SolarBee®

Circulating the World's Water

Paradigm shift for blue-green algae control through long-distance circulation:

Empirical experience with SolarBee® circulation since 2000

White Paper

Updated July 20, 2009

Photographs depicting lake water quality before and after long-distance circulation

Preface

The following memo summarizes our experience regarding the ecological relationships in lakes, ponds and reservoirs associated with the control of blue-green algae (cyanobacteria) blooms through SolarBee circulation. There are now over 300 such water bodies benefiting from SolarBee circulation. Our experience and knowledge continues to increase greatly, and we have strengthened considerably both the scientific and empirical support for the ecological relationships described below.

These relationships reveal a conceptually new paradigm for eutrophication control. Rather than trying to limit overall algal growth through reductions in nutrient availability (primarily phosphorus), SolarBee-induced long-distance circulation (LDC) prevents harmful algal blooms (HABs), primarily blue-green algae in freshwater and dinoflagellates in saltwater, through habitat disturbance. This form of bio-manipulation selects against HABs while favoring beneficial algae that enhance complex aquatic food webs. The sustainable benefits to overall lake ecology through LDC are contrasted against traditional in-lake management approaches dealing primarily with the symptoms of eutrophication.

Introduction

Eutrophication refers to the enrichment of available food in aquatic systems, with algal productivity (i.e., the rate of algal production) representing the cornerstone of the aquatic food web. Algae will grow as long as they have sufficient dissolved inorganic phosphorus (DIP; e.g., phosphates), dissolved inorganic nitrogen (DIN; e.g., nitrate and ammonia), light energy for photosynthesis, and suitable temperatures. The availability of dissolved inorganic carbon (DIC; e.g., carbon dioxide, bicarbonate) and micronutrients (e.g., silica, iron) can limit algal productivity, but DIP and/or DIN are typically the limiting nutrient(s) in freshwater lakes and reservoirs. So, algal productivity typically increases as more DIP and DIN enter a lake.

However, all algae are not functionally or ecologically equal. Blue-green algae (cyanobacteria) are both morphologically and functionally different from non-blue-greens, such as diatoms, greens, and flagellates. Blue-green algae are one of the few organisms on the planet that have adapted to stagnant conditions, and have evolved internal gas vesicles that allow them to regulate their buoyancy in the water column. During the day in calm waters, blue-green algae can come near the surface in order to give them a competitive advantage over non-blue-greens for light, atmospheric carbon dioxide, and atmospheric nitrogen (N_2, for those blue-greens capable of incorporating or “fixing” N_2 directly). At night they can settle down into deeper, more nutrient-rich waters. Many species of blue-green algae also contain a variety of cyanotoxins. One significant ecological implication of these cyanotoxins is that zooplankton, macroinvertebrates, and fish do not like to eat them. So when blue-greens die, they tend to sink to the bottom of the lake where their decomposition can deplete bottom waters of dissolved oxygen (DO). Anoxic bottom waters are not only detrimental to fish, but these conditions have other undesirable consequences characteristic of eutrophication (described below).

In contrast to the inedible blue-greens (as well as toxic dinoflagellates, that have also adapted to stagnation by using flagella for motility), non-blue-green algae can and do get consumed by aquatic organisms, thus moving energetically (and materially) up the food chain – improving water clarity while increasing biodiversity. It is not that all algae are bad, just primarily the toxic, non-edible HABs. Edible algae help sustain a vigorous fish community, while toxic HABs harm fisheries and degrade the entire aquatic ecosystem.

Thus, this new paradigm for controlling eutrophication is based on the recognition that food enrichment goes into two different directions depending upon whether or not algal productivity is dominated by HABs. When dominated by toxic blue-green algae, food enrichment remains at the microbial level cycling between blue-green blooms and microbial decomposition. When algal productivity is dominated by non-blue-green algae, however, both biomass and energy move up the food web into zooplankton, other invertebrates, and fish. When the latter happens, even with nutrient enrichment and relatively high algal productivity, the lake ecology is enhanced and the consequences of eutrophication minimized.

Problem identification

Perhaps the most visible indicator of lake eutrophication and impairment are blue-green algae blooms during summer months. These blooms are typically a result of high nutrient inputs (i.e., soluble inorganic nitrogen and phosphorus) and warm, stagnant waters. Because blue-green algae are not readily consumed by zooplankton, other invertebrates, or fish due to their intra-cellular cyanotoxins and relatively large size, they often remain on the water's surface upon death causing unsightly scum and noxious odors. When they die, uneaten blooms eventually settle to the lake sediments where microbial decomposition depletes DO from bottom waters. Anoxic bottom waters promote the sediment release of soluble iron (Fe) and manganese (Mn), causing taste and odor problems in drinking water reservoirs, as well as the release of hydrogen sulfide (H_2S) and soluble P. Hydrogen sulfide and anoxic waters are both detrimental to fish and other aquatic animals. Soluble P released from anoxic sediments into overlying waters can become available again for algal uptake following lake mixing events (e.g., fall turnover). This process is called "internal P loading", and has been major focus for many lake managers in their efforts to mitigate eutrophication (discussed more below).

In addition to the deleterious ecological consequences caused by uneaten blue-green algae, the intra-cellular toxins themselves can create a very unhealthy situation. Not all blue-green algae possess toxins, but bloom-forming blue-green algae are typically capable of producing neurotoxins, hepatotoxins, and/or dermatoxins. When these toxic blooms dominate the algal community, the rest of the lake biota suffers and biodiversity diminishes. Unfortunately, lake biota can also include humans and pets, and reported instances of severe illness and death from both groups have been attributed to accidental consumption of toxic blue-green algae. Although animal illness and deaths have been reported worldwide since the late 1800s, it has only been since around the late 1990s that the drinking water industry and the general public have begun to really appreciate the importance of cyanotoxins to public health. Controlling toxic blue-green algae, therefore, and not necessarily the edible non-blue-green algae, is really the critical lake management issue.

Traditional in-lake management approaches

Lake management as a science and profession is relatively new, and corresponds to the rapid increases in human populations and associated nutrient enrichment of water bodies during the second half of the 20th century. By the late 1960s it had been established that algal growth in most lakes in North America and Europe was limited by the availability of dissolved inorganic phosphorus (DIP). Not surprisingly, early lake management approaches focused on killing the algae, reducing DIP availability, and/or adding dissolved oxygen to anoxic bottom waters.

The theoretical principles behind these lake management approaches have solid scientific foundations, but the gap between theory and practical application has proven huge. By the end of the 20th century, the list of eutrophic and impaired lakes continued to grow unabated. In some lakes millions of dollars have been spent pursuing a whole suite of approaches, yet blue-green blooms and associated lake impairment persist. To help understand why these approaches have had very limited success – if at all - it is useful to discuss them with a focus on more specific questions, including:

1. When a lake management approach is said to have "worked", exactly what does that mean in terms of sustainable water quality improvements?
2. Does this approach preferentially restrict blue-green algae growth?
3. What is the probability that blue-green algae blooms will be consistently controlled for five years?
4. Are there any sustainable ecological benefits?
5. Are there any unintended ecological detriments?
6. Is biodiversity/ecological complexity desirably increased, or undesirably decreased?
7. What is the approximate cost per acre per year?

Copper-based algaecides: It has been known since the late 1800s that copper kills algae. The fact that the underlying physiological mechanism was not known did not reduce its lethal capabilities. This approach is still being used in some lakes, is but rapidly loosing favor and prohibited in many jurisdictions worldwide. Reflecting on the above questions indicates why:

1. Copper is said to have worked when the algae die and the waters clear up. Clear water may last while toxic conditions persist, but blue-green algae blooms frequently return within weeks. In recent years, some blue-green algae species (e.g., *Aphanizomenon* sp.) have gained resistance to copper necessitating increasingly stronger doses.
2. Copper kills many types of aquatic organisms, and is not preferential to blue-green algae.
3. The probability of sustainable blue-green algae growth inhibition for five years is zero.
4. No, there are no sustainable ecological benefits by adding copper-based toxins to the water.
5. Yes, there are unintended ecological detriments, including the killing of non-target organisms such as beneficial algal species, zooplankton, and other aquatic biota. Furthermore, copper can accumulate in the sediments creating a more sustainable detriment to the lake's ecology.
6. Biodiversity is undesirably decreased.
7. Estimates range around $750-$1,500/hectare/year ($300-600/acre/year), but copper is becoming more expensive due to higher demand in the world market, so these algaecides will likely continue to increase in cost.

Alum: One common approach still promoted by some lake managers is the chemical application of alum (aluminum sulfate). Aluminum can bind with P creating a precipitate that is essentially insoluble under oxic conditions. This is a well-established process in water treatment facilities, and logically applied for lake management. By restricting P availability, algal growth can be reduced.

In any P-inactivation approach there is an underlying assumption that algal productivity in a given lake is limited by the availability of soluble P, and so limiting P availability will reduce algal productivity. Without confirming data or conducting algal bioassays, this belief is not necessarily a given. In part because P can recycle in lakes more efficiently than N, algal productivity in eutrophic lakes are increasingly becoming more N (or co N+P, or light) limited. However, since even under N-limiting conditions it is still better to promote P-limitation when trying to reduce algal growth via nutrient control, the focus on P may still be appropriate.

Nevertheless, the effectiveness of alum treatments to reduce algal growth is in great part related to the relative P loading from the watershed versus internal recycling. The greater the watershed contributions, the less effective alum applications become. Furthermore, reducing P availability does not preferentially prevent blue-green algae blooms, though it may reduce the intensity. In some eutrophic waters, reducing toxic blue-green algae blooms even by 90% would still leave sufficient algal biomass to restrict waters for human contact according to World Heath Organization's guidelines on exposure to blue-green toxins.

Because summertime blue-green algae blooms are typically fueled by *externally derived* nutrients brought into the lake from summer stormwater runoff and tributary inputs, results from alum treatment are quite variable and lake-specific. In fact, P recycled from deep-water sediments typically has a minimal impact on summer blooms because thermal stratification separates anoxic, nutrient-rich bottom waters from surface waters where algae utilize nutrients for photosynthesis and growth. Therefore, the probability that a deep-water alum treatment would have a significant and enduring negative impact on summertime blue-green algae blooms is quite small. Treating near-shore waters can have a greater impact, but the duration may be severely limited by external loading and sediment disturbances from flows, wave action, bottom feeding fish, etc. Furthermore, recent studies indicate that up to 50% of alum-bound P can be released back into the water within 6 months. Although it has been known for many decades that alum can bind P, a 2005 survey identified only about 120 lakes in the US and a total of about 140 worldwide that had tried alum for algae control. Addressing the above 7 questions helps explain why:

1. Whenever alum is used for reducing algal growth, it is important for the lake owner to understand exactly how the lake manager/consultant defines "works". In most alum-treated lakes, alum applications are repeated every 2-5 years, though some urban lakes require more frequent treatments while protected forested lakes with minimal external nutrient loading can look good for >10 years. Since alum is applied in response to algal blooms, typical benefits do not last 2-5 years – it is within 2-5 years following an application that conditions have deteriorated to the point where subsequent applications are again deemed necessary. It is not a question of *if* subsequent applications are needed, just *when*. And, depending upon the amount of external P loading, presence of bottom feeding fish (e.g., bullheads and carps), invertebrate activity in the sediments, sediment disturbance from boating and wave action, and other factors that may reduce the effectiveness of alum treatments, the frequency of applications may be sooner than anticipated. So, when a lake management consultant recommends alum because of "scientific proof that it works", lake owners would be wise to ask the consultant to provide specific expectations for their lake, perhaps with some sort of money-back guarantee if not realized.

2. No, neither alum, nor other P-sequestering approaches inhibit blue-green algae preferentially.
3. There is some probability that algal bloom reduction could last up to 5 years. However, as discussed above in answer to the first question, there are many factors that can reduce the effectiveness; any projected longevity of impact should be lake-specific.
4. There are no sustainable ecological benefits, only a possible and temporary reduction in algal growth.
5. Undesirable ecological impacts can include unbalanced buffering, unintended fish kills, and potential aluminum toxicity issues as aluminum accumulates and becomes more soluble in anoxic sediments.
6. There is no reason to believe that biodiversity would naturally increase following alum applications. In fact, as aluminum is toxic to some aquatic organisms, biodiversity is more likely to decrease.
7. Depending on the required frequency of applications, costs could be from \$1,200 to \$2,500/hectare/year (\$500 to greater than \$1,000/acre/year).

Aeration: The last "traditional" in-lake management approached discussed here is the installation of air (or oxygen) diffusers in the bottom waters (i.e., hypolimnion) of thermally stratified lakes. The two main stated objectives are to 1) increase dissolved oxygen (DO) concentrations in bottom waters, and 2) provide an oxygen "cap" over the sediments in deep waters below the thermocline (i.e., hypolimnion) to keep sediment-based soluble P from diffusing upward into the water column and promoting algal blooms. The first objective is frequently met, as DO vertical profiles do demonstrate increased DO concentrations in the hypolimnion of lakes.

The second objective, however, is rarely met. It is true that soluble P concentrations may be reduced in bottom waters, but that is in part because waters rich in soluble P and N get transported upward into surface waters by rising bubbles. So instead of reducing internal nutrient loading, bottom diffusers can actually promote the transport of sediment-derived nutrients to surface waters making summertime algal blooms worse – a common occurrence in aerated lakes and reservoirs. Again, examining aeration in light of the above questions is useful:

1. When a lake consultant says that hypolimnetic aeration "works", this generally means that there was an increase in DO in bottom waters – what happens in surface waters is typically not part of the definition.
2. Hypolimnetic aeration as normally applied to lakes does not inhibit blue-green algae growth, and may in fact promote it by increasing summertime internal nutrient loading.
3. With hypolimnetic aeration as typically applied to lakes, the probability of sustainable blue-green algae growth inhibition for five years is practically zero.
4. Yes, there are benefits by maintaining higher DO concentrations in the water column, but it is not sustainable in the sense that land-based energy is constantly needed to run the equipment, and aeration machinery typically requires constant maintenance.
5. Yes, the promotion of algal blooms from the transport of sediment-based nutrients to surface waters is an unintended ecological consequence. When these blooms die and sink to the bottom, more DO is needed for their decomposition. Therefore, aeration is needed to deal with the oxygen depletion in bottom waters resulting from decomposing toxic algal blooms promoted by nutrient transport to surface waters from aeration.
6. Aeration could increase or decrease biodiversity, depending on lake specific characteristics and how much aeration was applied.

7. Aeration costs vary considerably; aeration systems can cost millions to install and hundreds of thousands of dollars per year to operate. Furthermore, equipment failure is common, even after only a few years, and energy costs continue to rise.

Except when transported to surface waters through bubbles rising from hypolimnetic aeration, P availability from anoxic sediments is typically NOT the primary cause of summertime blue-green algae blooms. The paradigm shift described in this memo changes the focus from nutrient availability for all algae to directing available nutrients into "good", edible algae that actually enhance the food web, promote biodiversity, and improve the overall ecological health of the lake. Therefore, the problem is NOT too much phosphorus. Phosphorus is not toxic to aquatic life – in fact, it is an essential food for all plants and a necessary component for nucleic acids and other life-supporting molecules. For effective lake management, the primary goal should not necessarily be to reduce phosphorus concentrations or overall lake productivity, but instead keep nutrients/energy moving up the food web and not remain stuck in a blue-green algae-bacterial decomposition loop. In other words, help P (and N) inputs become incorporated into edible algae rather than into toxic, inedible blue-green algae.

Habitat Disturbance to Selectively Prevent Harmful Algal Blooms

In addition to nutrient availability and suitable (generally warm) temperatures, a major requirement for HABs is quiet, stagnant waters. Both cyanobacteria and dinoflagellates (which dominate HABs in marine systems) have evolved mechanisms for regulating their position in the water column to maximize competitive advantages with other algae under stagnant conditions. Cyanobacteria contain gas vesicles that allow them to regulate their buoyancy, while dinoflagellates have flagella that enable them to move through stagnant waters. Many species from both groups also contain toxins that make them inedible to zooplankton and fish, further enhancing their survival.

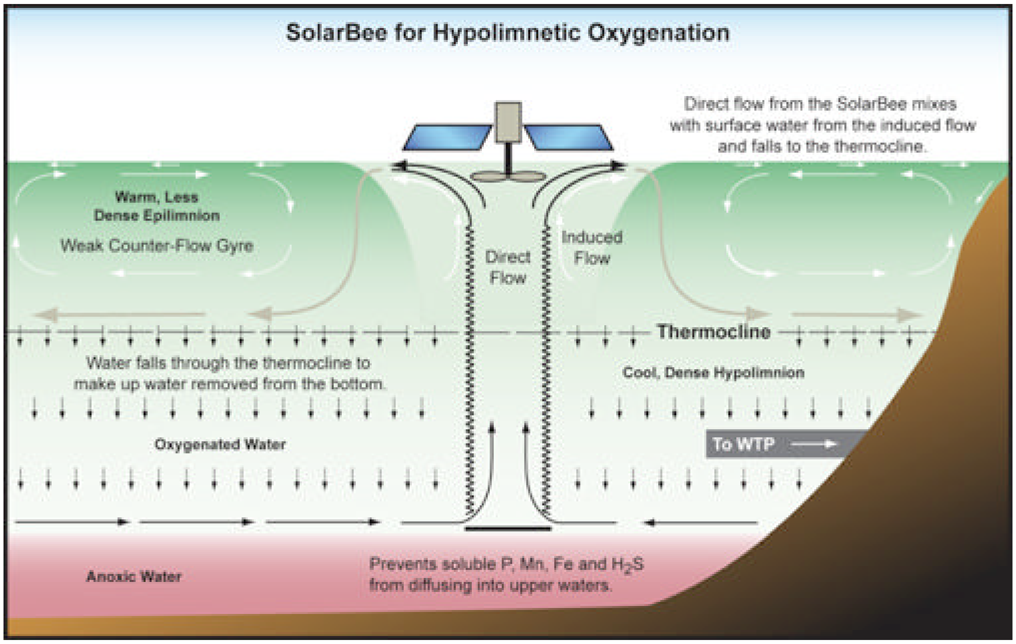
In the above discussion of traditional lake management approaches, aeration was discussed as typically applied to lakes. In these systems, there is sufficient aeration to add DO and transport nutrients into upper waters, but not enough to create sufficient mixing to prevent HABs. However, the wastewater industry has long appreciated that if sufficient mixing is applied through aeration to their wastewater lagoons, cyanobacteria blooms are prevented and the waters clear up. This has led some to believe that intense aeration can "kill" the algae, when in fact it is the mixing that inhibits the inedible cyanobacteria, allowing other edible algae to grow and get eaten by zooplankton, thus improving water clarity. Long-distance circulation (LDC) accomplishes the same thing, just on a larger scale.

Similar to the "scientific proof" that copper kills algae, alum binds P, and aeration increases hypolimnetic DO concentrations, the published, peer-reviewed scientific support that habitat disturbance through circulation inhibits HABs is both voluminous and has been around for several decades. It is important to appreciate that there is no controversy in the limnological or oceanographic communities that sufficiently disrupting stagnant waters can be very effective at preferentially preventing HABs while enhancing the rest of the aquatic community. The relevant and supportive peer-reviewed scientific literature we have accumulated to date includes the references listed in Appendix A.

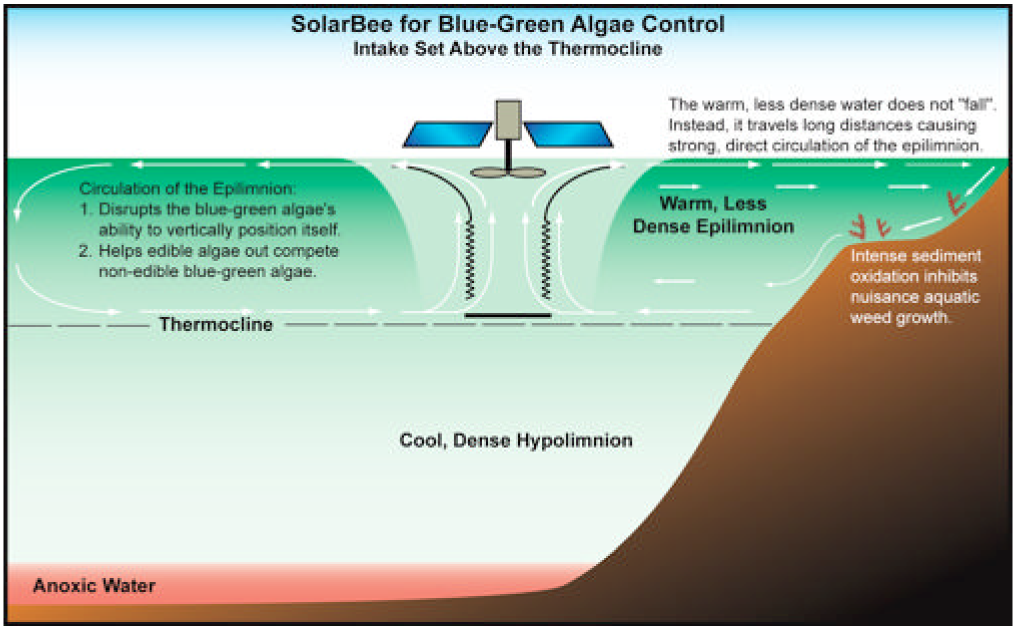
The SolarBee, Creating Long-Distance Circulation for Improving Lake Ecology

The SolarBee is a solar-powered, up-flow LDC machine capable of bringing water up from a desired depth and transporting it horizontally long distances across the lake surface. Water is brought to the SolarBee horizontally at the depth of the intake hose. Since water moves in layers, water can be pulled into the machine from long distances extending to shorelines. Water brought up to the surface is then moved radially in all directions away from the SolarBee. This circulation is fundamentally different from wind mixing, which tends to move water in shallow, vertical vortices with limited (and more unidirectional) long-distance transport. Generally speaking, the SolarBee can be deployed in two different manners to improve water quality and enhance lake ecology.

One method of deployment is a form of hypolimnetic oxygenation, where the SolarBee intake hose is set deep, near the bottom of the lake, in order to bring oxygen-poor water to the surface for natural re-oxygenation (both across the air-water interface and from algal photosynthesis). More oxygen-rich water gets transported downward to the depth of the SolarBee intake hose through displacement, effectively sealing sediments down to this depth with regards to the release of DIP under otherwise anoxic conditions. This method of deployment is most frequently used in drinking water supply reservoirs to keep deep waters below the level of the intake pipe to the water treatment plant oxygenated to prevent manganese and hydrogen sulfide intrusion. Uncertainties about lake-specific P dynamics notwithstanding, and because limiting P availability does not specifically eliminate blue-green algae blooms, this is NOT the approach we typically recommend for blue-green algae control.



With the second, preferred method of deployment for HAB control, the SolarBee intake hose is set shallower to only circulate waters where the algae grow. The effect is to physically disturb the favored habitat (i.e., calm, quiescent surface waters) of bloom-forming blue-green algae so they are unable to out-compete the edible, non-blue-green algae. Usually the SolarBee intake hose is set at or above the thermocline (i.e., the epilimnion, where water temperatures and corresponding densities are more uniform) but below the photic zone, usually about 2-4 m (6-13 ft) from the surface.



Water from this depth is brought up and spread radially from the machine. The SolarBee's patented distribution dish allows water to flow away from the machine in a near-laminar flow, enabling it to reach long distances (200 m or more). Surface waters then move downward along the lake's margins and back to the machine at the intake depth. Each SolarBee SB10000v18 pumps over 40,000 liters (14,000 gallons) per minute and can prevent blue-green blooms up to a 14-hectare (35 acres) circle with a 425 m (1,400 ft) diameter. Since the effect is additive, more units can be installed for controlling HABs in larger lakes (this issue is discussed further below). Because SolarBees run on solar energy and still impact up to 14 hectares per machine, they are the most effective and energy efficient LDC devices available.

This SolarBee-induced water movement has shown to be consistently effective at preventing blue-green algae blooms in over 300 fresh and saltwater bodies throughout North America since first introduced for this application in 2000. Without any changes to nutrient loading, typical results include significantly improved water clarity, lower pHs, reduced chlorophyll *a* and total P concentrations, increased biodiversity, increased secondary production (both zooplankton and fish), and reduced biochemical oxygen demand (BOD) to bottom waters. This epilimnetic circulation also keeps DO concentrations high throughout the water column above the thermocline, thus improving the fish environment.

It is important to remember that these water quality improvements are unrelated to nutrient concentrations – the elimination of blue-green algae blooms is by habitat manipulation which impairs their ability to out-compete non-blue-greens, and *not* by limiting their nutrient availability. For example, these results have been noted in drinking water reservoirs receiving secondary effluent from domestic sewage. Even with DIP concentrations reaching 0.5 mg/L and ammonia-N and nitrate-N concentrations exceeding several mg/L, blue-green algae blooms were eliminated, water clarity remained about 3-4 meters, chlorophyll *a* concentrations averaged 2-3 µg/L, and no unusual taste and odor problems were reported (MIB and geosmin, organic chemicals that cause taste and odor problems in drinking water, are typically associated with blue-green blooms). In fact, over 120 municipalities in North America have reduced or eliminated their taste and odor issues by employing SolarBees in their raw water storage reservoirs, often with considerable economic savings from reduced chemical and energy costs.

In addition to controlling blue-green algae blooms, SolarBee-induced circulation has also proven effective at improving fish spawning habitats in littoral (near shore) sediments as oxygenated surfaces waters move down along the sediments and back to the machine. By directing nutrients into edible algae and enhancing the overall food web, increased fish productivity, spawning, and fish vigor have been viewed very positively by owners/managers of over 30 lakes where SolarBees have been installed for blue-green bloom control. Lake users have also frequently noted that near-shore sediments are firmer and more compacted, a logical result of oxidizing the organic muck accumulated on the sediments.

Furthermore, this same oxygenated return flow that has benefited fish spawning and sediment compaction has also been effective at inhibiting several species of invasive submerged macrophytes (e.g., Eurasian watermilfoil, EWM (*Myriophyllum spicatum*)). Similar to many invasive aquatic weeds, EWM strongly favors ammonia-N over nitrate as its nitrogen source. Furthermore, these plants get their ammonia-N from the sediments, where concentrations may be 1,000 times greater than in overlying waters. SolarBee circulation moving oxygenated water along littoral sediments apparently oxidizes sediment ammonia to nitrate, creating N-limitation of EWM growth. The few remaining plants often have a sickly, yellowish look typical of N deficiency. Lightly rooted invasive species like EWM are affected, but native plants tend to be more deeply rooted and not similarly impacted. The elimination of blue-green blooms further promotes nitrogen limitation by reducing the amount of algae settling to the sediments that would otherwise release ammonia-N through their decomposition. We have seen EWM (as well as curly-leaf pond weed (*Potamogeton crispus*) and other lightly-rooted invasive species) become sickly and inhibited in over 20 lakes, even as water clarity significantly improved due to the elimination of blue-green algae blooms. For more information on this application, please refer to the 2009 white paper titled "*SolarBee Experience in Inhibiting Submersed Macrophyte Growth*" available at *www.solarbee.com*.

Proposed applications of SolarBees in large lakes do raise the issue of the scope of SolarBees' influence. There are currently units deployed in many lakes > 200 hectares (500 acres), though the focus in most of these lakes is on treating specific coves, marinas, areas around water treatment plant intake pipes, and other high value areas rather than the entire lake. Even very large lakes like the Salton Sea, CA (100,000 hectares), the most impaired water body in California, can benefit by targeting specific "hotspots" that suffer localized impacts from algal blooms. The largest partial lake application to date is at 4,850-hectare (12,000 acre) Lake Houston, Texas, where 20 SolarBees are treating a 240-hectare (600-acre) area in front of the 40 MGD water treatment plant. Not only have the serious taste and odor issues been resolved, the City of Houston reported a chemical savings of $500,000 during the first year of operation.

We also know that we can eliminate blue-green blooms from the entire lake if sufficient units are installed. We have been consistently successful from water bodies less than 1 acre up to a 200-hectare (500 acre) power plant cooling reservoir in Colorado. The negative ecological impact on individual blue-green algae cells is not a function of lake size. There is no reason to believe that a lake of any size with sufficient SolarBees would not experience the same ecological benefits as documented in over 300 ponds, lakes and reservoirs similarly treated since the year 2000.

The SolarBee technology is now over 10 years old. Although the company has been in the water movement business since 1978, the SolarBee was first invented in 1998 primarily to distribute photosynthetically produced DO more efficiently in wastewater lagoons (originally SolarBee was a division of Pump Systems, Inc., but has been SolarBee, Inc. since the beginning of 2007). Lake applications began in 2000, and started to grow rapidly in 2002 with the development of the larger machine capable of moving 40,000 liters/minute (10,000 GPM). Original lake applications also focused on facilitating DO distribution to deeper waters. However, the observed lake benefits of blue-green bloom prevention, fish habitat improvement, and submersed macrophyte control were originally unknown and unintended – we learned of these benefits from hundreds of independent lake and reservoir owners reporting their observations and data.

Although SolarBees have successfully and consistently eliminated blue-green algae blooms in more than 300 water bodies, lake owners have also helped identify some of the limitations of this application. Experience has shown that SolarBees may not be as effective for blue-green bloom control if: 1) if SolarBees are placed in only part of the lake while blue-green algae are blooming in an "upstream" and untreated part of the lake, and/or 2) if there is an untreated water body discharging blue-green algae into the SolarBee-treated lake. Also, on a handful of applications there was a temporary bloom at the beginning of the first summer following installation. We believe that improved conditions prompted resting spores (i.e., akinetes) of blue-green algae to germinate. Similar blooms were not observed in subsequent years. Even though the exact physiological mechanism(s) behind blue-green algae bloom control through habitat disturbance is still somewhat uncertain, we have a very reasonable and reliable expectation of success when the above limitations are accounted for.

Addressing the same 7 questions as applied above clearly distinguishes lake management and HAB control through SolarBee-induced long-distance circulation from traditional lake management approaches:

1. SolarBees are said to have "worked" when waters are no longer stagnant, blue-green algae blooms are prevented, water clarity improves, chlorophyll *a* concentrations are reduced, fish kills are prevented, fisheries are enhanced, pH is reduced, dissolved oxygen is better distributed in the water column, taste and odor issues in raw water storage reservoirs are prevented, invasive aquatic weeds are inhibited, near-shore sediments are firmer, and the lake owner is pleased with the results.
2. Yes, eliminating stagnation preferentially and negatively impacts harmful blue-green algae and dinoflagellates that require stagnation for bloom formation.
3. The probability that HABs will be controlled for five years is very high. SolarBees have proven effective in over 95% of the 300+ lakes that have used SolarBees, some since 2000. In a few lakes there were initial adjustments to machine number, placement, and/or hose depths; but once adjusted results have been very consistent, repetitive over a wide variety of lake size and conditions, and sustainable.
4. Yes, the benefits described in the answer to the first question are all sustainable.
5. When properly deployed, there are no sustainable negative impacts of circulation.
6. Circulation increases biodiversity, particularly when no toxins are added.

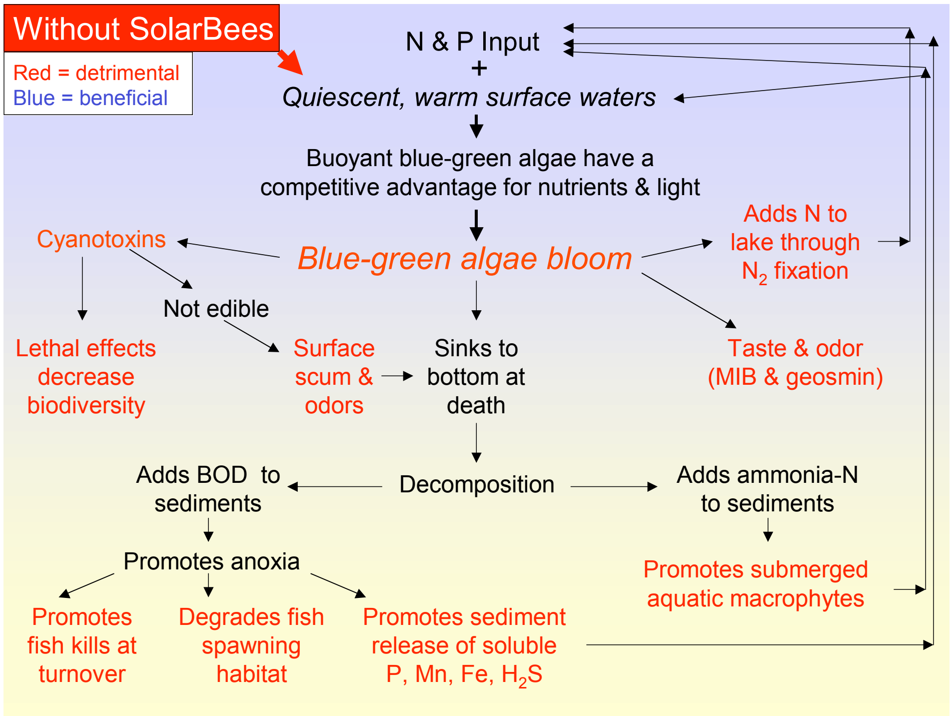
7. Over the 25+-year expected life of the SolarBee, costs are about \$200-\$300/hectare/year (\$80-\$120/acre/year).

Summary

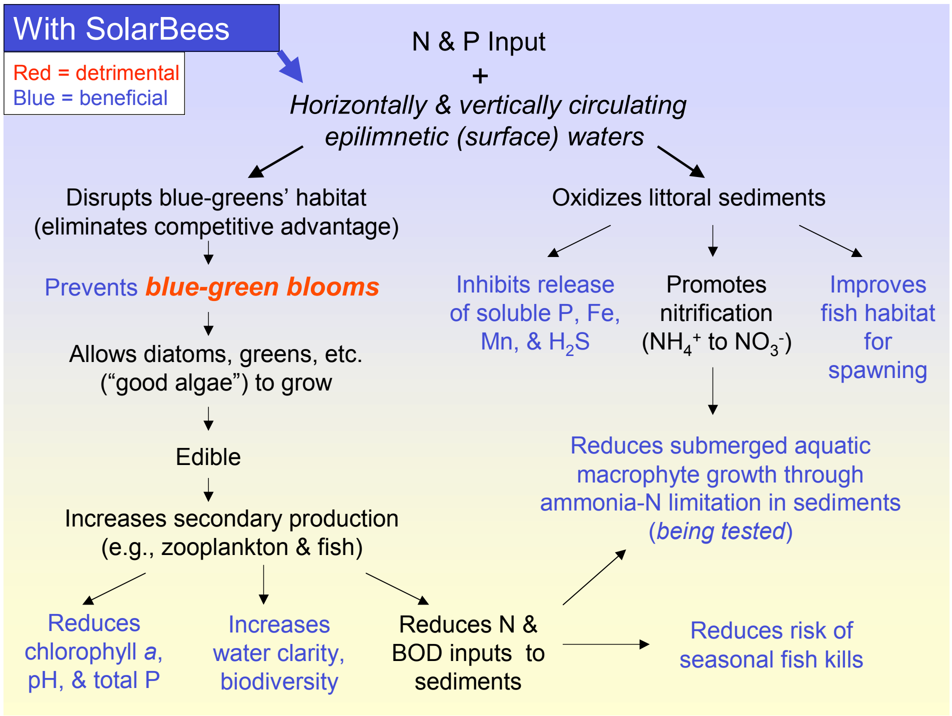
Metaphorically, traditional lake management approaches can be thought of as a lake physician. The "physician" approach often uses chemicals and invasive techniques to quickly treat the symptoms of a problem rather than the problem itself. For example, hypolimnetic aeration and alum additions are used to treat the symptoms of oxygen depletion and sediment P release caused by the death and settling of blue-green algae blooms. As long as the blooms continue each year, hypolimnetic oxygen depletion will also occur.

In contrast, the SolarBee approach is more like a holistic healer. This approach addresses the whole lake by eliminating the principal cause of the problem – blue-green algae blooms – while also eliminating the need for symptomatic treatments such as algaecides, alum or hypolimnetic aeration (but if desired, SolarBee intake tubes can be set off the bottom to circulate naturally oxygenated surface waters down into the hypolimnion). Phosphorus that would have otherwise gone into blue-greens now go into edible "good" algae (e.g., diatoms, greens, etc.) that do get consumed by aquatic animals - the result: lower algal biomass, no toxic algal blooms, greater secondary production (i.e., zooplankton and fish), lower pH, improved water clarity, and reduced organic loading to bottom waters. In fact, simply eliminating stagnation is very beneficial to a lake. This is all accomplished using only solar energy without toxic chemicals or land-based energy sources, making the SolarBee eco-friendly, energy efficient, and economical for long-term, sustainable benefits.

The implications and ecological benefits of controlling harmful algae blooms through bio-manipulation by eliminating stagnation are just recently becoming better appreciated. The two flowcharts below summarize the ecological relationships associated with this evolving concept as described above. The first flowchart illustrates that the negative ecological consequences associated with blue-green blooms that will occur regardless if the bloom dies naturally or killed by algaecides. It also shows that even if hypolimnetic oxygenation and/or alum were applied (eliminating the bottom left part of the flowchart), both blue-green blooms and most negative ecological consequences would still persist, albeit with reduced severity.



The second flowchart below shows that by eliminating blue-green algae blooms through habitat manipulation, not only are the negative symptoms of eutrophication minimized, the entire lake ecology significantly improves.



Appreciating these ecological linkages is the key to understanding how SolarBees can prevent eutrophication without controlling nutrient inputs. Although watershed management is very important for a large number of reasons, controlling P inputs to reduce eutrophication does not necessarily have to be one of them. In fact, many lake fisheries will actually benefit from P inputs directed into edible, non-blue-green algae. The SolarBee enhances natural ecological processes in lakes through horizontal and vertical circulation, thus benefiting the lakes, benefiting those who utilize the lakes, and benefiting those who would otherwise have to pay for expensive short-term treatment costs to mitigate the symptoms of eutrophication.

LDC is the most ecologically sensitive and holistic approach for sustainable lake management. The solar-powered SolarBee is by far the most efficient and effective LDC machine in the world. Finally, eutrophication can be reversed and aquatic systems restored, naturally.

Appendix A

The following is a partial list of scientific literature relevant to the topic of controlling blue-green algae and other harmful algae blooms by disturbing their preferred habitat of stagnant waters via induced turbulence and circulation.

Bailey-Watts, A.E., E.J. Wise, and A. Kirika. 1987. An experiment in phytoplankton ecology and applied fishery management: effect of artificial aeration on troublesome algal blooms in a small eutrophic loch. Aquaculture and Fisheries Management, 18:259-276.

Berdalet, E., 1992. Effects of turbulence on the marine dinoflagellate *Gymnodinium nelsonii*. J. Phycology. 28: 267-272.

Berdalet, E. and M. Estrada, 1993. Effects of turbulence on several dinoflagellates species, p. 737-740. In: Toxic phytoplankton blooms in the sea. Proc. 5th Int. Conf. on Toxic Marine Phytoplankton. Elsivier.

Cowell, B.C., C.J. Dawes, W.E. Gardiner, and S.M. Scheda. 1987. The influence of whole lake aeration on the limnology of a hypereutrophic lake in central Florida. Hydrobiologia, 148(1): 3-24.

de Bernardi and G. Giussani. 1990. Are blue-green algae a suitable food for zooplankton? An overview. Hydrobiologia 200/201: 29-41.

Donaghay, P.L. and T.R. Osborn, 1997. Towards a theory of biological-physical control of harmful algal bloom dynamics and impacts. Limnol. Oceanogr. 42(5, part2): 1283-1296.

Gibson, C.H. and W.H. Thomas, 1995. Effects of turbulence intermittency on growth inhibition of red tide dinoflagellate, Gonyaulax polyedra Stein. J. Geophys. Res. 100: 24,841-24,846.

Gachter, R. et B. Wehrli, 1998. Ten years of artificial mixing and oxygenation: No effect on the internal phosphorus loading of two eutrophic lakes. Environmental Science and Technology 32(23): 3659-3665.

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Hawkins, P.R. and D.J. Griffiths. 1993. Artficial destratification of a small tropical reservoir: effect upon phytoplankton. Hydrobiologia 254: 169-181.

Heo, W-M, B. Kim. 2004. The effect of artificial destratification on phytoplankton in a reservoir. Hydrobiologia, 524: 229-239.

Huisman, J., J. Sharples, J.M. Stroom, P.M. Visser, W.E.A. Kardinaal, J.M.H. Verspagen, and B. Sommeijer. 2004. Changes in turbulent mixing shift competition for light between phytoplankton species, Ecology, 85(11): 2960-2970.

Jungo, E., P.M. Visser, J. Stroom, and L.R. Mur. 2001. Artificial mixing to reduce growth of the blue-green alga *Microcystis* in Lake Nieuwe Meer, Amsterdam: an evaluation of 7 years of experience. Water Science and Technology: Water Supply, 1(1): 17-23.

Klener, A.R. and A.E. Konopka. 1989. Causes and consequences of blue-green algal (cyanobacterial) blooms. Lake and Reservoir Mngt 5: 9-19.

Klemer, A. R. and J. Barko, 1991. Effects of mixing and silica enrichment on phytoplankton seasonal succession. Hydrobiologia 210: 171-181.

Knoechel, R. and J. Kalff. 1975. Algal sedimentation: the cause of a diatom-blue-green succession. Verh. Int. Ver. Theor. Angew. Limnol. 19: 745-754.

Knoppert, P.L., J.J. Rook, et al. 1970. Destratification experiments in Rotterdam. Jour. Am. Water Works Assoc. 62: 448-454.

Lackey, R.T. 1973. Artificial reservoir destratification effects on phytoplankton. Journal Water Pollut. Control. Fed. 45(4): 668-673.

Osgood, R.A. and J.E. Steigler. 1990. The effects of artificial circulation on a hypereutrophic lake. Water Res. Bull. 26(2): 209-217.

Pastorok, R.A., T.C. Ginnet, M.W. Lorenzen, 1981. Evaluation of aeration/circulation as lake restoration technique. EPA 600/3-81-014.

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Pearl, H. W. and C.S. Tucker. 1995. Ecology of blue-green algae in aquaculture ponds. J. of the World Aquaculture Society, 26(2): 109-131.

Pollingher, U. and E. Zemel, 1981. In situ and experimental evidence of the influence of turbulence on cell division processes of *Peridinium cinctum* forma westii (Lemm.) Lefevre. Br. Phycol. J. 16: 281-287.

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Trimbee, A.M. and G.P. Harris. 1984. Phytoplankton population dynamics of a small reservoir: Effect of intermittent mixing on phytoplankton succession and the growth of blue-green algae. J. Plankton res. 6: 699-714.

Visser, P.M. et al., 1996. Artificial mixing prevents nuisance blooms of the cyanobacterium *Microcystis* in Lake Niewe Meer, The Netherlands. Freshwater Biology, 36: 435-450.

Webb, D.J., R.D. Robarts et E.E. Prepas, 1997. Influence of extended water column mixing during the first 2 years of hypolimnetic oxygenation on the phytoplankton community of Amisk Lake, Alberta. Canadian Journal of Fisheries and Aquatic Sciences 54(9): 2133-2145.

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