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Commentary

Protecting global aquatic resources from the mountains to the sea: growing need for dual nutrient (N and P) input controls along the freshwater-to-marine continuum

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We are entering a juncture of the Anthropocene and global climatic changes, with the combined impact being unprecedented pressures on our critical aquatic resources. Excessive human nutrient (nitrogen and phosphorus) inputs are accelerating eutrophication; with negative impacts on water quality and its safe use, altered habitats for biota ranging from microbes, plants, invertebrates, fish, mammals and threatening human use and health along the entire aquatic continuum, spanning mountain streams to the coastal ocean. Moreover, climatic changes taking place on regional to global scales exacerbate these pressures. For example, global warming has been shown to promote the harmful algal bloom (HAB) taxa, especially toxic cyanobacteria and dinoflagellates [1]. In addition, greater oscillations in the wet/dry cycle brought about by more extreme tropical and extra-tropical storms and rainfall events, interspersed by record-breaking droughts, are promoting HABs by introducing flood water nutrient pulses followed by stagnation [2], more extensive low oxygen (hypoxia) events, finfish and shellfish kills, while critically important sentinel species, including macrophytes, seagrasses, and corals are declining [3].

Unfortunately, we cannot effectively mitigate climatic changes taking place, at least not in the short run, although significantly reducing greenhouse gas emissions should receive high priority for long-term protection of the Earth's biotic resources. There is however a short-term mitigation strategy applicable to protecting these resources in virtually all aquatic ecosystems; namely, immediate and significant reductions in nutrient inputs. These reductions can be applied on their own or accompany other manipulative mitigation steps taking place to reverse eutrophication, including dredging nutrient-rich sediments, capping them, altering hydrological regimes by increasing water flushing, as well as short term "fixes" aiming at temporarily arresting HABs (algaeicides, sonication), and improving water column and sediment environmental conditions through artificial mixing and oxygenation [4]. In virtually all cases, these "fixes" should be accompanied by comprehensive nutrient management (reduction) plans for long-term control of eutrophication and HABs.

Traditionally, phosphorus (P) has been considered the major growth-limiting nutrient in the freshwater component, while nitrogen (N) limitation characterizes the marine component of the continuum. However, excessive loading of both nutrients over the past 5 decades has led to a buildup of nutrients in sediments and the water column as well as soils and groundwater as external input sources, leading to altered nutrient limitation; to the extent that this long-held paradigm no longer strictly applies. For example, the gradual buildup of P in the sediments and water column over decades has led to a legacy of continued P availability, and resultant shifts in nutrient controls of eutrophication from exclusive P to N&P co-limitation and N limitation in lakes, reservoirs and rivers [5]. Conversely, proliferating use of chemical fertilizers, increased urban, industrial and rural wastewater discharge has led to profound N enrichment, the impact of which has been to shift downstream riverine, estuarine and coastal water more towards N and P co-limitation or even P limitation [6].

We illustrate this evolving paradigm for one of the world's largest river systems (Yangtze, China) and a relatively small river system (Neuse River, North Carolina, USA). While the scales of nutrient-productivity dynamics vary greatly in these systems, they reveal a similar picture with regard to nutrient limitation and eutrophication dynamics; namely that both N and P limitation and co-limitation exist along their freshwater to marine components on seasonal and spatial scales.

(i) The Yangtze River System, China. The Yangtze River (YR) is the largest river in China and is the third longest in the world. It flows for 6300 km from the glaciers on the Qinghai-Tibet Plateau in Qinghai Province eastward across China before discharging into the East China Sea at Shanghai (Fig. 1) [7]. The YR basin has played an important role in the economy of China and accounts for more than 40% of China's gross domestic product (GDP). However, intensified human activities in the basin have led to increasing anthropogenic nutrient loads from agricultural and aquacultural activities, as well as industrial and domestic wastewater. Over the past three decades, the net anthropogenic N input has increased from $3537.0 \pm 615.3 \text{ kg N km}^{-2} \text{ a}^{-1}$ in 1980 to $8176.6 \pm 1442.1 \text{ kg N km}^{-2} \text{ a}^{-1}$ in 2012 [8]. The net anthropogenic P input has increased from $944 \text{ kg P km}^{-2} \text{ a}^{-1}$ in 1980 to $2308 \text{ kg P km}^{-2} \text{ a}^{-1}$ in 2015 [9].

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Fig. 1. Photographs of representative harmful algal blooms in the Yangtze and Neuse River systems. Upper figures, harmful cyanobacterial (*Microcystis* spp.-dominated) blooms in Lake Taihu, China. (a) A thick bloom in the open lake. (b) Bloom along the northwestern shore near Wuxi (photos by Hans Paerl). Lower figures, harmful blooms in the Neuse River estuary, North Carolina, USA. (c) Cyanobacterial (*Microcystis* spp.) in upper Neuse River estuary. (d) Dinoflagellate (*Heterocapsa triquetra*) bloom in the Neuse River Estuary, (photos, Hans Paerl).

The increasing N and P loads have accelerated eutrophication of the river and its impoundments, as well as downstream estuarine and adjacent coastal waters. Throughout the YR basin, harmful algal blooms and low oxygen conditions accompanied by loss of plant and animal biodiversity have become the main environmental concerns. Harmful cyanobacterial blooms (CyanoHABs) in the tributaries of a long (~700 km) dammed section of the YR Three Gorges Reservoir, have proliferated after impoundment of the Reservoir in 2003, as well as in its lateral tributaries [10]. CyanoHABs also frequently occur in several of lakes and reservoirs in YR basin [11]. In the summer of 2007, a severe CyanoHAB occurred in the third largest freshwater lake-Taihu and this event was extensively covered by the media (Fig. 1). This bloom produced a drinking water crisis for two million citizens in Wuxi City, Jiangsu Province.

Anthropogenic nutrient loading throughout the basin has also contributed significantly to the occurrence and increase of red tides in YR estuary and the adjacent coastal area in recent decades [12]. Overall, HABs have increased concomitant with increases in both N and P loading to the Yangtze estuary since the 1980s. The nutrient addition bioassays conducted in Xiangxi Bay of the Three Gorges Reservoir [13] and several of the large lakes in the YR basin (e.g., Taihu, Chaohu) show that N and P co-stimulation of the blooms is dominant over either N or P stimulation alone (Fig. 2). These results strongly suggest that both N and P input reductions are needed to stem this unwanted trend. Furthermore, this highlights the urgent need for controlling anthropogenic nutrient inputs in the YR basin for protecting the environmental health of the receiving estuarine and coastal ecosystems. Similar patterns also emerge in other large river systems of China, including the

Pearl River and Yellow River. Overall, both N and P fluxes were strongly correlated with primary production and various algal blooms from the river to marine continuum in China [14].

(ii) The Neuse River-Estuaries Continuum, North Carolina, USA. While much smaller in size than the Yangtze Basin, North Carolina's (USA) Neuse River (NR) Basin also exemplifies the need for enacting dual nutrient input constraints along the entire length of this river-estuarine continuum. The NR originates in the Piedmont of North Carolina and empties into the Pamlico Sound, part of the USA's second largest estuarine complex, the Albemarle-Pamlico Sound System. Its total length is approximately 443 km, and flow-wise, the largest river tributary of Pamlico Sound [15]. Its most upstream segment flows through mixed small urban centers-rural-forested region, while its mid-way segment flows through the more heavily populated and rapidly growing Research Triangle area (Raleigh, Durham, Chapel Hill). The downstream coastal plain segment largely drains agricultural lands, including row-crop and intensive poultry and swine operations. The NR Basin covers 16,149 km² of drainage area entirely within North Carolina. The basin supplies water to the population of nearly 1.4 million. Over the next 25 years, the human population in the watershed is expected to grow by 53%, while poultry operations are expected to increase by 39%. Approximately 80% of N and P loading to the NR is of non-point source origin, heavily dominated by agriculture (>50%), while 20% is from point sources, wastewater treatment plants and industrial discharges [15]. Agriculturally, almost all nutrients applied were from commercial fertilizer and animal waste.

Given rapid urban and agricultural development, the NR has experienced accelerated eutrophication, starting in the 1970's with

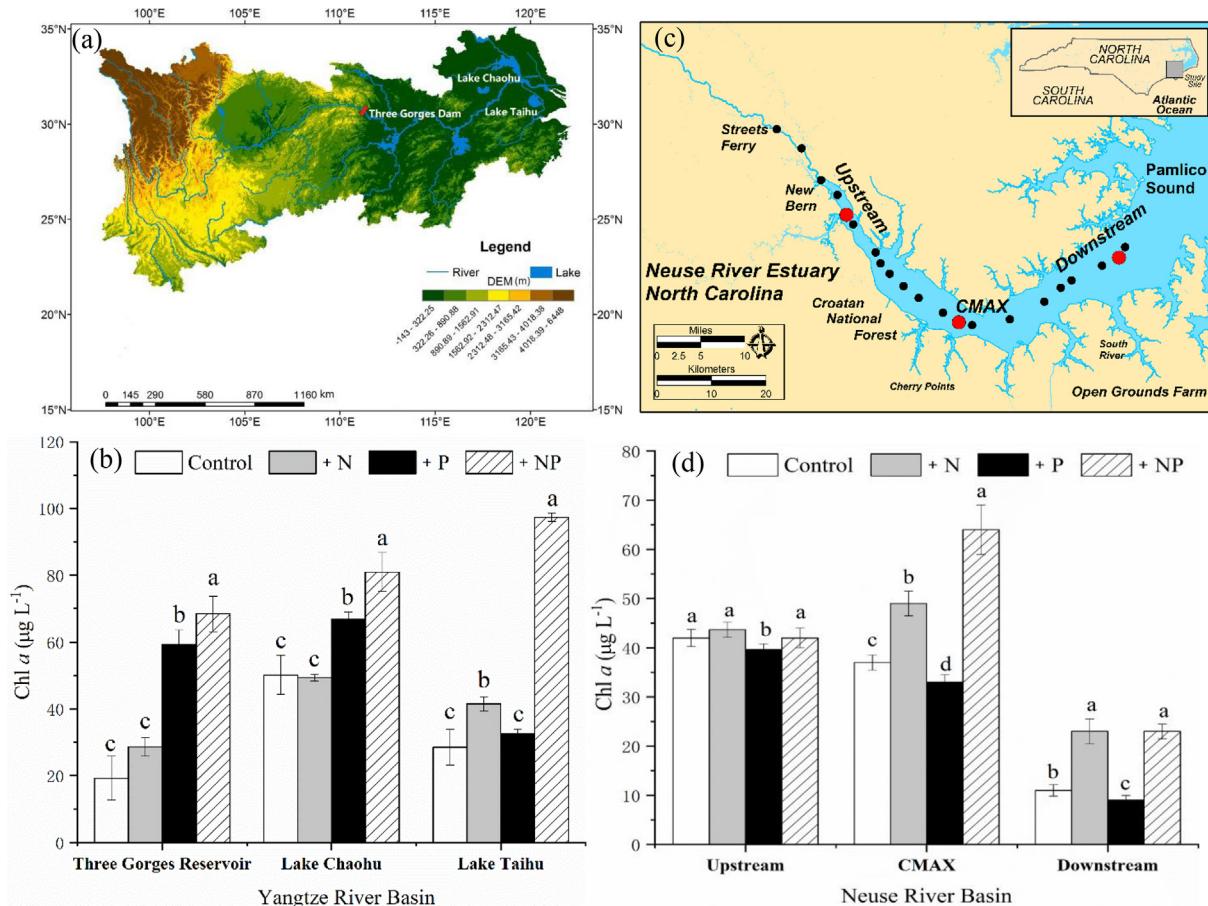


Fig. 2. Results from nutrient addition bioassays conducted in Yangtze River basin, including Lake Taihu, Lake Chaohu and Xiangxi Bay of Three Gorges Reservoir (a) and the Neuse River Estuary, NC, USA (c). The Yangtze River basin map is adapted from Ref. [7] (a). Phytoplankton growth response was measured as accumulation of chlorophyll α after 2 d incubation under natural light and temperature conditions during summer for Yangtze River Basin (b) and 3 d incubation for Neuse River Basin (d). Nitrogen (N) was added as nitrate (NO_3^-) at 1.0 mg/L final concentration for Yangtze River Basin and 0.14 mg/L for Neuse River Basin. Phosphorus (P) was added as phosphate (PO_4^{3-}) at 0.02 mg/L final concentration for Lake Taihu and Lake Chaohu and 0.1 mg/L for Xiangxi Bay of Three Gorges Reservoir, and 0.09 Neuse River Basin. Error bars represent $\pm 1\text{SD}$ of triplicate samples. Differences between treatments are shown based on ANOVA post hoc tests ($a > b > c; P < 0.05$). Data for Xiangxi Bay derived from Ref. [12]. These summertime bioassays indicate little evidence for nutrient limitation in the upstream riverine location. In the Neuse River Estuary, upstream locations (orange circle) showed no significant nutrient stimulation. However, increasing N limitation was observed in the more saline downstream estuarine locations (orange circles).

the appearance of elevated Chl α levels exceeding the State of North Carolina's "acceptable water quality standard" of 40 μg Chl α L^{-1} , accompanied by harmful cyanobacteria blooms (*Microcystis* spp., *Dolichospermum* spp.) in the upper estuary and dinoflagellate blooms in the more saline lower estuary (Figs. 1 and 2).

In an effort to mitigate the blooms, the State of North Carolina enacted a phosphate detergent ban in the mid 1980's, accompanied by mandated advanced wastewater treatment for P. This was effective in significantly reducing P loads, but no parallel N reductions were enacted. While addressing the upstream cyanobacterial bloom problems, the "P only" reduction strategy reduced the upstream algal biomass, and its ability to act as a "filter" for assimilating N, which turned out to be the limiting nutrient in the downstream estuarine segment of the NR continuum [15] (Fig. 2). As a result, while Chl α levels and blooms were reduced upstream, downstream N-driven eutrophication and blooms, as well as accompanying bottom water hypoxia problems and related fish kills increased in the estuary.

In response to expanding estuarine eutrophication, the State of North Carolina needed to reconsider its nutrient management strategy to include consideration of watershed N reductions as well. Historic increases in N loading, N addition and dilution bioassays and modeling efforts, pointed to the need for parallel N reductions on the order of at least 30%, which was adopted and enacted

by the State and the US EPA as a mandated Total Maximum Daily N load (TMDL) reduction of 30% (<https://deq.nc.gov/about/divisions/water-resources/planning/nonpoint-source-management/nutrient-strategies/neuse>). In retrospect, if the State had considered the nutrient limitation dynamics along the entire length of the NR continuum, it would have been wise and timely to have enacted a dual N & P reduction strategy back in the 1980's [15]. The need for dual nutrient reductions has now been realized for other large river to coast continua globally, including the Amazon River basin, the Mississippi River basin, and Chesapeake Bay (USA) watershed, numerous tributaries to the Baltic Sea (e.g., *Himmerfjorden*, Sweden), and the Rhine River watershed, just to set some examples [12,16].

Patterns observed in the YR and NR are paralleled in other large river systems globally. For example, the world's largest river system, the Amazon, exhibits very high freshwater discharge, which has a substantial influence on phytoplankton assemblages in the receiving waters of the Western Tropical North Atlantic Ocean [16]. Similar patterns also emerge in the Mississippi River plume in the Northern Gulf of Mexico, high spring runoff N fluxes promoted a spring bloom that was forced into P limitation, while N limitation prevailed during the lower discharge summer months [6].

These two eutrophying riverine systems, while differing dramatically in scale and location, similarly exhibit that dual nutrient

reductions will be needed if we are to control eutrophication and its unwanted symptoms along their freshwater to marine continua. This conclusion is based on the fact that single nutrient removal, while possibly effective in localized control of eutrophication, will not suffice as a control along the entire length of the continuum. In fact, upstream single nutrient reductions may make downstream water more susceptible to the negative symptoms of advanced eutrophication, including harmful algal blooms, oxygen depleted “dead zones”, accompanied by loss of habitat and biota [3,16]. Dual nutrient reduction strategies will be even more critical under the influence of climate change, where increases in temperature, altered wind speed and more extreme rainfall events and droughts will likely make the entire continuum more sensitive to cyanobacterial blooms thriving in the freshwater and dinoflagellate and other potentially harmful blooms in the downstream, more saline components of the continuum [17]. Non-point sources are often the dominant source of nutrients along the continua and hence need to be aggressively pursued from a nutrient management (reduction) perspective. With regard to point sources, the construction and upgrading of urban and rural wastewater treatment plants, while offering an attractive “low hanging fruit” option for nutrient input reduction, if practiced alone will likely only have a limited effect on controlling eutrophication and occurrences of downstream harmful algal blooms in the future.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (U22A20561, 41830757, and 41621002), the US National Science Foundation (1831096 and 1803697), the National Institutes of Health (1P01ES028939-01), and NOAA/North Carolina Sea Grant Program (R/MER-43 and R/MER-47). We thank Alan Joyner (University of North Carolina) for providing illustrative work.

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