Research Brief

Allied attack: climate change and eutrophication

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Abstract

Global warming and eutrophication in fresh and coastal waters may mutually reinforce the symptoms they express and thus the problems they cause.

Key words: costs, fish, food web, hydrology, latitude, nutrients, temperature

Introduction

"When sorrows come, they come not single spies, but in battalions," said the usurping king in the Denmark of Shakespeare's "Hamlet," and so might we, when, in ravaging Earth's resources, we multiply the problems. For decades we have faced the worldwide problem of eutrophication, first by treating symptoms with algicides, but increasingly by controlling nutrient loading. Now, especially from work on shallow lakes, we are realising that climate change is intensifying the symptoms of eutrophication in freshwaters (Jeppesen et al. 2010b; Fig. 1) and perhaps that eutrophication can concomitantly promote climate change (Fig. 2). In future we will need to intensify nutrient control just to hold the line, let alone make improvements to water quality (Trolle et al. 2011). We can control nutrients in waste waters, but those that run from the land are seemingly intractable. Climate change, by intensifying storms, affecting rainfall patterns, warming soils, and melting glaciers, will increase this diffuse nutrient loading (Jeppesen et al. 2011).

Eutrophication is costly (Dodds et al. 2009). The solution is to reduce nutrient inputs, usually phosphorus but often also nitrogen (Elser et al. 2009), but restructuring the ecosystem, through removal or treatment of sediment or manipulation of the fish community, sometimes speeds recovery. Piscivorous fish generally become scarcer with eutrophication, and the ultimate effect, through an increase in foraging fish and a decline in zooplankton grazers, is an increase in algae. The direct effects of nutrients are thus also tangled with the structure of food webs, and in turn the nature of food webs is influenced by climate.

Food webs and climate

Fish communities in warm waters have lower numbers of strictly piscivorous fish but harbour increasing numbers of omnivores (Meerhof et al. 2007a, Texeira de Mello et al. 2009, Moss 2010). Omnivores include small, rapidly reproducing fish (Jeppesen et al. 2010a), which, despite a longer growing season for zooplankton in warm waters, can remove virtually all effective grazers (Gyllstrøm et al. 2005). Between 60º and 20º N, there is a decline in mean size of Cladocera from 1.3 to 0.6 mm (Gillooly and Dodson 2000), with large *Daphnia* rare in low-latitude

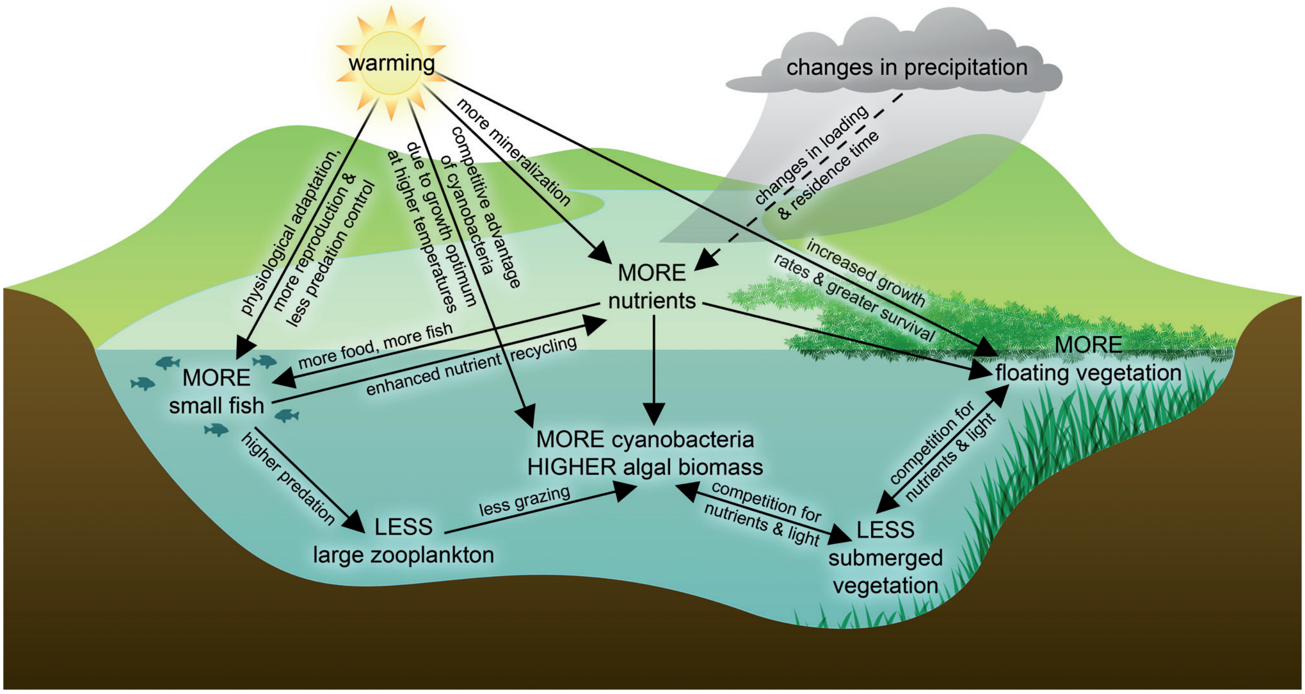

Fig. 1. Some relationships now established that link climate change and eutrophication symptoms.

lakes except at high altitude. These changes may be a direct response to higher water temperature (Moore et al. 1996) or driven by fish predation (Meerhoff et al. 2007a, Iglesias et al. 2011). Regardless, because climate change leads to warmer water, the biomass of large *Daphnia* will decline, and with it the ability to control phytoplankton. Other things being equal, algal crops will increase with warming, and because of the high temperature optima for growth of many cyanobacteria and their resistance to grazing by small zooplankters, the proportion of this sometimes-toxic group may increase (Elliot et al. 2006, Jöhnk et al. 2008, Paerl and Huisman 2008, Elliot 2010, Kosten et al. Forthcoming 2011). Together, cyanobacteria, through life histories that involve residence in sediments and vertical migration into the hypolimnion, and omnivorous, bottom-feeding fish that also mobilise phosphorus from the lake sediments to the surface waters, can create a positive feedback that frustrates attempts at nutrient control in warm waters (Havens and Schelske 2001).

Climate and the roles of plants

An important feature in shallow lakes and littoral zones is the presence of submerged plants, through whose refuges zooplankters and their predatory fish can coexist in lakes at high latitudes (Timms and Moss 1984). Submerged vegetation is often abundant in warm waters but is less effective as a zooplankton refuge because large numbers of small fish also find refuge there from their own predators (Meerhoff et al. 2007b). In both warm and cool waters a rise in phytoplankton tends to suppress submerged plants, but in warm waters submerged plants are often replaced by floating plants (Feuchtmayr et al. 2009, Netten et al. 2010), which are even less effective as refuges (Meerhoff et al. 2007b). Pristine cold waters thus tend to be clear and dominated by submerged plants, while pristine warm waters are more likely to be naturally turbid with algae and cyanobacteria and covered with floating plants, although the densest communities tend to be associated with eutrophication.

Warming increases eutrophication symptoms

Rising nutrient inputs and increasing temperatures tend mutually to intensify eutrophication symptoms. Cyanobacterial dominance, predominance of floating plants, and perhaps even complete loss of underwater vegetation, occurs at lower nutrient concentrations as temperatures increase (Kosten et al. 2009). The deoxygenation that may kill fish on still summer nights becomes worse as both nutrients and temperature increase. Moreover, rising temperature increases the nutrient

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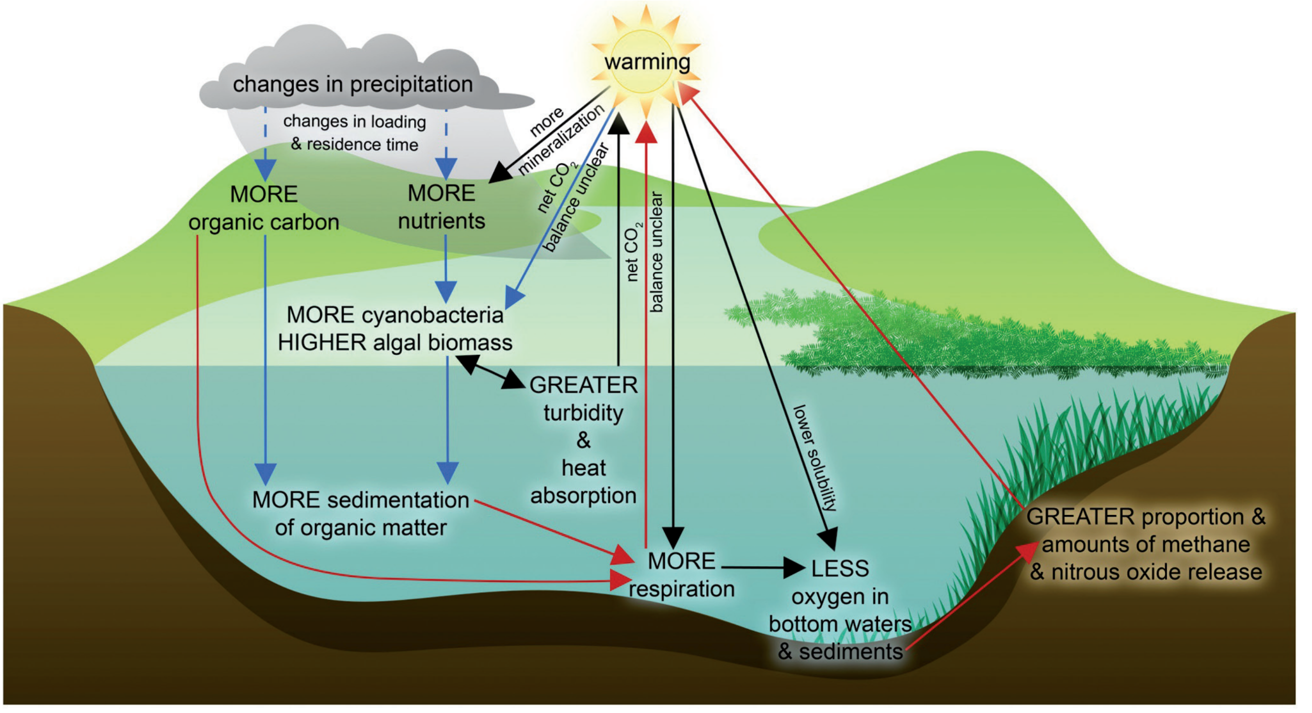

Fig. 2. Current indications of feedback effects of eutrophication on climate change. Blue arrows indicate carbon sequestration routes; red arrows indicate carbon emission routes; black arrows indicate other climate effects. Because CO_2 uptake and release may both increase with eutrophication, net CO_2 balance is unclear. The increase in methane and nitrous oxide is more probable. Dashed arrow indicates that changes in precipitation regimes may either lead to more or less organic carbon loading, depending on local and regional circumstances.

loading by increasing the rate of mineralization in catchment soils (Rustad et al. 2001, Brookshire et al. 2011) and causing greater deoxygenation at the surfaces of lake sediments, so that more nutrients are released in summer (Jensen and Andersen 1995). Also often associated with increasing temperature are short, intense storms that increase soil erosion and delivery of nutrients and decreased rainfall in summer or dry seasons. Consequent falling lake levels may concentrate the nutrients already present, expose marginal sediment to mineralization and nutrient release, and increase residence times, favouring bigger crops of slow-growing but persistent phytoplankters like cyanobacteria.

Does eutrophication promote climate change?

Eutrophication may also conversely promote climate change, although the evidence is less certain (Fig. 2). Freshwaters are often sources of carbon dioxide (Cole et al. 1994) because they metabolise organic matter washed in from vegetated catchments (Tranvik et al. 2009), or at least from surrounding swamps. Warming will increase the loss of dissolved organic carbon from land to freshwaters (Larsen et al. 2011). Eutrophication may lead to lower proportionate dependence on imported organic matter and greater autotrophic fixation of carbon dioxide; nonetheless, it also leads to increased absolute production and respiration, greater release of methane from deoxygenated waters and sediments, (Bastviken et al. 2008, 2011), and more nitrous oxide from denitrification (Huttunen et al. 2003). Both the latter gases are more effective greenhouse gases (by factors of 21 and 310, respectively) than carbon dioxide, but we do not yet know what the net balance of greenhouse gas release and heat retention due to eutrophication might be. Warming decreases the effectiveness of sediments in carbon storage (tropical soils and sediments tend to be more inorganic than temperate ones), releases more of the stored methane (Walter et al. 2006), and increases the community respiration to gross photosynthesis ratio in the short term at least (Gudasz et al. 2010, Moss 2010, Yvon-Durocher et al. 2010, 2011). There can be positive feedback effects on heat retention by denser blooms because turbid waters are more heat-retentive (Quayle et al. 2002), especially when blooms are present (Kahru et al. 1993). Warming may also promote invasion of productive cyanobacterial species to greater latitudes (Wiedner et al. 2007), where their potential dominance at high nutrient loading may reinforce warming effects. Likewise, endorheic lakes, which have large surface area to volume ratios, are major contributors to carbon dioxide release (Duarte et al. 2008). Warming-induced eutrophication will render them even more likely to release greenhouse gases as algal crops increase, sediments become intensely anaerobic, more heat is absorbed, and respiration rates accelerate. Clearly this is an area for future research.

Achieving a solution?

To date, climate change has not been factored into mitigation strategies for preexisting environmental impacts of our culture. It does not feature in the US Clean Water Act (US Government 1972) or the European Water Framework Directive (European Commission 2000), but where improvement of ecological or water quality is based on reference standards, the mutual effects of temperature and nutrient input will mean that existing standards will become harder to achieve and increasingly invalid (Bennion et al. 2011). Current policy in Europe is that climate mitigation should not compromise attempts to solve other environmental problems (European Commission 2009), and in the case of eutrophication, it might help that mitigation of both climate change and eutrophication requires some of the same approaches. But these two problem battalions are not alone, and all we have at present are some tactics to deflect them but no overall policy strategy to win the war.

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References

Bastviken D, Cole J, Pace ML, Van de Bogert MC. 2008. Fates of methane from different lake habitats: Connecting whole-lake budgets and CH_4 emissions. J Geophys Res-Biogeogr. J Geophys Res. 113, G02024, doi:10.1029/2007JG000608.

Bastviken D, Tranvik LJ, Downing JA, Crill PM, Enrich-Prast A. 2011. Freshwater methane emissions offset the continental carbon sink. Science. 331:50.

Bennion, H, Battarbee RW, Sayer CD, Simpson GL, Davison TA. 2011. Defining reference conditions and restoration targets for lake ecosystems using palaeolimnology: a synthesis. J Palaeolimnol. 45:533–544.

Brookshire ENJ, Gerber S, Webster JR, Nose JM, Swank WT. 2011. Direct effects of temperature on forest nitrogen cycling revealed through analysis of long-term watershed records. Glob Change Biol. 17:297–308.

Cole JJ, Caraco NF, Kling GW, Kratz TK. 1994. Carbon dioxide supersaturation in the surface waters of lakes. Science. 265: 1568–1570.

Dodds WK, Bouska WW, Eitzmann JL, Pilger TJ, Pitts KL. 2009. Eutrophication of U.S. freshwaters: analysis of potential economic damages. Environ Sci Technol. 43:12–19.

Duarte CM, Prairie YT, Montes C, Cole JJ, Striegl R, Melack J, Downing JA. 2008. CO_2 emissions from saline lakes: A global estimate of a surprisingly large flux. J Geophys Res. 113: G04041, DOI:10.1029/2007JG000637.

Elliot JA. 2010. The seasonal sensitivity of Cyanobacteria and other phytoplankton to changes in flushing rate and water temperature. Glob Change Biol. 16:864–876.

Elliot JA, Jones ID, Thackeray SJ. 2006. Testing the sensitivity of phytoplankton communities to changes in water temperature and nutrient load, in a temperate lake. Hydrobiologia. 559:401–411.

Elser JJ, Andersen T, Baron JS, Bergstrom A-K, Jansson M, Melack J, Downing JA. 2009. Shifts in lake N:P stoichiometry and nutrient limitation driven by atmospheric nitrogen deposition. Science. 326:835–837.

European Commission. 2000. Directive 2000/60/EC of October 23, 2000, of the European parliament and of the council establishing a framework for community action in the field of water policy. Official J Eur Community. L327:1–72.

European Commission. 2009. Common implementation strategy water framework directive. Guidance document No. 24. River basin management in a changing climate. Brussels.

Feuchtmayr H, Moran R, Hatton K, Connor L, Heyes T, Moss B, Harvey I, Atkinson D. 2009. Global warming and eutrophication: effects on water chemistry and autotrophic communities in experimental, hypertrophic, shallow lake mesocosms. J Appl Ecol. 46:713–723.

Gillooly JF, Dodson SI. 2000. Latitudinal patterns in the size distribution and seasonal dynamics of new world freshwater cladocerans. Limnol Oceanogr. 45: 22–30.

Gudasz C, Bastviken D, Steger K, Premke K, Sobek S, Tranvik LJ. 2010. Temperature-controlled organic carbon mineralization in lake sediments. Nature. 466:478–481.

Gyllstrøm M, Hansson L-A, Jeppesen E, Garcia-Criado F, Gross E, Irvine K, Kairesalo T, Kornijow R, Miracle MR, Nykänen M, et al. 2005. The role of climate in shaping zooplankton communities of shallow lakes. Limnol Oceanogr. 50:2008–2021.

Havens KE, Schelske CL. 2001. The importance of considering biological processes when setting total maximum loads for phosphorus in shallow lakes and reservoirs. Environ Pollut. 113:1–9.

Huttunen JT, Alm J, Liikanen A, Juutinen S, Larmola T, Hammar T, Silvola J, Martikainen PJ. 2003. Fluxes of methane, carbon dioxide and nitrous oxide in boreal lakes and potential anthropogenic effects on the aquatic greenhouse gas emissions. Chemosphere. 52:609–621.

Iglesias C, Mazzeo N, Meerhoff M, Lacerot G, Clemente JM, Scasso F, Kruk C, Goyenola G, Garcia-Alonso J, Amsinck SL, et al. 2011. High predation is of key importance for dominance of small-bodied zooplankton in warm shallow lakes: evidence from lakes, fish

 DOI: 10.5268/IW-1.2.359

exclosures and surface sediments. Hydrobiologia. DOI 10.1007/s10750-011-0645-0.

Jensen HS, Andersen FØ.1995. Importance of temperature, nitrate and pH for phosphorus release from aerobic sediments of four shallow, eutrophic lakes. Limnol Oceanogr. 37:577–589.

Jeppesen, E, Kronvang B, Olesen JE, Audet J, Sondergaard M, Hoffman CC, Andersen HE, Lauridsen T, Bjerring R, Conde-Porcuna JM, et al. 2011 Climate change effects on nitrogen loading from cultivated catchments in Europe: implications for nitrogen retention, ecological state of lakes and adaptation. Hydrobiologia. 663:1–21.

Jeppesen E, Meerhoff M, Holmgren K, González-Bergonzoni I, Teixeira-de Mello F, DeClerk SAJ, De Meester L, Søndergaard M, Lauridsen TL, Bjerring R, et al. 2010a. Impacts of climate warming on lake fish community structure and potential effects on ecosystem function. Hydrobiologia. 646:73–90.

Jeppesen, E, Moss B, Bennion H, Carvalho L, De Meester L, Feuchtmayr H, Friberg N, Gessner MO, Hefting M, Lauridsen TL, et al. 2010b. Interaction of climate change and eutrophication. In: Kernan M, Battarbee RW, Moss B, editors. Climate change impacts on freshwater ecosystems. Chichester (UK): Wiley-Blackwell. p. 119–151

Jöhnk K, Huisman J, Sharples J, Sommeijer B, Visser PM, Stroom JM. 2008. Summer heatwaves promote blooms of harmful cyanobacteria. Glob Change Biol. 14:495–512.

Kahru M, Leppänen JM, Rud O. 1993. Cyanobacterial blooms cause heating of the sea surface. Mar Ecol Prog Ser. 101:1–7.

Kosten S, Huszar V, Becares E, Costa L, Van Donk E, Hansson L-A, Jeppesen, E, Kruk C, Lacerot G, Mazzeo N, et al. Forthcoming 2011. Warmer climate boosts cyanobacterial dominance in shallow lakes. Glob Change Biol.

Kosten S, Kamarainen A, Jeppesen E, van Nes ET, Peeters HM, Mazzeo N, Sassk L, Hauxwell J, Hansel-Welch N, Lauridsen T et al. 2009. Climate-related differences in the dominance of submerged macrophytes in shallow lakes. Glob Change Biol. 15:2503–2517.

Larsen S, Andersen T, Hessen DO. 2011. Climate change predicted to cause severe increase of organic carbon in lakes. Glob Change Biol. 17:1186–192.

Meerhoff M, Clemente JM, Texeira de Mello F, Iglesias C, Pedersen A, Jeppesen E. 2007a. Can warm climate-related structure of littoral predator assemblies weaken the clear water state in shallow lakes? Glob Change Biol. 13:1888–1897.

Meerhoff M, Iglesias C, De Mello FT, Clemente JM, Jensen, E, Lauridsen TL, Jeppesen E. 2007b. Effects of habitat complexity on community structure and predator avoidance behaviour of littoral zooplankton in temperate versus subtropical shallow lakes. Freshwater Biol. 52:1009–1021.

Moore MV, Folt CF, Stemberger RS. 1996. Consequences of elevated temperatures for zooplankton assemblages in temperate lakes. Arch Hydrobiol. 135:289–319.

Moss B. 2010. Climate change, nutrient pollution and the bargain of Dr Faustus. Freshwater Biol. 55 (Supp 1):175–187.

Netten JC, Arts GHP, Gylstra R, van Nes E, Scheffer M, Roijackers MM. 2010. Effect of temperature and nutrients on the competition between free-floating Salvinia natans and submerged Elodea nuttallii in mesocosms Fund Appl Limnol. 177:125–132.

Paerl HW, Huisman J. 2008. Blooms like it hot. Science. 320:57–58.

Quayle W, Peck LS, Peat H, Ellis-Evans JC, Harrigan PR. 2002. Extreme responses to climate change in Antarctic lakes. Science. 295:645.

Rustad LE, Campbell JL, Marion GM, Norby RJ, Mitchell M, Hartley AE, Cornellissen JHC, Gurevitch J. 2001. A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. Oecologia.126:543–562.

Texeira de Mello F, Meerhoff M, Peckan-Hekim Z, Jeppesen E. 2009. Substantial differences in littoral fish community structure and dynamics in subtropical and temperate lakes. Freshwater Biol. 54:1202–1215.

Timms RM, Moss B. 1984. Prevention of growth of potentially dense phytoplankton populations by zooplankton grazing in the presence of zooplanktivorous fish, in a shallow wetland ecosystem. Limnol Oceanogr. 29:472–486.

Tranvik L, Downing JA, Cotner JB, Loiselle SA, Striegl RG, Balatore TJ, Dillon P, Finlay K, Fortino K et al. 2009. Lakes and reservoirs as regulators of carbon cycling and climate. Limnol Oceanogr. 54:2298–2314.

Trolle D, Hamilton DJ, Pilditch CA, Duggan IC, Jeppesen E. 2011. Predicting the effects of climate change on trophic status of three morphologically varying lakes: implications for lake restoration and management. Environ Model Softw. 26:354–370.

US Government. 1972. Federal Water Pollution Control Amendments of 1972. Washington (DC): 86 Stat. 816. Amended by the Clean Water Act of 1977 and Water Quality Act of 1987.

Walter KM, Zimov SA, Chanton JP, Verbyla D, Chapin FS III. 2006. Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. Nature. 443:71–75.

Wiedner C, Rucker J, Bruggemann R, Nixdorf B. 2007. Climate change affects timing and size of populations of an invasive cyanobacterium in temperate regions. Oecologia. 152:473–84.

Yvon-Durocher G, Jones JI, Trimmer M, Woodward G, Montoya JM. 2010. Warming alters the metabolic balance of ecosystems. Phil T Roy Soc B. 365:2117–2126.

Yvon-Durocher G, Montoya JM, Jones JI, Woodward G, Trimmer M. 2011. Warming alters the fraction of primary production released as methane in freshwater mesocosms. Glob Change Biol. 17: 1225–1234.