Science Bulletin 64 (2019) 1125–1128

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

Commentary

Eutrophication: a limiting nutrient is not necessarily an abating factor

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Eutrophication and algal blooms are a global environmental problem. In terms of nutrient control of eutrophic waters, there is still a heated debate on reducing P only or both P and N [1–3]. The core question is whether algal communities are P-limited or N-limited or co-limited; the basic assumption is that limiting nutrients are those which should be reduced [2]. But, is the assumption really true?

The law of limiting factors (so-called Liebig's Law of the Minimum) was first formed by Sprengel in 1828 in essence. He stated: when a plant needs 12 substances to develop, it will not grow if any one of these is missing, and it will always grow poorly, when one of these is not available in a sufficiently large amount as required by the nature of the plant [4]. Such an important finding was taken by Liebig in his book (1840) without proper acknowledgement, and thus it was proposed to call the rule the Sprengel-Liebig Law of the Minimum [4]. Up to now, applications of this law have extended from plants to various organisms, from individuals to populations to communities, from nutrient salts to various environmental factors. A limiting factor is the least available one and/or the slowest one that constrains survival, metabolism, growth, reproduction and distribution of organisms [5]. Practically, a limiting factor is directly determined by experiments, in which changing the factor towards the ecological optimum (e.g. nutrient addition) causes an increase in the rate of a biological process (e.g. primary productivity) or in the size of an important ecosystem compartment (e.g. biomass); short-term limitations are designated as proximate, and long-term ones as ultimate [6].

The definition and experiment criterion stated above clearly show that the purpose of identifying a limiting factor is to determine the factor of growth promotion (Fig. 1a1). The contrary is the factor of overgrowth control; we term it an abating factor, and define this new term as the most cost-effective factor that can reduce overgrowth of individuals, populations or communities in ecosystem managements, being either an essential environmental factor (indirect abating factor) or a physical/chemical/biological means of destroying organisms (direct abating factor) (Fig. 1a2).

The following example shows the five steps to determine an abating factor (Fig. 1b). Along the sides of our experimental ponds, hygrophytic and emergent weeds always overgrew, disturbing experiments by absorbing added nutrients. We identified the abating factor by analyzing: (a) Necessity: listing essential environmental factors and methods of destroying. The former includes light, temperature, carbon dioxide, water and essential nutrient elements, and the latter is cutting and herbicides. (b) Controllability: assessing which essential factors can be controlled and which methods of destroying can be effective, for a long time on an ecosystem scale. Shading is feasible due to the small area, but temperature, carbon dioxide and water cannot be controlled. Among possible limiting nutrients (N, P, K, etc.), P usually forms insoluble compounds and thus is easiest to control. Cutting and herbicides are effective if applied at some interval. (c) Practicability: analyzing negative effects of the abating factor candidates and the compatibility with management bottom lines. As herbicides will pollute the ponds, they were excluded. (d) Costs: selecting the cheapest one by comparing explicit and inexplicit costs of the abating factor candidates. Shading (bottom covers) costs less than P control and cutting due to only one-time spending and was identified as the abating factor. (e) Tests: verifying the abating factor by large scale experiments and application. We covered the pond sides with asbestos tiles in 2013 and the weeds have been eradicated.

The above example demonstrates convincingly that a non-limiting factor can become an abating factor, and a limiting factor is not necessarily an abating factor. Although P is the common limiting factor of land and wetland plants [6], it is almost impossible to control weeds and invasive plants through reducing P supply, while chemical, mechanical and biological control is widely used.

Fig. 1b shows that the abating factor of lake eutrophication is P. This conclusion has been verified by whole-lake experiments and lake restoration practices. In the Experimental Lakes Area (ELA) of Canada (49°N), long-term fertilization experiments in Lake 304 (1971–1976), Lake 226 (1973–1980) and Lake 302 (1982–1986) [1] have proved that P-only reduction can control algae blooms and eutrophication. Our fertilization experiment in ponds along the Yangtze River (30°N) (2010–2012) showed that Chl *a* (chlorophyll *a*) and biomass of phytoplankton in the +N pond had no significant difference with those in the pond without nutrient addition, being only 50%–60% of those in the +N + P pond [3] (Fig. 2a); this further proves the conclusion of P-only reduction. In high latitudes (42–59°N), there are many lakes that have successful recovered from eutrophication following the control of P inputs, such as Lake Washington, Lake Mälaren, Lake Constance [1]. In Lake Xihu (30°N) of China, water flushing and external loading reduction in 1987–2011 decreased water TP (total P) by 58.2%–78.3% (0.12 mg L^{-1} – 0.04 mg L^{-1}), but decreased TN (total N) by only 7.7%–16.7% (2.6 mg L^{-1} – 2.3 mg L^{-1}); however, this

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https://doi.org/10.1016/j.scib.2019.06.010

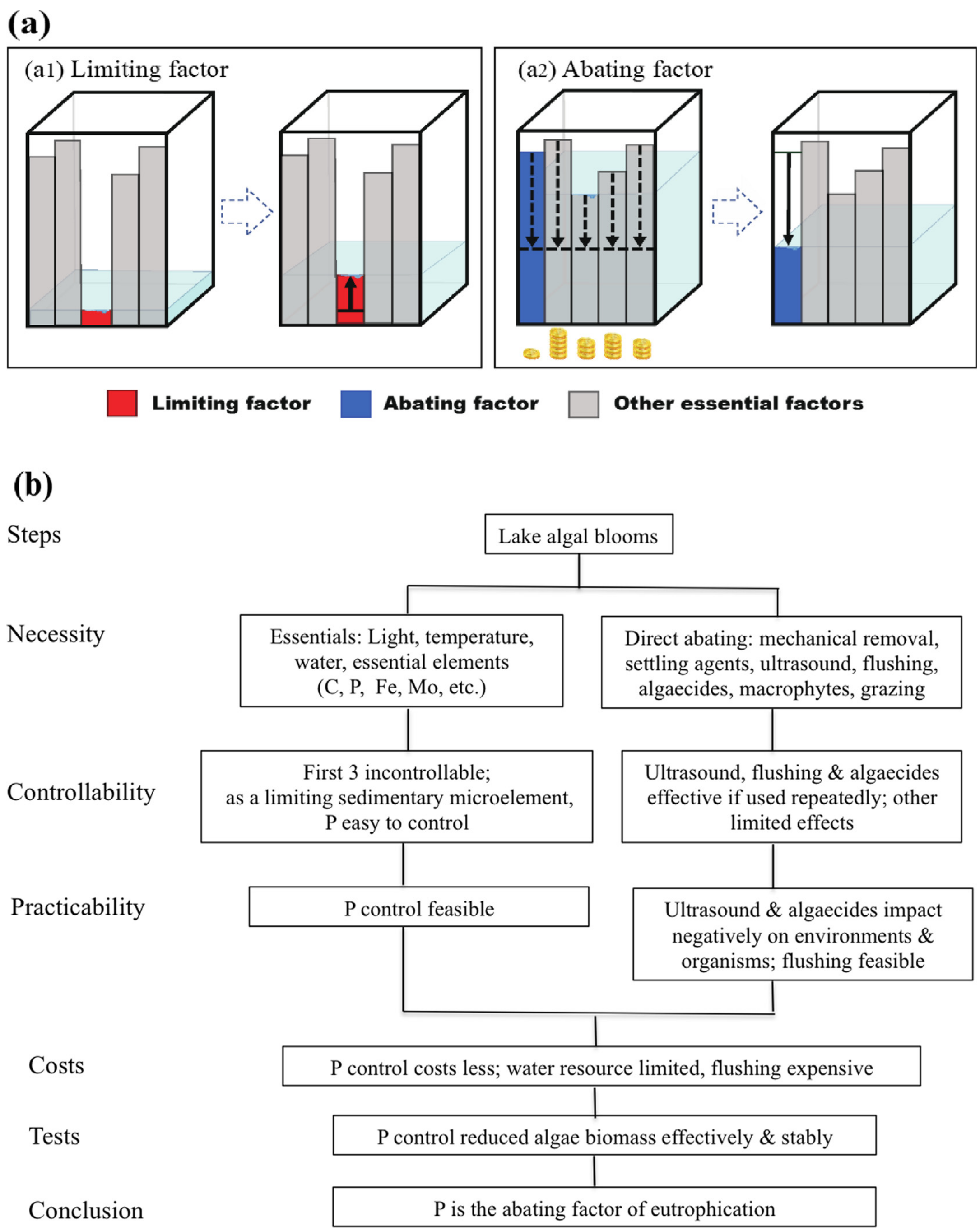

Fig. 1. Concept of an abating factor and its procedure of determination. (a) Diagrams of limiting factor (a1) and abating factor (a2) concepts, each using a water box with a multi-boards gate. a1: lengthening the shortest board (red) is the only way to raise the water level. a2: coins indicate costs to shorten each board to the same level, and shortening the blue board (not necessarily the shortest, as shown in this figure) is the most cost-effective way to lower the water level. (b) Procedure to determine the abating factor of algal blooms in lakes.

result in the decrease of Chl *a* by 68.8%–93.8% (160 μg L^{-1} – 30 μg L^{-1}); correlations ($n = 11$) indicate that the changes of Chl *a* were caused by those of TP ($r = 0.87$, $P = 0.001$), but independent of those of TN ($r = 0.005$, $P = 0.99$) (Fig. 2b).

The opinion of reducing N is mainly based on the deductions of seasonality of N and P limitation or co-limitation in some waterbodies [2]. The deductions were based on small-scale fertilization experiments or the N/P hypothesis. Such experiments were conducted in bottles and mesocosms, lasting for serval hours to several weeks, and they can only judge proximate limiting nutrients; moreover, container water of some tests was from eutrophicated waterbodies, and the results cannot be used to deduce the culprit of algae over-propagation. The N/P hypothesis has been denied by our previous studies [7]; it is a subjective assumption without conclusive evidence, and the N/P ratio cannot be used to judge nutrient limitation of algae. Obviously, the small-scale experiments and the N/P ratio cannot determine the ultimate limiting factor, let alone the abating factor. In fact, the viewpoint of N reduction has been ultimately denied by whole-lake experiments. In ELA, long-term fertilization experiments in Lake 261 (1973–1976) [1] and Lake 227 (1969–2014) [8] has proved that reducing N input cannot decrease total phytoplankton biomass as it favors N-fixing cyanobacteria. In Seathwaite Tarn (54°N) (1992–1993) of England, P-only addition increased Chl *a* [3]. Our

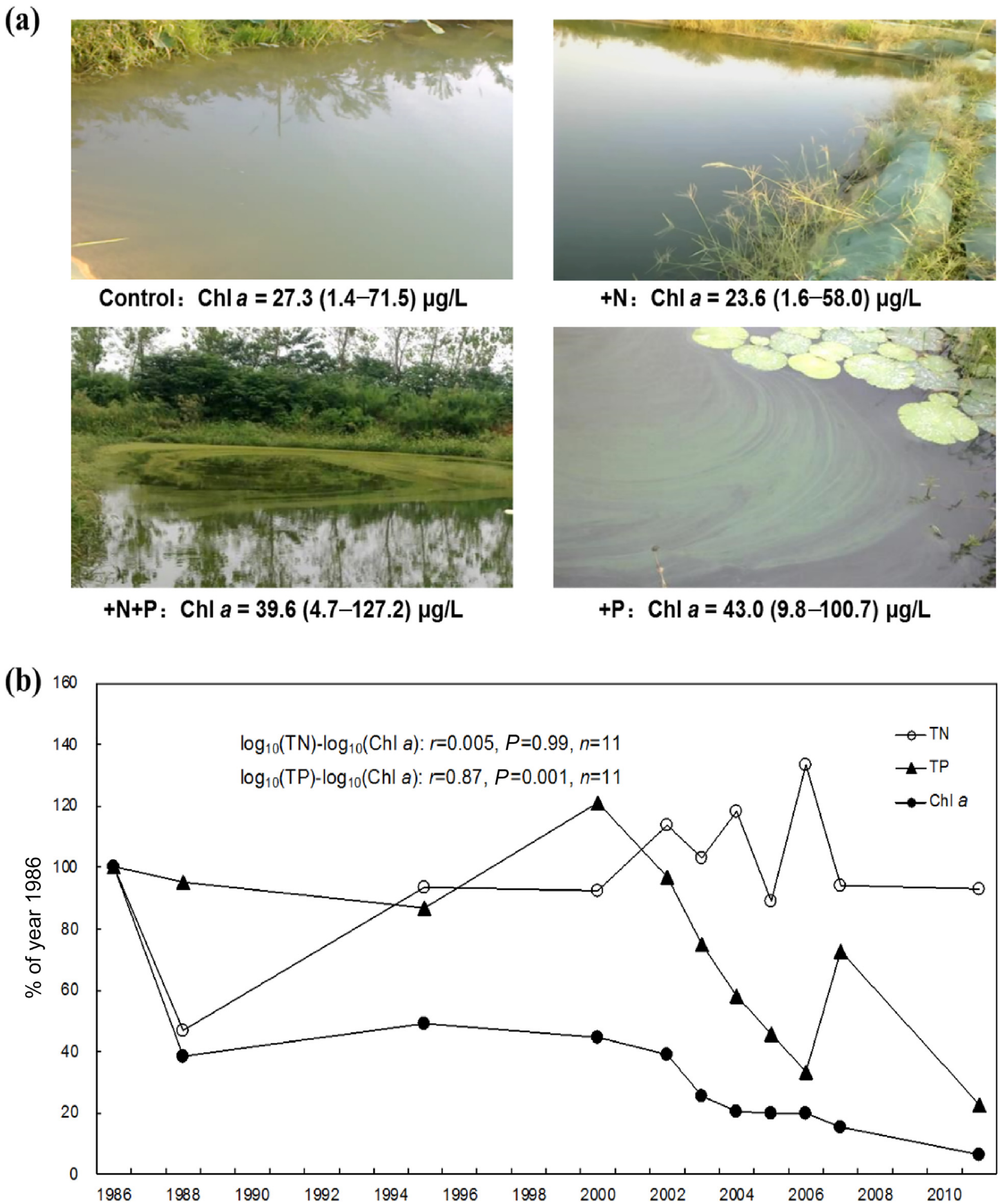

Fig. 2. Tests of the abating factor of eutrophication. (a) The fertilization experiment in the ponds in the middle Yangtze Basin. (b) Changes in total nitrogen (TN), total phosphorus (TP), and phytoplankton chlorophyll *a* (Chl *a*) in Lake Xihu (1986–2011). The 1986 values, plotted as 100 percent, were (in mg L^{-1}): TN, 2.8; TP, 1.2; and Chl *a*, 0.16 [3].

pond experiments showed that Chl *a* and biomass of phytoplankton in the +P pond were similar to those in the +N + P pond, being 1.6–3.6 times as much as those in the ponds without P addition (Fig. 2a); the heterocyst density in the +P pond was 4.5 times as much as that in the +N + P pond, and TN in the former was close to that in the latter from the 4th month [3]. Our result further verifies the above ELA conclusion, but also finds that it takes much shorter time to offset N deficiency in lakes of subtropics than high latitudes (serval months vs. several years).

On the basis of nutrient addition experiments and the phenomenon that N-fixing planktonic cyanobacteria with heterocysts are few or absent in waters with salinities more than 10‰–12‰, many researchers believe that N is the limiting factor of estuarine and marine phytoplankton, and thus reducing N and P is needed to control the eutrophication [2,9]. But, this opinion lacks convincing evidences. First, "limiting" does not identically equal "abating", as mentioned above. Second, the experiments were too small in scale, with the largest only in mesocosms of 13.1 m^3 lasting for 9 weeks [9]. Third, recent researches show that non-heterocystous filamentous cyanobacteria (e.g. *Trichodesmium*) and unicellular cyanobacteria (e.g. *Gloeocapsa*) and bacterioplankton make a substantial contribution to N fixation, and a few species can even fix N_2 aerobically [10,11]; in coastal benthos, heterotrophic N fixation can switch sediments from being N sinks to being N sources [12]. In fact, the Stockholm Archipelago estuary has been recovered from eutrophication mainly by reducing P loading [1].

Mainly based upon above-mentioned "N limitation", strict N control has been required to reverse eutrophication by Europe, USA, China, etc. [3] incorrectly. The TN standards for surface water are 0.2 mg L^{-1}–2 mg L^{-1} in China (GB 3838-2002). Considering that very high N levels (5 mg L^{-1}–10 mg L^{-1}) have some stresses on organisms (submerged macrophytes, fishes, etc.) and can promote sediment phosphorus release [13], we advocate loosening N control and focusing on P abatement in eutrophication mitigation so as to reduce costs substantially. Reducing both N and P costs 4–15 times as much as reducing P only [1].

Based upon a critical review of literatures and our long-time studies, we draw the following conclusions:

(i) The purpose of identifying a limiting factor is to determine the factor to promote growth of organisms.
(ii) An abating factor is defined as the most cost-effective factor that can reduce overgrowth of individuals, populations or communities in ecosystem managements.
(iii) A non-limiting factor can become an abating factor, and a limiting factor is not necessarily an abating factor.
(iv) The abating nutrients of eutrophication are not N + P but P only.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgment

This work was supported by State Key Laboratory of Freshwater Ecology and Biotechnology (2016FBZ09) and the Science and Technology Support Program of Hubei Province (2015BBA225). Hai-Jun Wang was supported by the Youth Innovation Association of Chinese Academy of Sciences (2014312). We thank Yan Li, Shuo-Nan Ma and Shu-Ran Wang for their assistance in data collection and graph preparation.

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