, L., DeMeester, L., Feuchtmayr, H., Friberg, N., Gessner, M. O., Hefting, M., Lauridsen, T. L., Liboriussen, L., Malmquist, H. J., May, L., Meerhoff, M., Olafsson, J. S., Soons, M. B., and Verhoeven, J. T. A. (2010). Interaction of climate change and eutrophication. In 'Climate Change Impacts on Freshwater Ecosystems'. (Eds M. Kernan, R. W. Battarbee, and B. Moss.) pp. 119–151. (Wiley-Blackwell: Oxford, UK.) doi:10.1002/9781444327397.CH6

Jeppesen, E., Søndergaard, M., and Liu, Z. (2017). Lake restoration. In 'Routledge Handbook of Ecological and Environmental Restoration'. (Eds S. K. Allison and S. D. Murphy.) pp. 226–242. (Springer: Dordrecht, Netherlands.) doi:10.4324/9781315685977

Ji, X., Verspagen, J. M. H., Stomp, M., and Huisman, J. (2017). Competition between cyanobacteria and green algae at low versus elevated CO_2: who will win, and why? *Journal of Experimental Botany* **68**(14), 3815–3828. doi:10.1093/JXB/ERX027

Jöhnk, K. D., Huisman, J., Sharples, J., Sommeijer, B., Visser, P. M., and Stroom, J. M. (2008). Summer heatwaves promote blooms of harmful cyanobacteria. *Global Change Biology* **14**, 495–512. doi:10.1111/J.1365-2486.2007.01510.X

Kalesnikaite, V. (2019). Keeping cities afloat: climate change adaptation and collaborative governance at the local level. *Public Performance & Management Review* **42**(4), 864–888. doi:10.1080/15309576.2018.1526091

Katsiapi, M., Mazaris, A. D., Charalampous, E., and Moustaka-Gouni, M. (2012). Watershed land use types as drivers of freshwater phytoplankton structure. *Hydrobiologia* **698**(1), 121–131. doi:10.1007/S10750-012-1095-Z

Kundzewicz, Z. W., Krysanova, V., Benestad, R. E., Hov, Ø., Piniewski, M., and Otto, I. M. (2018). Uncertainty in climate change impacts on water resources. *Environmental Science & Policy* **79**, 1–8. doi:10.1016/J.ENVSCI.2017.10.008

Lacoul, P., and Freedman, B. (2006). Environmental influences on aquatic plants in freshwater ecosystems. *Environmental Reviews* **14**(2), 89–136. doi:10.1139/A06-001

Lahsen, M., Sanchez-Rodriguez, R., Lankao, P. R., Dube, P., Leemans, R., Gaffney, O., Mirza, M., Pinho, P., Osman-Elasha, B., and Smith, M. S. (2010). Impacts, adaptation and vulnerability to global environmental change: challenges and pathways for an action-oriented research agenda for middle-income and low-income countries. *Current Opinion in Environmental Sustainability* **2**(5–6), 364–374. doi:10.1016/J.COSUST.2010.10.009

Laininen, E. (2018). Transforming our worldview towards a sustainable future. In 'Sustainability, Human Well-being, and the Future of Education'. (Ed. J. Cook.) pp. 161–200. (Palgrave Macmillan.) doi:10.1007/978-3-319-78580-6_5

Loudière, D., and Gourbesville, P. (2020). World water development report – water and climate change. *Houille Blanche* **106**(3), 76–81. doi:10.1051/LHB/2020024

Lovell, S. T., and Sullivan, W. C. (2006). Environmental benefits of conservation buffers in the United States: evidence, promise, and open questions. *Agriculture, Ecosystems & Environment* **112**(4), 249–260. doi:10.1016/J.AGEE.2005.08.002

Mackay, E. B., Maberly, S. C., Pan, G., Reitzel, K., Bruere, A., Corker, N., Douglas, G., Egemose, S., Hamilton, D., Hatton-Ellis, T., Huser, B., Li, W., Meis, S., Moss, B., Lürling, M., Phillips, G., Yasseri, S., and Spears, B. M. (2014). Geoengineering in lakes: welcome attraction or fatal distraction? *Inland Waters* **4**(4), 349–356. doi:10.5268/IW-4.4.769

Macleod, C. J. A., Scholefield, D., and Haygarth, P. M. (2007). Integration for sustainable catchment management. *The Science of the Total Environment* **373**(2–3), 591–602. doi:10.1016/J.SCITOTENV.2006.12.029

Maye, D., and Duncan, J. (2017). Understanding sustainable food system transitions: practice, assessment and governance. *Sociologia Ruralis* **57**(3), 267–273. doi:10.1111/SORU.12177

Mertz, O., Halsnæs, K., Olesen, J. E., and Rasmussen, K. (2009). Adaptation to climate change in developing countries. *Environmental Management* **43**(5), 743–752. doi:10.1007/S00267-008-9259-3

Mitroi, V., Ahi, K. C., Bulot, P. Y., Tra, F., Deroubaix, J. F., Ahoutou, M. K., Quiblier, C., Koné, M., Kalpy, J. C., and Humbert, J. F. (2020). Can participatory approaches strengthen the monitoring of cyanobacterial blooms in developing countries? Results from a pilot study conducted in the Lagoon Aghien (Ivory Coast). *PLoS One* **15**, e0238832. doi:10.1371/JOURNAL.PONE.0238832

Monchamp, M. E., Spaak, P., Domaizon, I., Dubois, N., Bouffard, D., and Pomati, F. (2018). Homogenization of lake cyanobacterial communities over a century of climate change and eutrophication. *Nature Ecology & Evolution* **2**(2), 317–324. doi:10.1038/S41559-017-0407-0

Moser, S., and Ekstrom, J. (2010). A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences of the United States of America* **107**(51), 22026–22031. doi:10.1073/PNAS.1007887107

Moss, B., Kosten, S., Meerhoff, M., Battarbee, R. W., Jeppesen, E., Mazzeo, N., Havens, K., Lacerot, G., Liu, Z., De Meester, L., Paerl, H., and Scheffer, M. (2011). Allied attack: climate change and eutrophication. *Inland Waters* **1**(2), 101–105. doi:10.5268/IW-1.2.359

Murdoch, P. S., Baron, J. S., and Miller, T. L. (2000). Potential effects of climate change on surface-water quality in North America. *Journal of the American Water Resources Association* **36**(2), 347–366. doi:10.1111/J.1752-1688.2000.TB04273.X

Natalia, P., Silvia, F., Silvina, S., and Miguel, P. (2020). Climate change in northern Patagonia: critical decrease in water resources. *Theoretical and Applied Climatology* **140**(3–4), 807–822. doi:10.1007/S00704-020-03104-8

Nath, P. K., and Behera, B. (2011). A critical review of impact of and adaptation to climate change in developed and developing economies. *Environment, Development and Sustainability* **13**(1), 141–162. doi:10.1007/S10668-010-9253-9

Noble, I. R., Huq, S., Anokhin, Y. A., Carmin, J. A., Goudou, D., Lansigan, F. P., Osman-Elasha, B., Villamizar, A., Patt, A., Takeuchi, K., and Chu, E. (2015). Chapter 14 – Adaptation needs and options. In 'Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change'. (Eds C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, and P. R. Mastrandrea, and L. L. White.) pp. 833–868. (Cambridge University Press: Cambridge, UK.) doi:10.1017/CBO9781107415379.019

O'Neil, J. M., Davis, T. W., Burford, M. A., and Gobler, C. J. (2012). The rise of harmful cyanobacteria blooms: the potential roles of eutrophication and climate change. *Harmful Algae* **14**, 313–334. doi:10.1016/J.HAL.2011.10.027

Organisation for Economic Co-operation and Development (2020). Nature-based solutions for adapting to water-related climate risks. OECD Environment Policy Papers 21, OECD, Paris, France.

Pade, N., and Hagemann, M. (2014). Salt acclimation of cyanobacteria and their application in biotechnology. *Life* **5**(1), 25–49. doi:10.3390/LIFE5010025

Paerl, H. (2014). Mitigating harmful cyanobacterial blooms in a human- and climatically impacted world. *Life* **4**, 988–1012. doi:10.3390/LIFE4040988

Paerl, H. W., and Huisman, J. (2009). Climate change: a catalyst for global expansion of harmful cyanobacterial blooms. *Environmental Microbiology Reports* **1**(1), 27–37. doi:10.1111/J.1758-2229.2008.00004.X

Paerl, H., and Otten, T. G. (2013). Harmful cyanobacterial blooms: causes, consequences, and controls. *Microbial Ecology* **65**(4), 995–1010. doi:10.1007/S00248-012-0159-Y

Paerl, H. W., and Ustach, J. F. (1982). Blue-green algal scums: an explanation for their occurrence during freshwater blooms. *Limnology and Oceanography* **27**(2), 212–217. doi:10.4319/LO.1982.27.2.0212

Paerl, H. W., Tucker, J., and Bland, P. T. (1983). Carotenoid enhancement and its role in maintaining blue-green algal (*Microcystis aeruginosa*) surface blooms. *Limnology and Oceanography* **28**(5), 847–857. doi:10.4319/LO.1983.28.5.0847

Paerl, H., Gardner, W., Havens, K., Joyner, A., McCarthy, M., Newell, S., Qin, B., and Scott, J. (2016). Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients. *Harmful Algae* **54**, 213–222. doi:10.1016/J.HAL.2015.09.009

Paerl, H. W., Havens, K. E., Hall, N. S., Otten, T. G., Zhu, M., Xu, H., Zhu, G., and Qin, B. (2020). Mitigating a global expansion of toxic cyanobacterial blooms: confounding effects and challenges posed by climate change. *Marine and Freshwater Research* **71**(5), 579–592. doi:10.1071/MF18392

Paludan, C., Alexeyev, F. E., Drews, H., Fleischer, S., Fuglsang, A., Kindt, T., Kowalski, P., Moos, M., Radlowski, A., Stromfors, G., Westberg, V., and Wolter, K. (2002). Wetland management to reduce Baltic Sea eutrophication. *Water Science and Technology* **45**, 87–94. doi:10.2166/WST.2002.0211

Reichwaldt, E. S., and Ghadouani, A. (2012). Effects of rainfall patterns on toxic cyanobacterial blooms in a changing climate: between simplistic scenarios and complex dynamics. *Water Research* **46**(5), 1372–1393. doi:10.1016/J.WATRES.2011.11.052

Reynolds, C. S., Oliver, R. L., and Walsby, A. E. (1987). Cyanobacterial dominance: the role of buoyancy regulation in dynamic lake environments. *New Zealand Journal of Marine and Freshwater Research* **21**(3), 379–390. doi:10.1080/00288330.1987.9516234

Rivadeneira Vera, J. F., Zambrano Mera, Y. E., and Pérez-Martín, M. Á. (2020). Adapting water resources systems to climate change in tropical areas: Ecuadorian coast. *The Science of the Total Environment* **703**, 135554. doi:10.1016/J.SCITOTENV.2019.135554

Rodríguez-Gallego, L. R., Mazzeo, N., Gorga, J., Meerhoff, M., Clemente, J., Kruk, C., Scasso, F., Lacerot, G., García, J., and Quintans, F. (2004). The effects of an artificial wetland dominated by free-floating plants on the restoration of a subtropical, hypertrophic lake. *Lakes and Reservoirs: Research and Management* **9**(3–4), 203–215. doi:10.1111/J.1440-1770.2004.00245.X

Romo, S., Villena, M. J., Sahuquillo, M., Soria, J. M., Giménez, M., Alfonso, T., Vicente, E., and Miracle, M. R. (2005). Response of a shallow Mediterranean lake to nutrient diversion: does it follow similar patterns as in northern shallow lakes? *Freshwater Biology* **50**(10), 1706–1717. doi:10.1111/J.1365-2427.2005.01432.X

Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., and Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical*

Transactions of the Royal Society of London – B. Biological Sciences **375**, 20190120. doi:10.1098/RSTB.2019.0120

Sharpley, A. (2016). Managing agricultural phosphorus to minimize water quality impacts. *Scientia Agrícola* **73**(1), 1–8. doi:10.1590/0103-9016-2015-0107

Silvarrey Barruffa, A., Faggian, R., Sposito, V., and Duarte Guigou, M. (2021). Using models to inform water policy in a changing climate: comparing the Australian and Uruguayan experiences. *Marine and Freshwater Research* **72**(2), 275–287. doi:10.1071/MF19266

Sinha, E., Michalak, A. M., Calvin, K. V., and Lawrence, P. J. (2019). Societal decisions about climate mitigation will have dramatic impacts on eutrophication in the 21st century. *Nature Communications* **10**(1), 939. doi:10.1038/S41467-019-08884-W

Sydeman, W. J., García-Reyes, M., Schoeman, D. S., Rykaczewski, R. R., Thompson, S. A., Black, B. A., and Bograd, S. J. (2014). Climate change and wind intensification in coastal upwelling ecosystems. *Science* **345**(6192), 77–80. doi:10.1126/SCIENCE.1251635

Tesfahunegn, G. B., and Gebru, T. A. (2020). Smallholder farmers' level of understanding on the impacts of climate change on water resources in northern Ethiopia catchment. *GeoJournal*. doi:10.1007/S10708-020-10265-6

Tonk, L., Bosch, K., Visser, P. M., and Huisman, J. (2007). Salt tolerance of the harmful cyanobacterium *Microcystis aeruginosa*. *Aquatic Microbial Ecology* **46**, 117–123. doi:10.3354/AME046117

Ullah, H., Nagelkerken, I., Goldenberg, S. U., and Fordham, D. A. (2018). Climate change could drive marine food web collapse through altered trophic flows and cyanobacterial proliferation. *PLoS Biology* **16**(1), e2003446. doi:10.1371/JOURNAL.PBIO.2003446

United Nations (2010). 'Guidance on Water and Adaptation to Climate Change.' (Economic Commission for Europe Convention on the Protection and Use of Transboundary Watercourses and International Lakes, United Nations: Geneva, Switzerland.) Available at https://www.un-ilibrary.org/content/books/9789210543422

United Nations Educational, Scientific and Cultural Organization (2020). The United Nations world water development report 2020: water and climate change. UNESCO, Paris, France. Available at https://unesdoc.unesco.org/ark:/48223/pf0000372985.locale=en [Verified 3 February 2021].

United Nations Framework Convention on Climate Change (2007). Climate Change: Impacts, Vulnerabilities and Adaptation in Developing Countries. UNFCCC 68. (United Nations Framework Convention on Climate Change (UNFCCC) Climate Change Secretariat: Bonn, Germany.) Available at https://unfccc.int/resource/docs/publications/impacts.pdf

Van de Waal, D. B., Verspagen, J. M. H., Finke, J. F., Vournazou, V., Immers, A. K., Kardinaal, W. E. A., Tonk, L., Becker, S., Van Donk, E., Visser, P. M., and Huisman, J. (2011). Reversal in competitive dominance of a toxic versus non-toxic cyanobacterium in response to rising CO_2. *The ISME Journal* **5**(9), 1438–1450. doi:10.1038/ISMEJ.2011.28

Vaughan, H., Brydges, T., Fenech, A., and Lumb, A. (2001). Monitoring long-term ecological changes through the ecological monitoring and assessment network: science-based and policy relevant. *Environmental Monitoring and Assessment* **67**(1–2), 3–28. doi:10.1023/A:1006423432114

Visser, P. M., Verspagen, J. M. H., Sandrini, G., Stal, L. J., Matthijs, H. C. P., Davis, T. W., Paerl, H., and Huisman, J. (2016). How rising CO_2 and global warming may stimulate harmful cyanobacterial blooms. *Harmful Algae* **54**, 145–159. doi:10.1016/J.HAL.2015.12.006

Wang, H., Zhang, Z., Liang, D., Du, H., Pang, Y., Hu, K., and Wang, J. (2016). Separation of wind's influence on harmful cyanobacterial blooms. *Water Research* **98**, 280–292. doi:10.1016/J.WATRES.2016.04.037

Watts, R. J., Richter, B. D., Opperman, J. J., and Bowmer, K. H. (2011). Dam reoperation in an era of climate change. *Marine and Freshwater Research* **62**(3), 321. doi:10.1071/MF10047

Wilcock, R., Elliott, S., Hudson, N., Parkyn, S., and Quinn, J. (2008). Climate change mitigation for agriculture: water quality benefits and costs. *Water Science and Technology* **58**(11), 2093–2099. doi:10.2166/WST.2008.906

Xia, R., Zhang, Y., Critto, A., Wu, J., Fan, J., Zheng, Z., and Zhang, Y. (2016). The potential impacts of climate change factors on freshwater eutrophication: Implications for research and countermeasures of water management in China. *Sustainability* **8**(3), 229. doi:10.3390/SU8030229

Yang, X. E., Wu, X., Hao, H. L., and He, Z. L. (2008). Mechanisms and assessment of water eutrophication. *Journal of Zhejiang University, Science – B* **9**(3), 197–209. doi:10.1631/JZUS.B0710626

Yohe, G., and Tol, R. S. J. (2002). Indicators for social and economic coping capacity – moving toward a working definition of adaptive capacity. *Global Environmental Change* **12**(1), 25–40. doi:10.1016/S0959-3780(01)00026-7

Zhang, Y., Ma, R., Duan, H., Loiselle, S., and Xu, J. (2016). Satellite analysis to identify changes and drivers of CyanoHABs dynamics in Lake Taihu. *Water Science and Technology: Water Supply* **16**(5), 1451–1466. doi:10.2166/WS.2016.074

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