The Rise and Fall of Algal Blooms – Systemic Aversion from Limits to Growth, I

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Abstract: Rising trends in contemporary local ubiquitous algal blooms worldwide are positively associated with historic unprecedented rates of C, N, and P accumulations in waters and sediments in all types of aquatic ecosystems. A synthesis of patterns, processes, and mechanisms of algal blooms from different spatial and temporal scales reveals that they are a symptom of systemic changes in the intensity of the trophic and the detrital food webs scaffolded through the interaction of warming, fertilization and over fishing. Research with reference sites within protected areas; on ecological stoichiometry; and on socio-ecological systems are recommended in forecasting, monitoring, and policy regarding algal blooms to timely avert from limits to growth without unintended consequences.

Keywords: Aquatic ecosystems transformations, Dynamic systems modeling, Socio-ecological systems.

1. INTRODUCTION

Nutrients' input into aquatic ecosystems range from spring algal blooms through shifts in trophic states to massive kills of biota [1, 2]. The contemporary algal blooms documented from all types and sizes of aquatic ecosystems from all over the world are alarming because of four reasons: species identity (toxic or nuisance), unexpectedness (in either space or time), intensity (from annoying to overwhelming), and frequency (on the rise) [3].

In this review/synthesis, I show that the accumulation of evidence from small (cells to species), intermediate (ecosystem processes) and large (biogeochemical cycles) spatio/temporal scales and their cross-scale interactions align well to indicate that synergies among changes in biogeochemical cycles of C, N, P and O are changing the structure of foodwebs through spatial and temporal shifts and other types of mis-matches, which, in turn, change the flow of energy in aquatic ecosystems through replacement of predation pumping by decomposition pumping. The contemporary rise of local ubiquituous algal blooms worldwide constitutes manifestation of the scaffolding of systemic changes in the flow of energy in aquatic ecosystems. Because the suite of contemporary changes in biogeochemical cycles of C, N, P and O constitute anomalies within the palaeo/geo/ecological record, the contemporary scaffolded systemic changes in the flow of energy in aquatic ecosystems is not only unprecedented in spatial scale and temporal rate, and thus beyond our ability to predict with confidence and adapt in time but also degrading for aquatic ecosystems as (our) life supporting systems. Thus, the fall of ubiquitous algal blooms world wide requires systemic changes in the way we obtain energy and use materials. The review progresses with evidence to answer three questions: 1) Why there is rise in algal blooms worldwide? 2) How is this rise interpreted? And 3) How best induce the fall in algal blooms worldwide?

The objective/aim of this study was to review patterns, processes and mechanisms within and across the global, the ecosystem, and the cellular spatio/temporal scales in biogeochemical cycling of C, N, P, and O (the cause) and algal blooms (the effect) in aquatic ecosystems.

2. BIOGEOCHEMICAL CYCLES – RECENT HISTORIC ANOMALIES AND UNAMBIGUOUS CAUSES

Biogeochemical cycles describe the rate of movement of elements, such as C, N, P and O, among and their abundance within the atmospheric, the aquatic, the (terrestrial/aquatic) depositional/-sedimentary, and the living compartments.

Mobilization of (reduced) hydrocarbon fossils from the geologic depositional compartment and their burning (oxidation) to produce energy have increased CO_2 in the atmospheric compartment. The 48% increase in atmospheric mean global CO_2 concentration (412 ppm) took place at an exponentially increasing temporal trend since pre-industrial times (278 ppm) denoting virtually no assimilative capacity (available) for this trace atmospheric gas [4], which has never before exceeded 315 ppm along the last seven successive cycles of glacial advance and retreat during the last 800,000 years [5]. Because CO_2 is a trace, with

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relatively large molecular weight, and inert atmospheric gas, it is neither its mass nor its partial pressure of importance; rather it is its heat trapping property that has the potential to increase water temperature in aquatic ecosystems through heat convection. Because temperature is fundamental, it can force all other physical, chemical, and biological properties and processes in these systems. Oceans have been taking up about 93% of the excessive trapped heat at the expense of a strongest mean global warming anomaly of 0.11 ^{0}C per decade in the upper 750 m between 1971 and 2010 [6]. With virtually no assimilative capacity for CO_2 available, there will be required a century to reduce both CO_2 and heat content to pre-industrial levels [7].

Nitrogen lacks a depositional compartment and its major stock is the atmosphere as gaseous N_2 while phosphorus lacks an atmospheric compartment and its major stock is in soils and sediments as soluble and reactive $PO4^{-3}$; both are the most abundant macro-nutrients of the living compartment after carbon. Mobilization of atmospheric nitrogen and depositional phosphorus to fertilize intensive agricultural fields and the runoff of their excess (riverine discharge), the discharge of (treated) organic sewage into aquatic ecosystems, and land use/cover conversions and modifications all combined have doubled the global net anthropogenic riverine delivery of nitrogen (19 to 37 Tg N yr−1) and phosphorus (2 to 4 Tg P yr−1) to the coastal zone [8-10] while the burning of fossil fuels and biomass and the breakdown of animal excretions have almost doubled atmospheric emissions of nitrogen, that are deposited on terrestrial and freshwater ecosystems with rain and snow, since pre-industrial times [in 11]. Toward the opposite direction, global fisheries and aquaculture have been redistributing these macro-nutrients within the living compartment by exporting primary and secondary production from aquatic toward terrestrial ecosystems with a mean annual growth rate of 37.7% since the 1950's, which peaked at 171 million tons in 2017 [12]. The ratio, however, of N bound in fish to N bound in fertilizers has decreased from 60 to 20% since 1960 [13]. The macro-nutrients based intensification of fisheries, aquaculture and agriculture supported our population growth from 2.5 to 7 billion people during the last 70 years [14, 15]. Legacy N and P already accumulated in waters and sediments of aquatic ecosystems require decades to centuries to assimilate depending on policy decisions and management practices [16, 17].

Trends of exponential accumulations of organic matter, N, and P in sediments cores from intensively studied and intensively eutrophied aquatic ecosystems [18-20] reveal that these trends have been both independently and interactively unprecedented in recent and distant history. Although we anticipated the beneficial effect of the interaction of the increase in temperature and increase in nutrients on the stimulation of biomass production in aquatic ecosystems, we do observe exponentially increasing trends of both the extent and intensity of eutrophication [21-23], hypoxia [24], and harmful algal blooms [25-28] in aquatic ecosystems. Because the same choices of how to obtain energy, how to increase aquatic productivity, and how to dispose our waste have taken place at myriad localities all over the world, the results of exponentially accelerating and interacting trends in warming, aquatic fertilization, and hypoxia are global regardless of limited or lacking documentation from many regions and localities.

What is now left to confirm the causal links between recent historic changes in biogeochemical cycles and contemporary algal blooms beyond correlations among exponential trends in long term time series' variables is that sampling and analysis of algal blooms and their eutrophied / hypoxic environments is taking place from sites that do exhibit increasing trends in algal blooms (impacted sites) and from comparable sites that do not experience algal blooms (reference sites) before, during and after the algal bloom [29]. In this way, we can also decipher not only the relative importance but also the strength of the warming and fertilization interaction on algal blooming aquatic ecosystems. We will also be able to verify the extent of the exogenous and endogenous sources of CO_2, N and P nutrients for harmful algal blooms to occur given their accumulations in the atmosphere, the waters, and the sediments and the long residence times of their loading. Systems dynamics modeling [30], where algal blooms is one of the phenomena that can be generated by an aquatic ecosystem, can utilize the data and results of other available modeling efforts [31] as well as data from real-time *in situ* environmental monitoring to provide the valuable insights necessary to determine and prioritize appropriate short-, intermediate-, and long-term policy responses. The root cause, however, of harmful algal blooms emanates from choice; neither science nor management.

In retrospect, we can now appreciate that our choice to mobilize geologic carbon to obtain energy when at (global) CO_2 and temperature maxima explains why there must had been not much assimilative capacity for either CO_2 or heat, and for that matter nutrients, left in ecosystems right from the start of the industrial revolution. Also, our choice to dispose our waste utilizing the free of charge assimilate capacity of aquatic ecosystems for single macro-nutrients, such as N and P, was based on an economically attractive incentive but on biologically and ecologically poorly justified premises / expectations that incessant chronic fertilization of microscopic primary producers in inverse biomass aquatic pyramids must not be that much different from fertilization of macroscopic crop plants in upright biomass terrestrial pyramids of agricultural fields; that single nutrients added will be fully assimilated and only by the species of interest; and, finally, having no idea about how to measure the size of the ecosystem's assimilative capacity for heat and nutrients. That's why concomitant continuous environmental monitoring of O_2 concentration ensued so as to obtain a relatively easily tractable warning of the limit of this assimilative capacity for aquatic ecosystems as sinks of CO_2 and nutrients.

3. AQUATIC ECOSYSTEMS - TRANSFORMATIONS AND DEGRADATIONS

Species and ecosystems function within a range of normality with optima, be it for temperature, nutrients or oxygen because of negative feedback loops, that is reciprocally causal stabilizing relationships. Temperature, nutrients, and oxygen concentration affect the metabolic rate of all species within an aquatic ecosystem; those which capture sunlight and turn it into biochemical energy through photosynthesis (producers: cyanobacteria, phytoplankton, macrophytes); those which participate in the flow / pumping of this biochemical energy toward higher trophic levels through predation (consumers: herbivores and carnivores); and those which mineralize dead organic matter from all trophic levels through chemical breakdown (mineralizers: bacteria and mycetes). By extention, they affect the range of normality and the optima of rates of ecosystem processes, such as production, consumption, storage, and mineralization, that incessantly and inter-dependently cycle all nutrients within ecosystems. Because all species consume dissolved O_2 to respire irrespective of the depth where they are found but only producers release new O_2 through photosynthesis above the compensation depth, where light intensity is around 1% compared to that reaching the water surface, the rates of production, consumption, mineralization, and storage of organic matter in sediments are not only interdependent or coupled within and among the above-compensation depth, below-compensation depth, and within-benthic sediments functional zones of an aquatic ecosystem, as are the water temperature, oxygen, pH, total carbon, total nitrogen, and total phosphorus profiles across the water column and across sediments, but are also constrained by dissolved O_2 concentration. Such differences in distributional patterns of physical and chemical variables, organic matter, and ecosystem processes rates imply differences in regulating mechanisms that we have just started deciphering [Figures 1-3 in [32]].

Our choices of how to obtain energy, how to increase aquatic productivity, and how to dispose our waste have been increasing temperature and transferring N and P from large size and long term accumulating stocks into aquatic ecosystems, whose continuous and progressive transformations ever since further corroborate to the lack of any assimilative capacity, affecting species with many orders of magnitude and body size-related variation in the duration of their life cycle. Warming and fertilization is already directionally forcing all aquatic ecosystems and all species because temperature and nutrient availability are fundamental properties of their ambient environment. Warming reduces solubility of oxygen from the atmosphere and into the water column, intensifies water column stratification, affects the phenology of vital biological processes of species, such as timing of reproduction, as environmental cue, induces species' migrations, geographic range expansions, and replacement, and de-coupling among species in food web trophodynamics [6]. The addition of N and P in all types of aquatic ecosystems is accompanied by dramatic change in their primary producers: benthic macrophytes-dependent and clear water oligotrophic lakes turn into phytoplankton-based and turbid water eutrophic lakes, that accumulate benthic sediments; endosymbiotic zooxanthellate algae-dependent tropical coral reefs in oligotrophic clear coastal waters turn into macroalgal-dominated turbid coastal waters, that accrete less biogenic calcium carbonate; Florida Everglades wetlands flip between seagrass and cattail dominated communities depending on soil phosphorus concentration as this is affected by periodic disturbances [33]. Transition to a transformed / alternate state is associated with increase in community variance [34] and leads to the replacement of dominant, fine- tuned species with narrow P and N environmental niches by species with wider respective niches (*e.g.* [35]). Since, in principle, form affects function at every level of organization of life, change in primary producers, as the basal components of trophic food webs, affects relationships among species along the trophic and the mineralizing food webs, and, thus, the functioning of ecosystems or else the rate with which production, consumption, storage, and mineralization of organic matter take place. From change in primary producers, enhancement and deposition of more organic production, enhancement of decomposition and mineralization, and reduction in oxygen levels, eutrophication progresses with symptoms of transient mass mortalities of biota due to further oxygen reduction while the build up of nutrients and organic matter in sediments continues. Further eutrophication is associated with symptoms of what seems like boom and bust dynamics of animal populations, which may also / probably be the result of reversible migration of animals from areas of hypoxia at deeper depths to areas with adequate oxygen at shallower depths, as nutrients and organic matter further accumulate in sediments and now hypoxia becomes periodic/seasonal [36].

Sequential bloom of main producer phytoplankton species is an example of optima within the range of normality that naturally occur during the whole spring season in temperate and sub polar waters every single year when rising temperatures, increased day light intensity and duration, available nutrients from riverine runoff during winter and decomposition within the water column and sediments, and abundant oxygen coincide, follow Liebig's law of the nutrient of minimum supply, and last until nutrients are depleted, phytoplankton grazers consume them and / or summer water stratification establishes [37-38]. In contrast to spring phytoplankton regular "pulses", harmful algal "outbreaks" occur suddenly and unexpectedly, in all types of aquatic ecosystems, from polar through temperate to tropical waters, mainly in summer, when there is poor water mixing or else water stratification, involve most often single species with low abundance among primary producers but some of them in high densities within thin layers [39], are many orders of magnitude denser, decline suddenly, are of such density so as to negate consumer/grazing control, and induce localized vertical and benthic O_2 reduction from their *en mass* death, sinking, and deposition on benthos [40]. Their frequency and intensity were found unrelated with one another but independently related positively with nitrogen and negatively with oxygen levels, respectively, in shallow estuaries in Denmark [41] and reliant on reduced and organic forms of N along the coast of the east China Sea [42]. Oxygen concentration of waters at the interface with sediments affects O_2 and pH profiles within sediments as well as the type of mineralization taking place and its products; the upper oxic zone of sediments that receives little and relatively recent sediments promotes rapid mineralization of recently deposited organic matter and produces CO_2, NO_3^-, and PO_4^{-3} while the lower hypoxic and anoxic zones of sediments, which develop below accumulating and relatively older sediments, promote slow anaerobic mineralization of organic matter and produce N_2, NH_4^+, PO_4^{-3}, CH_4, and H_2S under redox, that is reduced pH, conditions [Figure 1 in [43]]. The oxygen available in overlaying benthic waters effectively "blocks" the diffusion of reduced forms of nutrients from the underlying stock of old sediments to overlaying waters and "locks" them permanently within sediments as they bond with metals, such as Fe, Mn, and Co, unless sediments are steered or / and these metals are exhausted; in such case, the reduced forms of nutrients in old stocks of sediments with no available metals to bond with are directly released into the water column and react with O_2. While O_2 concentrations between 2 and 0.2 mg/lt, which is the hypoxia range by convention, in waters overlaying sediments prevent macroscopic life from surviving in hypoxic zones, it is the complete lack of O_2 or else anoxia that gradually eliminates the upper "blocking" oxic zone within benthic sediments and, if there are no available metals, enables the direct release of NH_4^+, CH_4 and H_2S from old and large stocks of nutrients into the water column [36, 44, 45]. Establishment of anoxia leads to lateral and vertical migrations of the mobile fauna, suffocation of the sessile benthic epifauna and infauna, elimination of the oxic sediment zone, and establishment of anaerobic microbial communities, that release reduced forms of (gaseous) nutrients in the water column. Because the reduced forms of nutrients now released from benthos react with O_2 on their ascend to shallower depths in the water column, they not only retain / establish anoxia just above benthos, but also further reduce O_2 levels on their upward ascend to shallower depths, reduce the productive volume of the ecosystem, and effectively reverses the fundamental dependence of aquatic ecosystems on O_2 [46]. Apparently, such an aquatic ecosystem that has been forced to produce more via warming and fertilization also accumulates more organic matter on its benthos, undergoes from shrinkage to elimination of the oxic zone in its benthic sediments, and shifts its O_2 concentration profile in both its water column and its sediments toward lower concentrations. It is illuminating to find out whether the "biochemical detonation" of harmful algal blooms is associated with hypoxic / anoxic benthos by geo-relating harmful algal blooms (Harmful Algae Event -HAEDAT, http://haedat.iode.org) with anoxia (Global Ocean

Observing System-GOOS, http://www.goosocean.org) events and after correcting for hydrodynamic effects. Interestingly, nutrient inputs have decreased by 1/3 since the 1960’s at the second largest hypoxic / anoxic zone in the world, yet this has been expanding ever since [47] pointing to the propagation of algal blooms via a positive feedback loop with hypoxic / anoxic sediments. In addition, there have been documented higher N_2O concentration in upwelling waters off the west coast of India, which is one of the first, oldest, and largest documented coastal / oceanic hypoxic areas [48].

There is more diversity than unity in life traits of harmful and blooming algal species, including type, timing and duration of reproduction as well as diversity of feeding modes and habitat type [49], under the same warming and fertilization forcing [50], which belong to very different taxonomic groups; photosynthetic and N-fixing cyanobacteria in freshwaters and dinoflagellates and diatoms in marine waters. In particular, is it adaptations to increased levels of N and P macro-nutrient concentrations, that may also function as effective deterrents against grazers [51, 52] or is it lower demand for other limiting and stoichiometrically rarer micro-nutrient elements that enable “winner” harmful algal species due to the extented beyond C, N, and P elements net stoichiometric imbalance between anthropogenic inputs of a few nutrients (fossil fuels, fertilizers, sewage) for producers and anthropogenic outputs of all nutrients (fisheries / aquaculture biomass) from highest trophic levels or both? Are summer harmful algal blooms an extension of spring algal blooms with a suite of harmful species, that they too follow Liebig’s law of the minimum as water stratification becomes stronger, or are supported by a new flux of (reduced) nutrients emanating from hypoxic / anoxic waters and then ascending into waters above the compensation depth during disruptions or turnover of water stratification? As for C, it was found that dinoflagellate species that form harmful algal blooms not only show wider but also stronger positive response to increase in pCO_2 compared to either other groups of phytoplankton species that form harmful algal blooms or to dinoflagellate species that do not form harmful algal blooms in a meta-analysis of laboratory experiments of the effects of elevated pCO_2 and temperature under nutrients saturated environments [53]. Density records of calcifying, and thus fossilizable species of dinoflaggelates that form cysts, from relatively recent sediments (tens of years) of eutrophied coasts in Oslo fjords have showed that nutrients from fertilizers do not affect the density of those species that typically bloom in spring but rather increase the density of other species that bloom in summer; that sewage, in particular, favors heterotrophic species within this group; and that because summer species blooms may be disrupting trophodynamics of fish larvae, they are implicated in the commercial collapse of local fisheries (in [54]). Appreciable fisheries losses have also been identified in hypoxic areas that receive raw sewage effluent among all hypoxic areas reviewed [55]. Global wild fish catches have stabilized since the 1990’s according to official records [12] or have started declining according to recent corrected catch records [56] or have been halved [57]; undergone intensively debated changes in species and sizes composition ever since 1950’s [58]; already exported 90% of the biomass of the highest trophic levels to land [59] instead of recycling it. The recovery of commercially collapsed fish stocks necessitates that this recovery does not coincide with strong environmental forcing [60]. Such strong environmental forcing may very well include that fish do not find the food they need either because of ongoing warming induced shifts in phenology [61-62], and thus density of their food, since detonating blooms with almost always dominant algal species form all the more often in ecosystems finite in nutrients and oxygen. Coasts and continental shelves exhibit the highest fisheries productivity rates per unit of area and oceans the highest production due to their size (trophic pathway) compared to all other types of aquatic ecosystems [63]. Coasts and continental shelves tend now to accumulate more fisheries biomass at shallower depths and more sediments on their reduced O_2 / hypoxic / anoxic benthos while oceans show a shift in the Redfield ratio of the “average” phytoplankton from C : N : P = 106 : 16 : 1 to a Redfield ratio of the “median” of particulate organic matter to C : N : P = 163 : 22 : 1 during the last 90 years, which is largely correlated with reduction in nutrients [64]. A recent explanation integrates species size, tissue stoichiometry, and growth rate in an attempt to explain shifts toward primary producers of different sizes in aquatic ecosystems with (harmful) algal blooms [65]; larger sizes of phytoplankton or/and increased ratio of carbon to a limiting nutrient increase the rate of “sinking” of phytoplakton toward sediments; however, cyanobacteria and dinoflaggelates, that form harmful algal blooms vary four orders of magnitude and there are also other organisms that form massive blooms, such as an asexual macrophyte *Sargassum* sp. all over the Caribbean basin [66] after already a number of ocean Fe^{+3} fertilization experiments have taken place [67]. On the other hand, explanations of the recurrent box jelly fish blooms and increasing abundance in the majority of large marine ecosystems around the world [68] and of the corallivorous starfish *Acanthaster planci* infestations on coral reefs of the IndoPacific since the 1980's still revolve around eutrophication induced increase in larval survival of *A.planci* and cascading trophic effects of overfishing [69]. Ecosystem transitions through alternate states under directional environmental forcing involve directional changes in primary producers, species composition of trophic and detrital food webs, and the allocation of ecosystem energy between the trophic and the detrital pathways through loss in ecosystem resilience, which is defined as the ability of an ecosystem to bounce back after disturbance. For example, the directional forcing of eutrophication and overfishing is forcing micro-algae-symbiosis-dependent and coral-engineered tropical coral reefs, through the macro-algal dominated algal state, into slime-dominated coral rubble reefs (*e.g.* [70]). However, unlike natural acute disturbances that maintain high biodiversity at intermediate levels of frequency and/or intensity [71-72], chronic warming, eutrophication and overfishing are entangling aquatic ecosystems into a downward vortex of ecosystem transitions and transformations. The rate of transition from an alternate state to another increases because contemporary environmental forcing is getting stronger while successive states are progressively less resilient. In other words, hypoxic / anoxic areas expansion is faster than water collumn eutrophication expansion in coastal ecosystems because eutrophied aquatic ecosystems today are less resilient and because many stressors are interacting. Because it is species that fast move the biogeochemical cycles in ecosystems, we can attempt to assess the direction and magnitude of our change of the biogeochemical cycles within an aquatic ecosystem by aligning the extended, that is beyond C, N, and P, elemental stoichiometry of our inputs, of water and sediments media, of the trophic and the detrital food webs, and of single producer, consumer and mineralizing organisms (*e.g.* [73-75]); this alignment determines elemental budgets and flows within and among the interdependent production, consumption and mineralization compartments of an aquatic ecosystem; core zones inside protected areas are our (not pristine but) best available reference systems/sites; the Integrated Long Term Ecological Research (ILTER, https://www.ilter.network/) and the International Group for Marine Ecological Time Series (IGMETS, http://igmets.net/) networks of research programs and sites are our broadest and most relevant platforms. In this way, we will be able to link elemental stoichiometry ratios with rates of productivity, consumption and mineralization in different types of aquatic ecosystems that do not develop unwanted and unintended symptoms of pathology; such a suite of rates can provide direction for the active management of watersheds and aquatic ecosystems with such symptoms [76]. No alternate / transformed ecosystem state, nevertheless, may be considered stable or expected to stabilize since the directional forcing that led to its successive transformation states is aggravating; the longer aquatic ecosystems are forced, the more they will be getting transformed. Along this downward trajectory, transformed aquatic ecosystems at alternate states, including those with anoxic sediments, provide different goods and services to societies. When oligotrophic lakes turn into eutrophic, we select for (fisheries) production and against water purification services. When full of oxygen, eutrophic coastal zones turn into hypoxic / anoxic eutrophied systems, we select against (fisheries) production and for detrital decomposition. Harmful algal blooms stand out as one more symptom of the progressing pathology of natural resources due to overemphasis on ecosystem production processes at the expense of ecosystem resilience based on structural and functional integrity ([77]; Regime shifts database, http://www.regimeshifts.org/), which requires spatially (among ecosystem compartments/zones) and temporally (days, months, years, decades) co-ordinated rates of ecosystem production, consumption, and mineralization within all compartments of an aquatic ecosystem; we do expect these to differ among and within different zones and different types of aquatic ecosystems but cannot afford / accept to be out of tune given contemporary human population size. Already mobilized N, and P trapped in the atmosphere and inside aquatic ecosystems will not get back to their large size, and long time accumulating stocks any time soon given their turn over rates. Reversal of such a succession of transformed states for warming and eutrophied aquatic ecosystems cannot but beg to address the root causes of such forcing so as to timely disentangle from unintended warming and fertilization ecosystem pathologies [78-80].

4. INDUCING THE FALL IN ALGAL BLOOMS – PUTTING BACK THE BIOGEOCHEMICAL CYCLES INTO THEIR PLACE

There are a handful of approaches recommended for dealing with such alterations in structure and function of aquatic ecosystems. One of them revolves around adaptive management by viewing progressive alteration as an opportunity to monitor, experiment, and poke into irreducible, incomprehensible, and uncertain complexity [81]. Another one revolves around increase in resilience by focusing on keystone structuring processes at multiple scales, sources of renewal and reformation, and on multiple sources of capital and skills [82-84] although it has been largely advocated through reducing the strength of anthropogenic forcing other than climatic anomaly. A third approach uses multidisciplinarity for choice and decision types of problems to collapse complexity [85], systems dynamic modeling analytic tools to avoid counter-intuitive unintended consequences [86], and system levers of differential power / effect [87] to appropriately intervene into the system of interest. Disentanglement from the "greenhouse" and the "fertilization" downward reinforcing requires evolution in system structure for resilience (lever 4: self-re-organization), which corresponds to a different source / stock of energy and a different flow of materials from linear to cyclical.

Since algal blooms is a phenomenon emanating from choices on how to obtain energy, fertilize, and dispose our waste, its system of occurrence and of our intervention is a socio-ecological system, which consists of ecological, social and economic components, whose behavior is explained with panarchy theory [88-89]. The first, most robust, and most popularized attempt to model the behavior of our global socio-ecological system in the 1970's provided an early warning forthsight of an irreversible and, after some point, beyond our control collapse, which can be grossly translated within the context of this work as massive human kills, due to the interaction of accumulating pollution from all sources and human overpopulation assuming no change in our fossil-based sources of energy and our linear flow of materials [90-91]. Comparison of the actual system behavior with the simulated behavior confirms that, regardless of all best intentions and actions, we still remain on the same trajectory [92]; in fact, four of the nine planetary boundaries, including those of temperature, nitrogen, and phosphorus, have already been crossed [93]. A derivative model of this first exemplary attempt to adequately simplify so as to better understand the behavior of our global socio-ecological system, nevertheless, hind sighted that driving off this beaten path of an irreversible collapse requires simultaneous and without delay demographic transition through improvement in living standards for over populous nations, 100% substitution of fossil with renewable sources of energy, and a 70% recycling rate of materials [94]. Our exponentially increasing and highly advanced conceptual, analytic, connectivity, organizational, decision making, and streamlining capabilities developed ever since the industrial revolution [95-96] and our historic experience or "memory" in dealing with pollution, *e.g.* refilling of the ozone layer above the Antarctic, eliminating acid rain in boreal forests, are perfectly able to now turn around decline toward crossing planetary boundaries into impulse for the appropriate systemic changes in the way we obtain our energy and use our materials to timely fend off from such limits.

Simultaneous and without delay self-re-organizational response requires freedom / peace to choose own alternatives, data veracity, and "alignment of the stars" type of organization [Figures 13.2 13.3 in [97]] for collaborative [98], trans-disciplinary (values, policy, economy, technology, management), and bi-directional flow [99-100] across the hierarchical levels of a socio-ecological system, be it the globe, a nation or a watershed. Also, direct coupling of the unwanted exponential increases (*e.g.* CO_2 and nutrient accumulations-cause) with the unwanted exponential declines (*e.g.* ecosystem degradation-effect) provides for efficiency and non-bouncing back rates of change. For example, instead of paying to be allowed to pollute/degrade aquatic ecosystems through pollution charges, penalties, or even trading-off pollution, while exceeding threshold limits that are getting continuously lower because of synergies among pollution agents and accelerating development trends using fossil-based and incomplete recycling technologies, the same payments could be used to replace the fossil-based and incomplete recycling technologies with renewable sources of energy and complete, that is whole life cycle, recycling technologies; such incentives' structure not only align but also bring in synergy the environmentally benign, socially acceptable, and economically feasible goals of the new development paradigm of sustainability [101]. In addition, prudent evolution of the structure of a socio-ecological system not only caters for the elimination of currently unwanted and exacerbating phenomena, such as harmful algal blooms, but also caters for the avoidance of future unwanted and unintended pollution phenomena emanating from new but comparable choices made today, such as (novel) synthetic bio- and nano- entities. In this way, a new safe basin of attraction or "lighthouse" for our socio-ecological system stands out. Finally, alignment and congruence of the "who", "what", "when", "where", and "how" of embedded projects within programs within strategies to replace the fossil-based sources of energy and restore the biogeochemical flows ensures that this envisioned and attainable basin of attraction is not getting displaced in the long run.

5. CONCLUSION

Using the system's approach, this synthesis prompts the reader to position ubiquitous algal blooms within a gradient of progressive transformation in aquatic ecosystems ever since pre-industrial times driven primarily by the forcing of interacting warming, fertilization, and overfishing; evaluate contemporary rates of this change since the 1950's as these are reflected in aquatic ecosystems transformation extent and rate; ponder on the interventions required to disentangle from this degenerative for our life supporting systems forcing; and proposes the following critical research links:

1. To verify the causal mechanisms that generate harmful algal blooms and busts, employ research designs and analytic methods that compare and contrast sites with and without, before and after algal blooms.

2. To establish the involvement of hypoxia / anoxia in the generation of harmful algal blooms, geo-relate the global databases of harmful algal blooms and O_2 concentration.

3. To decipher elemental deficiency in waters of aquatic ecosystems, compare and contrast the extended beyond C, N, and P stoichiometry of spring algal blooming and summer algal blooming species.

4. To appreciate the direction and magnitude of deviation of aquatic ecosystems' stoichiometry, compare and contrast the rates and stoichiometry of input, production, consumption, re-mineralization, storage, and export rates within different zones of the same type of aquatic ecosystem and between different types of aquatic ecosystems under different intensity of anthropogenic pressure with comparable and equivalent core zones in protected areas.

5. To expedite "disentanglement" from warming and fertilization forcing through self-re-organization, use panarchical organization and to avoid unintended consequences use dynamic systems modeling.

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