Cladophora in the Great Lakes: Guidance for Water Quality Managers

State of the Ecosystem

Cladophora is a native, filamentous, green alga that is found attached to solid substrate in all of the Laurentian Great Lakes (Figure 1). The alga grows sparsely in a few locations in Lake Superior (Jackson et al. 1990), is typically associated with tributary and point source phosphorus inputs in Lake Huron (Auer et al. 1982) and occurs as widespread blooms in the comparatively phosphorus-rich waters of Lakes Erie (Higgins et al. 2005a), Michigan (Greb et al. 2004) and Ontario (Wilson et al. 2006). While *Cladophora* can successfully colonize offshore reefs where supported by whole-lake nutrient conditions, it is the nuisance growths observed in nearshore regions of Lakes Erie, Michigan and Ontario (Figure 2) that have drawn the attention of those involved in public recreation, operation of utilities and water quality management. Public awareness of the problem has been heightened by reports in the popular press of beach fouling and the shutdown of nuclear power plants, concerns that incidences of avian botulism are linked to *Cladophora*, (New York Sea Grant and Pennsylvania Sea Grant 2001) and scientific studies linking *Cladophora* and human pathogens (Byappanahalli et al. 2003; Ishii et al. 2006; Olapade et al. 2006; Englebert et al. 2008). Nuisance growth of *Cladophora*, with attendant beach accumulation, will demand the attention of those re-writing the Great Lakes Water Quality Agreement (GLWQA) because the negative effects of the phenomenon are manifested in a manner and at locations that influence public perception of water quality.

The Historical Context

Cladophora has been known to the Great Lakes scientific community for over 150 years, with nuisance conditions noted as far back as the mid-20th century (Taft and Kishler 1973). Regulatory and research interest became more focused with the publication, in the mid-1970s, of an International Joint Commission (IJC) report entitled, "*Cladophora* in the Great Lakes" (Shear and Konasewich 1975). Although the 1978 GLWQA specifically referenced nuisance algae problems and excessive *Cladophora* growth was identified as an emerging issue (Task Group III), it was concluded that there was insufficient scientific information available to develop effective control strategies (Vallentyne and Thomas 1978).

Following publication of the IJC report, the U.S. Environmental Protection Agency and the Ontario Ministry of the Environment supported a series of scientific and modeling initiatives, seeking to develop a more complete scientific understanding of the *Cladophora* problem. The results of these and other studies were presented in a special issue of the *Journal of Great Lakes Research* devoted to the ecology of filamentous algae (Auer 1982). It was the general sense of this body of work that the phosphorus management strategies being implemented under the GLWQA could lead to the control of nuisance conditions.

There is evidence that phosphorus control strategies have played a role in reducing nuisance conditions of *Cladophora* growth. Canale and Auer (1982a) reported a dramatic local decline in *Cladophora* biomass following implementation of phosphorus removal at a wastewater treatment facility at Harbor Beach, Michigan on Lake Huron. The work of Painter and Kamaitis (1987) strongly suggests that phosphorus abatement efforts had a marked effect on *Cladophora* in Lake Ontario. They reported that, between 1972 and 1982-83, *Cladophora* biomass and *Cladophora* tissue (stored) phosphorus levels declined almost 60% in response to a 67% reduction in spring soluble reactive phosphorus concentrations. Levels of *Cladophora* biomass observed in 1982-83 were generally at or below the threshold for nuisance conditions (<50 gDW·m^{-2}; cf. Canale and Auer 1982a). If one considers these few reports as representative of the post-phosphorus abatement, pre-dreissenid period, it can be concluded that the management strategies mandated under the GLWQA achieved the desired effect (cf. Neilson et al. 1995). Interest in *Cladophora*, as evidenced in the publication record of the *Journal of Great Lakes Research*, began to decline in the mid-1980s and the issue of nuisance growths received little attention through the balance of the 20th Century.

Resurgence?

A suite of papers recently published in the *Journal of Great Lakes Research* (Higgins et al. 2005a, 2005b, 2006) and a workshop convened at the Great Lakes Water Institute of the University of Wisconsin – Milwaukee (Bootsma et al. 2004a) have signaled a rekindling of attention to the topic of nuisance *Cladophora* growth. It is not clear to what degree renewed interest reflects a true resurgence of the problem as the relative dearth of data makes it difficult to compare the magnitude of past *Cladophora* problems with those reported currently (Young and Berges 2004). No systematic, basinwide surveys of *Cladophora* distribution and biomass were made during the period of peak interest and little is known about nearshore phosphorus levels or *Cladophora* colonization over the period of declining attention (Higgins et al. 2005a).

It is clear, however, that nuisance growth of Cladophora is a significant water quality problem as we move into the 21st Century. Over the period 1995-2002 (an interval following dreissenid establishment), the Ontario Ministry of the Environment supported a series of surveillance investigations into shoreline fouling by *Cladophora* in Lake Erie where nuisance blooms were a regular occurrence. Survey results, published by Higgins et al. (2005a), indicate that *Cladophora* colonizes nearly 100% of the available substrate along the north shore of Lake Erie and that abundance (standing crop) reaches levels equivalent to those of the 'nuisance growth' period of the 1970s. The Ontario Water Works Research Consortium initiated studies of the occurrence of *Cladophora* in western Lake Ontario in 2002. In late summer (a sub-optimal period) of 2003, *Cladophora* coverage at a 5m depth at 25 locations along the lake's north shore averaged 57% and attained a greater substrate coverage than in similar surveys in 1981 and 1991 (Wilson et al. 2006). Anecdotal evidence for Lake Michigan suggests an increase in *Cladophora* biomass in recent years (Greb et al. 2004) with a noticeable increase in the number of incidents of beach fouling along the Lake Michigan shoreline (Bootsma et al. 2004b). Today, *Cladophora* is abundant along Wisconsin's entire Lake Michigan shoreline with colonization exceeding 80% in areas of suitable substrate (Greb et al. 2004) and with nuisance levels of standing crop (200-400 $gDW \cdot m^{-2}$; Bootsma et al. 2004b).

The high *Cladophora* abundance in these lakes is somewhat paradoxical in light of the fact that concentrations of dissolved phosphorus in the pelagic zones have been declining and, with the exception of Lake Erie, are below the target levels set by the Great Lakes Water Quality Agreement (Barbiero et al. 2002; Dolan and McGunagle 2005). This, along with observations of extensive *Cladophora* coverage in regions that are relatively remote from point nutrient sources (e.g. Greb et al. 2004), suggests that there have been fundamental changes in how nutrients and energy move through these large ecosystems. These changes may also be reflected in other recent trends, including the decline in plankton abundance in Lakes Huron and Michigan (Environment Canada and USEPA 2007), declines in the benthic amphipod *Diporeia* spp. (Nalepa et al. 2005), changes in the condition of lake whitefish and salmonids (Schneeberger et al. 2005; Claramunt et al. 2007), decimation of the yellow perch population (Marsden and Robillard 2004), and increased prevalence of Type E botulism in fish and birds. Causes of these various trends require further exploration, but there are plausible mechanisms by which they may be connected (e.g. Hecky et al. 2004). For example, consumption of plankton by dreissenids may promote *Cladophora* growth by increasing water clarity and nutrient supply in the nearshore zone, while at the same time depleting pelagic food resources. Therefore the problem of excessive *Cladophora* growth should not be considered in isolation, but within the larger ecosystem context. While excessive *Cladophora* growth is a problem in itself, it may reflect ecosystem changes that have larger ecological and economic consequences.

Pressures

How Does Your Garden Grow?

Like other aquatic and terrestrial plants, *Cladophora* requires a suite of inorganic nutrients to support growth and flourishes over a particular range of temperature and light conditions. There is consensus that phosphorus is the growth-limiting nutrient for *Cladophora* in the Great Lakes (see Higgins et al. 2008 for a review) and phosphorus has been and remains the appropriate target for management actions. Where SRP levels meet the growth requirement lakewide, nuisance conditions may be observed wherever solid substrate is present, extending to depths where light availability limits growth. Lakewide support of *Cladophora* growth occurs in Lakes Erie, Michigan and Ontario (as described above) and management of nuisance growth will require attention to whole lake phosphorus levels. In cases where SRP levels do not meet the growth requirement lakewide, nuisance conditions occur in the vicinity of point sources of nutrients, with the extent of colonization being limited by phosphorus availability (dilution by whole lake waters) or the light environment (with increasing depth offshore). As with some other algae, Cladophora has the capacity to store phosphorus beyond its immediate needs (Auer and Canale 1982a). Exposure to transient sources of phosphorus (e.g. plume migration and runoff events) for less than one day can provide sufficient phosphorus to support a ten-fold increase in biomass (Auer and Canale 1982b). It should also be noted that mixed conditions occur where a site is impacted by both whole lake and point source conditions. Managers should bear this in mind when evaluating the impact of controlling one source of phosphorus or the other. The case of nuisance *Cladophora* growth in the Lake Michigan nearshore may provide an example of such a case.

The response of *Cladophora* growth to phosphorus availability is non-linear, an occurrence which has importance when developing expectations for the outcome of nutrient management programs. The growth rate of *Cladophora* increases in a linear fashion as the amount of stored phosphorus increases from its minimum value, then becomes less sensitive to additional increase in available phosphorus and eventually reaches an asymptote (Figure 3). From a management perspective, this figure should be examined from the opposite direction, i.e. high levels of phosphorus availability. Where *Cladophora* growth is supported by whole-lake nutrient levels, initial reductions in available phosphorus may not yield a striking response because the system remains within the P-saturated region of the curve. Subsequent reductions, however, will place the system within the linear region where changes in *Cladophora* growth will track changes in phosphorus loading.

Given an adequate supply of nutrients, *Cladophora* growth is governed by conditions of light and temperature. The alga grows most rapidly in late spring and early summer (May-June in Lake Huron) when water temperatures are in the optimum range (13-17 °C; Graham et al. 1982). The mid-summer sloughing period (Canale and Auer 1982b, Higgins et al. (2005a), where *Cladophora* detaches from the substrate and accumulates on beaches, occurs as temperatures reach 22-24 °C (July-August in Lake Huron). However, no experimentally-verified relationship between sloughing and temperature has been developed, and the mechanisms responsible for sloughing remain poorly understood (cf. Higgins et al. 2008). Light availability determines the depth to which *Cladophora* may colonize substrate at a particular site. An important metric in this regard is the compensation point, i.e. the light intensity above which net growth is positive. Graham et al. (1982) determined that this critical light intensity lies between 25 and 35 μE·m-2·s-1 for temperatures ranging from 5-20 °C. Assuming an incident light intensity of 1000 μE·m-2·s-1 and a light extinction coefficient representative of pre-dreissenid conditions (e.g. 0.46 m-1 for Lake Ontario; Auer et al. 2008), the maximum depth of colonization by *Cladophora* would be on the order of 8 m, with optimal light intensities occurring in shallower waters (1.5-3.0 m). The significance of these growth mediating environmental conditions as influenced through nutrient enrichment and ecosystem changes with respect to light penetration is discussed below.

Management Implications

Modeling Support for Management

The critical role of mathematical modeling in providing support for water quality management is now widely recognized. A build and measure approach, where remedial actions are implemented and assessed iteratively without guidance from model projections, has been largely rejected. This is especially the case for large lake ecosystems where high costs and long response times can lead to significant socioeconomic burdens. For example, phosphorus control measures mandated by the GLWQA benefited from rigorous model testing before implementation.

The first model for Great Lakes *Cladophora* was developed by Canale and Auer (1982b; and accompanying papers). More recently, two modeling tools (CGM, the *Cladophora* Growth Model (Higgins et al. 2005) and GLCM, the Great Lakes *Cladophora* Model (Tomlinson et al. 2008)) have been developed by expanding on and revising that framework. The CGM was applied to Lakes Erie (Higgins et al. 2005b) and Ontario (Malkin et al. 2008) and the GLCM to Lakes Huron and Michigan (Tomlinson et al. 2008). CGM and GLCM developers joined forces in a bi-national effort to examine the impacts of phosphorus management and ecosystem changes associated with the proliferation of dreissenids (Auer et al. 2008; discussed below).

Models for *Cladophora* in the Great Lakes are based on the principle of mass balance, a concept which may be likened to a checking account, i.e. the rate of change in the account balance is equal to inputs from deposits less outputs to checks written plus or minus changes due to ‘reaction’ such as interest or fees for bad checks. In its application to *Cladophora* (Figure 4) the mass balance includes inputs (or gains) due to growth, outputs (or losses) due to respiration and a loss ‘reaction’ associated with physical detachment (sloughing). The mass balance itself is straightforward; however, characterization and quantification of the factors mediating the input, output and reaction terms (e.g. the roles of light, temperature and nutrients) must be well supported by science. While it may seem that the more comprehensive (i.e. complex) a model becomes, the better it represents nature, adding complexity without appropriate scientific support leads to a decline in model reliability (Figure 5), an important concern in management applications. The art in modeling (and perhaps in managing) is to select an approach that resides at the optimum position on the complexity-reliability continuum.

Not Your Mother’s Ecosystem

Research efforts in the 1980s and 1990s made it clear that the distribution and abundance of *Cladophora* was governed by phosphorus availability (Auer and Canale 1982a,b; Painter and Kamaitis 1987) and the underwater light climate (Graham et al. 1982; Lorenz et al. 1991). It has been concluded from hindcast modeling (Auer et al. 2008) that phosphorus loading reduction mandated under the GLWQA achieved the desired effect with respect to nuisance conditions. It is also clear, however, that nuisance *Cladophora* growth has today reclaimed its position as a serious water quality problem in the Great Lakes. Scientists familiar with the ecology of *Cladophora* have recognized that changes in the Great Lakes associated with the dreissenid invasion could have profound (Lowe and Pillsbury 1995; Higgins et al. 2005a, 2005b) and previously unrecognized (Hecky et al. 2004; Higgins et al. 2008) effects. Dreissenid mussels can potentially impact *Cladophora* growth by providing substrate for attachment

(Wilson et al. 2006), altering pathways of phosphorus cycling (Hecky et al. 2004) and modifying the underwater light climate (Holland 1993; Howell et al. 1996; Auer et al. 2008).

With respect to alteration of the underwater light climate, the case is undeniable. Auer et al. (2008) estimated that, following the establishment of dreissenids, the average light attenuation coefficient for Lakes Erie, Michigan and Ontario dropped from 0.46 to 0.29 per meter, extending the depth to which *Cladophora* could colonize substrate by 6m. Model calculations indicated a corresponding increase in *Cladophora* growth potential of ~50%, an amount sufficient to significantly offset reductions in growth potential achieved previously through management of phosphorus loads.

A second effect, alteration of pathways for phosphorus cycling, remains an intriguing, but unproven hypothesis. The underlying premise is that filtration of the water column by mussels, with subsequent excretion of soluble phosphorus (the nearshore phosphorus shunt, Hecky et al. 2004) would provide a source of phosphorus for *Cladophora* that was previously unavailable. The hypothesis is intellectually satisfying because mussels have the potential to capture and recycle particulate inorganic phosphorus originating from nearshore sources that would historically have been transported to offshore depositional sites before being solubilized and made available to the algae. Further, mussels capture and recycle particulate organic phosphorus in the form of phytoplankton, an activity which may promote *Cladophora* growth by increasing dissolved P availability (Heath et al. 1995; Arnott and Vanni 1996) while eliminating a competitor for those resources.

Into the 21st Century

Managers seeking to control the nuisance growth of *Cladophora* will encounter a Great Lakes ecosystem profoundly changed by the proliferation of dreissenids. A bi-national modeling study (Auer et al. 2008) concluded that gains made through phosphorus loading reduction have been offset by dreissenid-driven changes in water clarity that extended the depth of colonization of *Cladophora*, increasing total production. Attendant impacts relating to dreissenid mediation of phosphorus cycling have not been isolated and identified. Barring a dramatic reduction in mussel abundance, it is unlikely that the Great Lakes light environment will return to pre-dreissenid conditions. This leaves the management of nearshore phosphorus levels as the only means of addressing the conditions of nuisance *Cladophora* growth presently experienced in Great Lakes waters. That management effort will require an integrated program of scientific study, mathematical modeling and field monitoring to establish targets for phosphorus control and to assess the efficacy of remedial measures. Such a program would also inform other management decisions not directly related to *Cladophora*. For example, an improved understanding of phosphorus and carbon exchange between the pelagic and nearshore zones will provide insight into how plankton consumption by dreissenids may affect food supply for pelagic and nearshore fish communities.

Hindcast Assessment

No systematic, comprehensive, basinwide monitoring programs for *Cladophora* have ever been implemented. Our knowledge of the extent and magnitude of the *Cladophora* problem consists of observations by individual investigators at isolated sites and regional surveys conducted by state and provincial authorities for limited periods. Because of this, scientists exploring the apparent resurgence of *Cladophora* cannot confidently state that conditions have truly worsened, only that nuisance conditions are occurring at present (cf. Auer et al. 2008). It would be prudent, as a prelude to development and implementation of new phosphorus management strategies, to utilize archival remote sensing data (see below) and hindcast modeling to properly characterize the development of today's conditions.

Supporting Science

Development of a management plan for *Cladophora* in the Great Lakes nearshore will be guided by model simulations, testing the system response to changes in phosphorus loads. The current models incorporate a framework linking external phosphorus loads to the ambient nutrient concentration to which the alga is exposed (Figure 6). That framework is no longer complete in its description of those linkages. Scientific studies will be required to describe the role of the nearshore shunt in mediating phosphorus dynamics, identifying and quantifying pathways that have evolved with the advent of dreissenid populations. This new framework should accommodate the transformation of in-lake (i.e. phytoplankton) and watershed (i.e. terrigenous) particulate P to SRP (dashed lines in Figure 6) and the dynamics of *Cladophora* utilization of that phosphorus (ambient SRP → P stored in the alga) in the post-dreissenid ecosystem.

In addition to science that directly supports *Cladophora* models, there is a need for research that addresses eco-dynamics in nearshore zones supporting large amounts of benthic algae biomass. This growth sequesters a significant amount of phosphorus and produces large amounts of organic carbon, but the fate of these materials is unknown. Critical questions include the contribution of this carbon and phosphorus to the nearshore food web, and the effect of decomposing algae on dissolved oxygen and redox conditions in the nearshore benthos.

Modeling

The *Cladophora* models currently available to the management community (CGM and GLCM) compare favorably with those routinely applied in simulating nutrient-phytoplankton dynamics in offshore waters. The nature of the *Cladophora* issue requires that only a single species be addressed, making a rigorous characterization of the alga's physiology more tractable (although recent outbreaks of other filamentous algae, such as *Lyngbya* sp., in Lake Erie may eventually expand the need for physiological and ecological studies). The reliability of *Cladophora* models for management applications would benefit from additional consideration of sloughing mechanisms and from further testing of model capabilities in simulating the response to the light environment in the post-dreissenid era.

The true challenge from a modeling perspective is to place the subroutines describing phosphorus kinetics within the context of a nearshore phosphorus model. Here, the model would simulate ambient SRP conditions by accommodating TP loads, cycling of particulate P through the dreissenid shunt, uptake of SRP and horizontal and vertical transport. The only extant example of such an application is that of Canale and Auer (1982b) for a site on Lake Huron, however this framework does not include cycling by dreissenids and the treatment of mass transport would be considered quite simple by today's standards. It will be necessary to integrate models for *Cladophora* growth with newly-developed information on phosphorus cycling and couple these with a nearshore hydrodynamic (mass transport) model.

Monitoring

Efforts to manage nuisance growth of *Cladophora* through phosphorus management must be supported by a comprehensive and systematic monitoring program, documenting biological, chemical and physical conditions over a statistically-defined grid in time and space. The appropriate metric for assessing the status of the *Cladophora* problem is annual biomass production, as it is this that determines the quantity of algae available for transport to the extreme nearshore, fouling beaches and clogging water intakes. It is infeasible to measure production directly; however, it may be estimated as the product of the alga's areal coverage, its biomass density and its growth rate (~ phosphorus status).

It is believed that extension of areal coverage to new habit has occurred in response to dreissenid-induced increases in transparency. Reductions in ambient phosphorus levels, resulting from newly-implemented management programs, will stress *Cladophora* populations colonizing substrate at the lower limits of available light, leading to a reduction in areal coverage. Areal coverage may be effectively monitored through remote sensing using established (Figure 7a; cf. Lekan and Coney 1982) and emerging technologies (Figure 7b; NASA 2008).

Monitoring biomass density, in a manner similar to that for chlorophyll in pelagic habitats, has historically been a favored metric for assessing the status of *Cladophora* populations. Biomass density presents particular challenges with respect to *Cladophora*, however, because substrate is irregularly colonized (sand/silt patch, uncolonized solid substrates) and because the stochastic sloughing phenomenon uncouples standing crop from production. These challenges may be overcome by expanding the space and time scale of the monitoring program but this is logistically prohibitive. Benthic sampling often requires SCUBA, which is technically more demanding and time-consuming than conventional water quality sampling with bottles deployed from a research vessel. The most promising avenue in this regard may be evolving remote sensing technologies that can quantify biomass as well as areal coverage.

Phosphorus status may be one of the most powerful metrics for assessing the status of *Cladophora* as the relationship between stored P and growth (and thus production) is well defined. Because the alga has the capability to accumulate phosphorus beyond its present needs, stored phosphorus levels provide an integrated picture of the ambient SRP environment (information not available from grab samples of ambient SRP). This approach was successfully used to assess the response of *Cladophora* to phosphorus controls in Lake Ontario (Painter and Kamaitis 1987). Monitoring of stored P also offers advantages logistically as the required level of sampling intensity is more tractable. However, it is important that irradiance is also monitored, as light availability alters the relationship between ambient dissolved P and *Cladophora* phosphorus status (Bootsma et al. 2004b).

Summary

Cladophora is a filamentous alga that grows attached to solid substrate in nearshore waters and on offshore reefs in the Great Lakes. Where phosphorus resources are sufficient, the alga can grow to nuisance proportions, fouling beaches and clogging water intakes. It is believed that phosphorus management efforts implemented in the latter decades of the 20th Century were successful in reducing the frequency of nuisance conditions. Changes in the underwater light climate, occurring in response to colonization by dreissenids, permitted *Cladophora* to expand its range and increase overall production to levels that resulted in significant beach accumulation and problems with water intake structures.

Management of the apparent resurgence in *Cladophora* growth will appropriately focus on further reductions in ambient levels of soluble reactive phosphorus. The identification of target loads for phosphorus should be guided by mathematical models of *Cladophora* growth. It will be necessary to couple those models with simulations of nearshore phosphorus dynamics, taking into account the role of dreissenids in mediating phosphorus cycling. Emerging remote sensing technologies and on-site measurements of the stored phosphorus content of the alga hold promise as a means of assessing the response of *Cladophora* populations to management actions.

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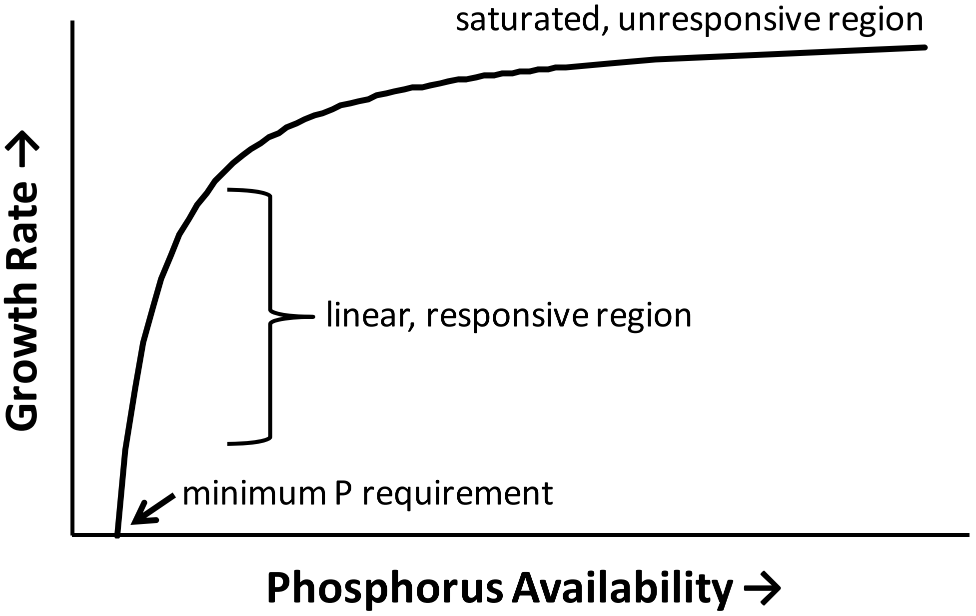

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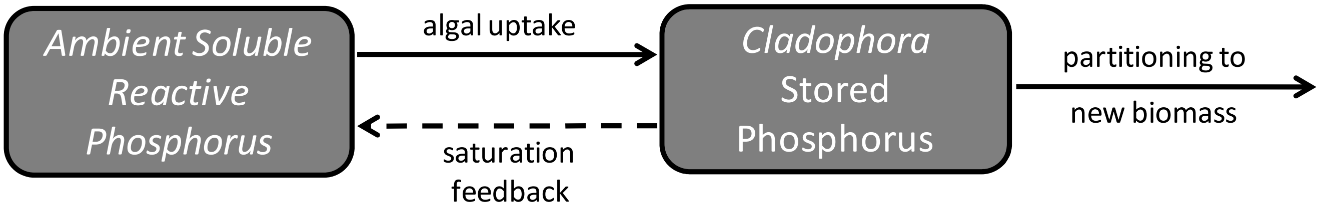

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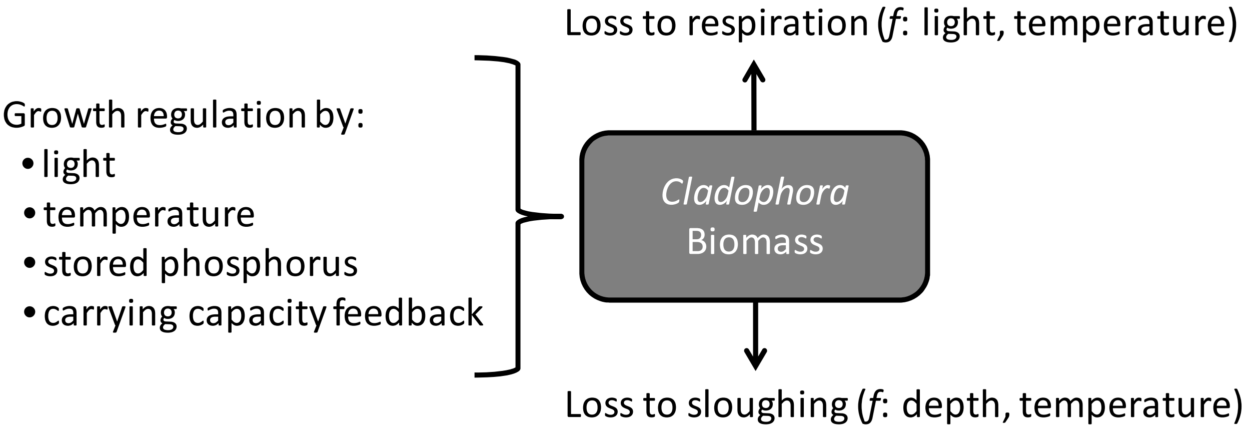

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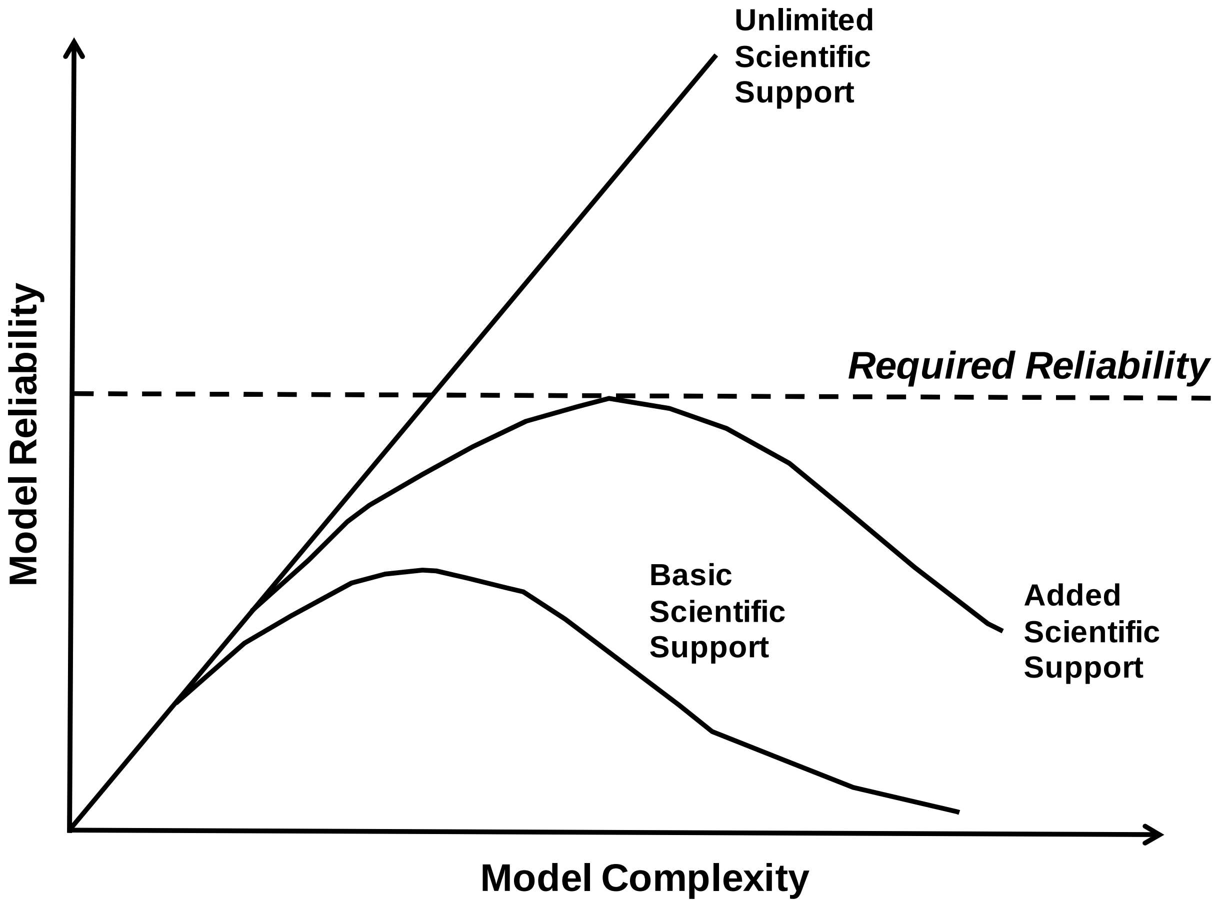

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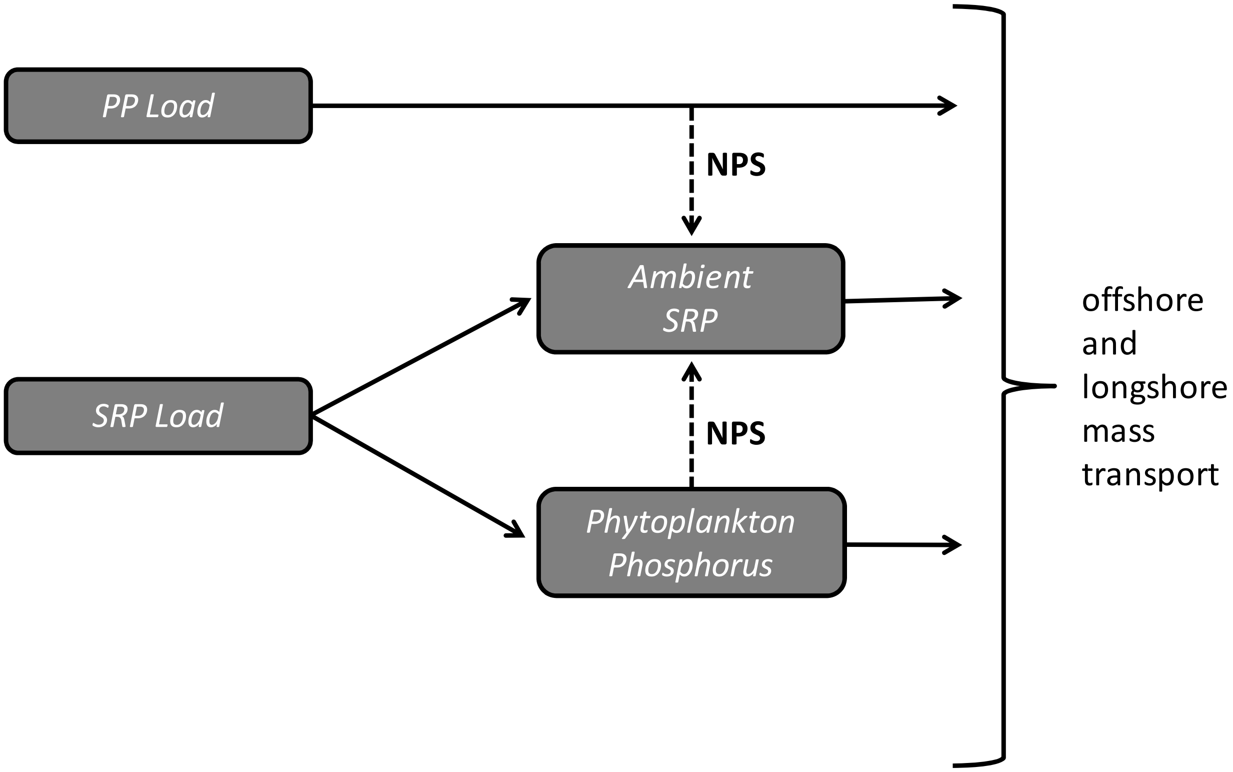

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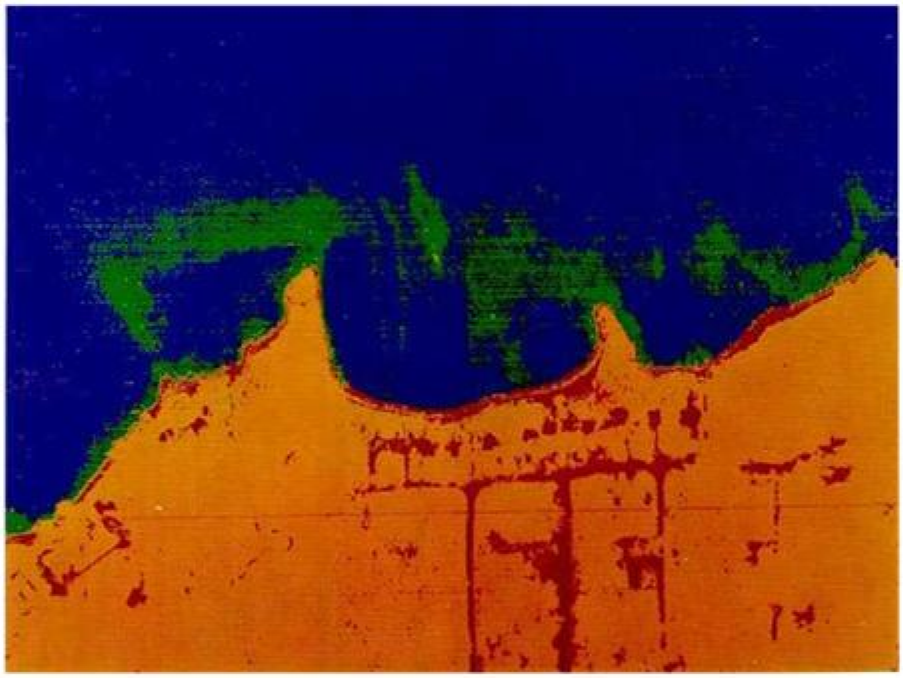

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