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# Turbulence and nutrient interactions that control benthic algal production in an engineered cultivation raceway

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ABSTRACT

Flow turbulence can be a controlling factor to the growth of benthic algae, but few studies have quantified this relationship in engineered cultivation systems. Experiments were performed to understand the limiting role of turbulence to algal productivity in an algal turf scrubber (ATS) for benthic algal cultivation. Volumetric flow rate and wave surge frequency were independently manipulated in an ATS operating over a range of nitrogen loading rates, and the effects on algal biomass productivity were measured through periodic sacrificial harvest. Productivity followed a saturation relationship versus nitrogen loading rate for the range of turbulence conditions. When flow rate was held constant, a maximum productivity of 26.8 g dW $m^{-2}$ $d^{-1}$ was observed at a wave surge frequency of 17 $min^{-1}$ at high nitrogen loading rates, with lower productivities at higher and lower frequencies. The productivity was similar (26.4 g dW $m^{-2}$ $d^{-1}$) when the volumetric flow rate was increased with surge frequency held constant. Productivity was influenced by wave surge power, itself strongly determined by wave amplitude as set by volumetric flow rate. These results contribute to the understanding of the limiting factor effects of flow turbulence on algal production that can inform the optimization of the benthic algal cultivation.

## 1. Introduction

Engineered systems for the cultivation of benthic algae have been developed for high productivities for pollutant removal from natural waters or wastewater [1–5]. As benthic algae grows, it adsorbs pollutant nutrients in its biomass, and periodic harvesting of this biomass removes those pollutants from the water stream, thereby providing a potential tool for mitigating nutrient loading problems in natural waters. Benthic algal cultivation systems such as the algal turf scrubber (ATS™) have been examined as a potentially cost-effective technology for nutrient removal from municipal wastewaters [3]; aquaria [6]; liquid waste from dairy [7–11] and swine [12] operations; and natural waters [13–15].

In benthic algal cultivation systems such as the ATS, flow turbulence provided by wave action stimulates algal growth and selects for benthic filamentous algae over other morphologies [4]. It is known that the productivity of a benthic algal community can show a saturation relationship with increasing flow velocity [16–20]. In a typical field operation of an ATS, the turbulence regime is created by a combination of fluid flow velocity and a periodic wave surge [3,13,21]. It has been observed that low levels of turbulence in an ATS result in lower productivities [22], the mechanism of which is either through diffusive limitations on nutrient transport, through light limitation because of self-shading, or through a combination of both [23]. It is also well known that high levels of turbulence can damage and increase export of standing algal biomass [24–26]. It might therefore be expected that algal productivity in an ATS is maximized within a range of moderate turbulence levels, and that this range might shift for different light intensities, nutrient loading rates, and algal species assemblages. Numerous empirical studies have demonstrated the stimulatory effects of flow velocity on the productivity of an algal turf, showing an increase in biomass production rate [18,24,27,28] or measures of ecosystem metabolism [24,27–29] with flow velocities increasing from 10 to 150 cm $s^{-1}$. Additional stimulatory effects have been observed in a flow environment dominated by oscillatory wave surge action, where benthic algae subjected to a wave surge exhibited higher productivity than the same turfs at comparable base flow velocities [21,22]. Subsequent research indicates that oscillatory flow can overcome mass transfer diffusion limitations of dissolved inorganic carbon [30] and nutrients [31,32] into algal turfs at low flow velocities. This effect has been employed with success in cultivation systems for benthic filamentous algae [5].

The objective of this study was to investigate the interaction between flow turbulence and nutrient concentration on the productivity

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of benthic algae in an ATS. The productivity was expected to follow a saturation relationship with increasing nutrient concentration, and be further modulated by turbulence at higher levels of nutrient concentration. Under these conditions, the productivity would first increase and then decrease as the flow turbulence increases, as the opposing stimulatory and deleterious mechanisms respectively dominate.

## 2. Materials and methods

Four separate, identical laboratory-scale ATS units containing 1 $m^2$ of growing area were each operated in semi-continuous mode by recirculating 150 L of freshwater nutrient solution to its own reservoir using a centrifugal pond pump (Supreme Mag Drive, Model MD18, Danner Manufacturing, Islandia, New York, USA), as previously described in [9] and [12] (Fig. 1). Each ATS unit was operated under near continuous light (23:1 h light:dark cycle, to preserve bulb lifetime) under its own set of two 400 W metal halide lights. Photosynthetic photon flux density on the algal growth screens averaged 390 (range 240–630) $\mu mol\ s^{-1}\ m^{-2}$ over the entire ATS bed, with a maximum intensity at the center of the screen, as measured with a quantum flux meter and probe (LI-250 Light Meter and LI-190 Quantum Sensor, LI-COR Biosciences, Lincoln, Nebraska, USA). Water temperatures were maintained within 2 °C of ambient (22 °C) by thermostat-controlled cooling fans that activated when temperatures were high to increase evaporation. Water volume was maintained through daily additions of fresh distilled water to replace evaporative losses, typically about 5 $L\ d^{-1}$.

The nutrient source for all tests was anaerobically digested dairy manure, collected periodically as needed from an anaerobic digester at the USDA ARS Beltsville (Maryland, USA) dairy, as in [8]. Measured manure effluent nutrient values for this study were 1620 $mg\ L^{-1}$ ammonia nitrogen ($NH_3$-N) and 240 $mg\ L^{-1}$ total phosphorus (TP), with a ratio of N:P of 6.75:1, suggesting that digested manure as a nutrient source is particularly rich in nitrogen for algal growth needs [33]. A measured volume of digested manure was added daily to the reservoir of each ATS unit to achieve the desired nitrogen loading rate (NLR), ranging throughout all tests between 0.3 and 1.6 g $NH_3$-N $m^{-2}\ d^{-1}$, and reflecting conditions ranging from meso- to eutrophic metabolic states for aquatic systems. Nitrate concentration was monitored weekly with Reflectoquant® test strips and an RQflex® reflectometer (EMD Chemicals, Gibbstown, NJ, USA) to ensure no accumulation of nitrogen in the reservoir. For all ATS units, $CO_2$ gas was bubbled in the drum reservoir, maintaining the pH level near neutral. The ATS units were previously seeded through in situ colonization with algal consortia from a nearby stream in Beltsville, Maryland. The benthic algae were established on square screens (100 cm sides) of black polyethylene (3×4 mm mesh, Industrial Netting, Minneapolis, MN). The algal community was dominated by a mixed community of green algae *Rhizoclonium* and *Microspora* species, with the blue-green *Oscillatoria* present as well.

Algal productivities were measured through weekly sacrificial harvest of biomass on the entire growing area in each ATS unit using a commercially-available wet/dry vacuum (Rigid, Model WD1637, Emerson Electric Company, St. Louis, Missouri, USA). The algal biomass and accompanying water were decanted from the vacuum into a 1.5-mm mesh polypropylene filter bag (SCB2 spat bag, Aquatic Eco-Systems Inc., Apopka, Florida, USA). The biomass in the bag was squeezed to dewater and was spread flat in front of a fan to air dry. Once air dry (after approximately 48 h), the total biomass was weighed using a laboratory balance. A subsample of each biomass sample was oven-dried at 50 °C for 12 h to determine the water content for determination of the dry weight of the entire sample.

In an ATS, turbulence in the growth bed is a function of both the wave surge volume and frequency, and both are related to the volume of the wave surge bucket and the volumetric flow rate. Experiments were performed in which the bed turbulence was manipulated by two different methods: (1) through manipulation of the wave surge frequency while the volumetric flow rate was held constant; and (2) through manipulation of the volumetric flow rate while the wave surge frequency was held constant. Volumetric flow rate was modulated through the addition of recirculation pumps operating in parallel. Wave surge frequency was modulated by filling the wave surge bucket with polystyrene closed-cell foam blocks cut

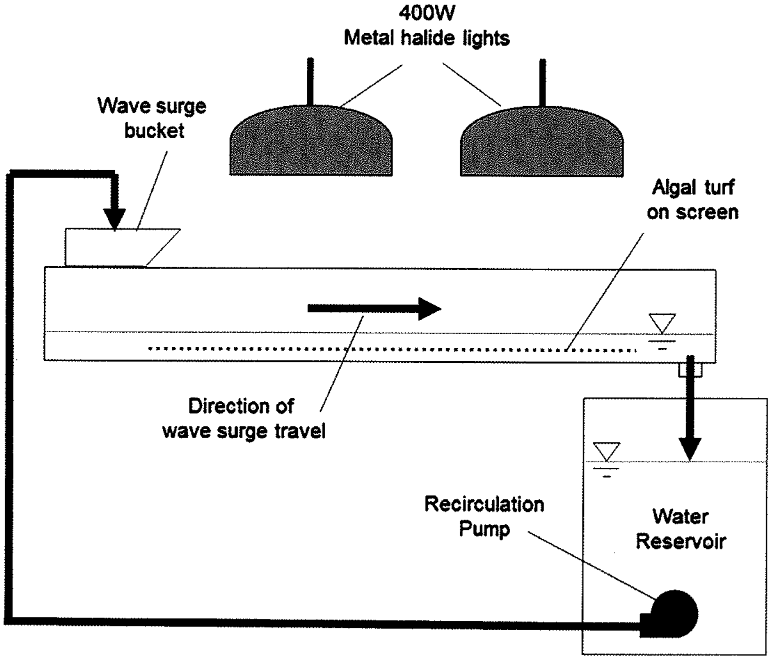

Fig. 1. Schematic of a laboratory-scale, recirculating ATS unit used in experiments.

from commercially-available insulation (Foamular F-250, Owens Corning, Toledo, Ohio, USA), reducing the available fluid volume in the dump bucket to yield the intended frequency for a given volumetric flow rate. For each method of bed turbulence manipulation, an orthogonal design was used crossing nitrogen loading rate with turbulence condition. Nitrogen loading rates (NLRs) were applied in low (0.4 g $NH_3$-N $m^{-2}$ $d^{-1}$), medium (0.8 g $NH_3$-N $m^{-2}$ $d^{-1}$), and high (1.3–1.6 g $NH_3$-N $m^{-2}$ $d^{-1}$) rates. For experiments holding volumetric flow rate constant at 60 L $m^{-2}$ $min^{-1}$, wave surge frequency was applied at low (5 $min^{-1}$), medium (17 $min^{-1}$), and high (30 $min^{-1}$) conditions (Table S-1). For experiments holding wave surge frequency constant at 8 $min^{-1}$, volumetric flow rate was supplied at low (25 L $m^{-2}$ $min^{-1}$), medium (60 L $m^{-2}$ $min^{-1}$), and high (95 L $m^{-2}$ $min^{-1}$) conditions (Table S-2). Turbulence and NLR conditions on each ATS unit were held constant for multiple biomass harvests until replicate samples were collected, with sample sizes ranging from 2 to 7. Daily algal productivity was calculated as the total harvested biomass normalized over the harvest time period (typically 5 to 7 days). Mean productivity values for replicate turbulence/NLR conditions were calculated.

To combine experimental results from both methods of turbulence manipulation, the wave surge power (energy per unit time) was calculated for each flow combination. Power delivery can be considered proportional to both the volume and frequency of the wave surge. The power metric was calculated for each of the various flow rate/surge frequency combinations as the product of the energy delivered with each wave surge and the surge frequency (Table 1). The energy delivered with each surge was calculated as the gravitational potential energy of the volume of water falling from the wave surge bucket:

$$E = mg\bar{y}$$

where $m$ is the mass of water with each tip, $g$ is the acceleration of gravity, and $\bar{y}$ is the height of the centroid of the vertical cross-section of water at depth in the wave surge bucket for a given surge volume. Data were analyzed by calculating the mean and standard deviation of the productivity for each operating condition orthogonal to NLR with sample sizes ranging from 3 to 12 (Table S-3).

The main effects and interactions of NLR and each flow turbulence variable (volumetric flow rate with wave surge frequency held constant, wave surge frequency with volumetric flow rate held constant, and both combined as wave surge power) were analyzed by two-way unbalanced ANOVA. Significance reported indicates that the probability of the null hypothesis is $p<0.05$. Comparison of the means at each NLR was performed with a Bonferroni post-hoc test with a significance level of $p<0.05$.

## 3. Results

The algal productivity generally increased with increasing nitrogen loading rate (NLR) for all wave surge frequencies held at a constant volumetric flow rate (Fig. 2). The results trace a series of curves where productivity continued to increase for increasing NLR. Across all NLRs, the highest productivity was observed consistently at a wave surge frequency of 17 $min^{-1}$ with the greatest productivity (26.8 ± 4.2 g dW $m^{-2}$ $d^{-1}$) at high NLR. Results of ANOVA testing showed that the main effect of NLR was significant ($F[2,39]=28.8$, $p<0.0001$), as was the main effect of wave surge frequency ($F[2,39]=31.8$, $p<0.0001$). The interaction effect was non-significant ($F[4,39]=0.28$, $p=0.892$). Bonferroni post test results indicate that the pairwise comparison difference between wave surge frequencies of 17 $min^{-1}$ and 5 $min^{-1}$ was significant ($p<0.01$) for all NLRs, and between 17 $min^{-1}$ and 30 $min^{-1}$ was significant ($p<0.01$) for the medium NLR (0.8 g $NH_3$-N $m^{-2}$ $d^{-1}$). All other pairwise comparisons of differences were non-significant ($p>0.05$).

**Table 1**
Power calculations for the various flow characteristics for operating conditions for algal turf scrubbers. Six different combinations of volumetric flow rate and wave surge frequency were tested. The power of the wave surge was calculated as the product of the gravitational potential energy delivered with each wave surge and the wave surge frequency.

| Flow rate (L $m^{-2}$ $min^{-1}$) | Surge frequency ($min^{-1}$) | Power (J $m^{-2}$ $min^{-1}$) |
|---|---|---|
| 25 | 8 | 18.4 |
| 60 | 17 | 34.3 |
| 60 | 30 | 34.7 |
| 60 | 5 | 37.0 |
| 60 | 8 | 38.8 |
| 95 | 8 | 56.4 |

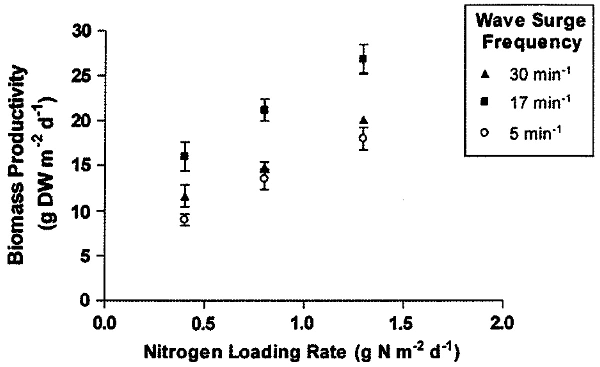

Fig. 2. Algal biomass productivity versus nitrogen loading rate for a range of wave surge frequencies at a flow rate of 60 L $m^{-2}$ $min^{-1}$.

The productivity also generally increased with increasing NLR for all volumetric flow rates held at a constant wave surge frequency (Fig. 3). Productivity was lowest at low NLR for all volumetric flow rates, increased for all flow rates at moderate NLR, and leveled out at the highest NLR. The productivity was similar for all volumetric flow rates at low and medium NLR (0.5 and 0.8 g $NH_3$-N $m^{-2}$ $d^{-1}$), yet diverged at high NLR, where the greatest productivity (26.4 ± 3.2 g dW $m^{-2}d^{-1}$) was seen at the highest volumetric flow rate of 95 L $m^{-2}$ $min^{-1}$. Results of ANOVA testing showed that the main effect of NLR was significant ($F[2,31]=56.0$, $p<0.0001$). The main effect of volumetric flow rate was marginally significant ($F[2,31]=2.74$, $p=0.080$). The interaction effect was non-significant ($F[4,31]=2.03$, $p=0.114$). Bonferroni post test results indicate that the pairwise comparison difference between productivities at the flow rates of 25 and 95 L $m^{-2}$ $min^{-1}$ was significant ($p<0.05$) for high NLR

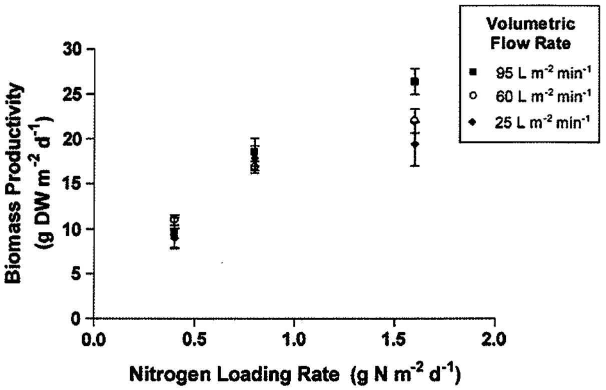

Fig. 3. Algal biomass productivity versus nitrogen loading rate for a range of volumetric flow rates for a wave surge frequency of 8 $min^{-1}$.

(1.6 g $NH_3$-N $m^{-2}$ $d^{-1}$). All other pairwise comparisons of differences were non-significant ($p > 0.05$).

Combining all results from the wave surge frequency and volumetric flow rate experiments using the wave surge power metric, the productivity increased with increasing NLR for all power levels (Fig. 4). The results trace a series of curves where the productivity was lowest at low NLR for all wave surge power levels, increased for all wave surge power levels at moderate NLR, and leveled out at the highest NLR. At low NLR, the productivity was highest for a wave surge power of 34.5 J $m^{-2}$ $min^{-1}$, and otherwise lower for all other wave surge powers. At medium NLR, productivity was not significantly different across all wave surge powers. At high NLR, the productivity diverged across all wave surge powers, where the greatest productivity ($26.4 \pm 3.2$ g dW $m^{-2}$ $d^{-1}$) was seen at the highest wave surge power of 56.4 J $m^{-2}$ $min^{-1}$. Results of ANOVA testing showed that the main effect of NLR was significant ($F[2,20] = 35.2$, $p < 0.0001$). The main effect of wave surge power was marginally significant ($F[1,20] = 4.40$, $p = 0.0488$). The interaction effect was non-significant ($F[4,31] = 2.57$, $p = 0.102$). Bonferroni post test results indicate that the pairwise comparison difference between 18.4 and 56.4 J $m^{-2}$ $min^{-1}$ was significant ($p < 0.05$) for high NLR (1.6 g $NH_3$-N $m^{-2}$ $d^{-1}$). All other pairwise comparisons of differences were non-significant ($p > 0.05$).

## 4. Discussion and conclusions

Because algal productivity generally increased with increasing nitrogen loading rate with no nitrogen accumulation in the reservoir, nitrogen availability was shown to be the main control on algal growth in most conditions. Flow turbulence, however, was shown to stimulate productivity under certain nitrogen loading rates. Increasing productivity versus nitrogen loading rate was observed for all wave surge frequencies with volumetric flow rate held constant (Fig. 2), and this relationship was consistent for all wave surge frequencies. For each NLR, productivity was at a maximum at a wave surge frequency of 17 $min^{-1}$, in the middle of the range of wave surge frequencies tested, and showed a decrease at higher and lower frequencies that was significant. This suggests that there is an optimum wave surge frequency for a given volumetric flow rate at which growth is maximized.

The productivity was observed to be especially responsive to the volumetric flow rate when wave surge frequency was held constant. At low and medium nitrogen loading rates, the productivity showed no significant difference across all flow rates. The productivity showed a significant increase, however, for increasing volumetric flow rates at high NLR (Fig. 3), with a globally high value ($26.4 \pm 3.2$ g dW $m^{-2}$ $d^{-1}$) at the maximum volumetric flow rate of 95 L $m^{-2}$ $min^{-1}$. In addition, the curve of productivity versus NLR exhibits a pattern of declining returns with increasing NLR for low and medium (25 and 60 L $m^{-2}$ $min^{-1}$) volumetric flow rates (Fig. 3), suggesting saturation of nitrogen availability. This trend was less pronounced, however, for the high volumetric flow rate (95 L $m^{-2}$ $min^{-1}$), where productivity was significantly higher than other flow rates at a high NLR. This suggests that turbulence from modulation of the wave amplitude, as set by the volume of water delivered with each wave surge, provides a subsidy to algal growth when nitrogen is not limiting.

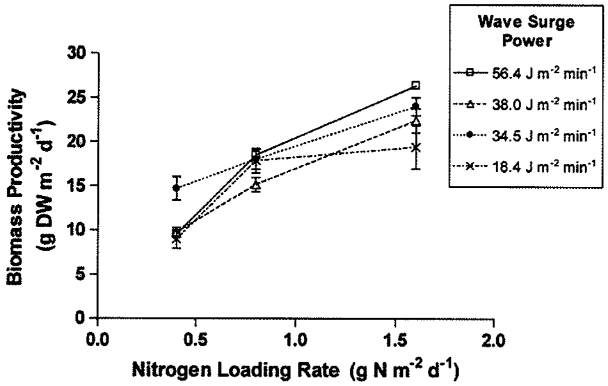

**Fig. 4.** Algal biomass productivity versus nitrogen loading rate for a range of wave surge power for all combinations of surge volumes and frequencies.

Wave surge power was a poor predictor of the productivity in an ATS. Power was calculated to put all flow rate-wave surge combinations on a common scale. All wave surge frequencies for a constant flow rate had similar wave surge power, and the power delivered to the algal bed was controlled strongly by the volumetric flow rate (Table 1). When wave surge frequency was varied at a constant volumetric flow rate, wave surge power varied over a narrow range (34 to 39 J $m^{-2}$ $min^{-1}$) for all conditions. Wave surge power was a control on the productivity at both low and high NLR (Fig. 4). At low NLR, productivity was maximized at the middle of the range of wave surge power (34.5 J $m^{-2}$ $min^{-1}$), suggesting a strong influence of wave surge frequency for this particular operating condition. At high NLR, productivity was greatest at the highest wave surge power (56.4 J $m^{-2}$ $min^{-1}$) and least at the lowest power (18.4 J $m^{-2}$ $min^{-1}$), suggesting a strong influence of wave surge volume for this particular operating condition. The peak productivity at the lower wave surge power at low NLR emerges as a result of modulation of the surge frequency, while the peak at the higher wave surge power at high NLR emerges as a result of modulation of the amplitude of the wave surge as set by the volumetric flow rate. This suggests that the wave surge characteristics impact the productivity in two separate ways in an ATS. First, the wave surge affects the availability of light to the algal turf by minimizing self-shading through induced motion of the algal filaments. The maximum productivity is thus calibrated to an optimum frequency of this motion, which is generally seen as a peak of production at lower wave surge power and is thus observed at low NLR. Second, the wave surge affects the availability of nitrogen to the algal filaments through increased mixing thereby reducing the diffusive boundary layer surrounding the algal turf. Maximum productivity is thus calibrated to a maximum mixing power, and is represented by the upper peak of productivity at high wave surge power in conditions of higher nitrogen availability. This suggests that effects of frequency modulation and amplitude modulation of the wave surge dominate in different ranges of overall wave surge power and nutrient availability.

Based on these observations, a causal relationship model can be developed to represent the interrelationships that link the design and operation of an ATS, the consequent effects on light and nutrient factor availability, and the resulting effect on the growth of algae (Fig. 5). In this model, the parameters that are directly controlled by the ATS operator include the wave surge bucket volume, volumetric flow rate, water depth, light intensity, and nitrogen loading rate. The rate of energy delivery to the algae, expressed as bed turbulence, is directly influenced by the amplitude and frequency of the wave surge which are functions of the wave surge bucket volume and volumetric flow rate. Turbulence is also inversely affected by water depth, where deeper water may dampen the effect of the wave surge by increasing the rate of dispersion of the wave surge energy. Increased bed turbulence is envisioned to have both positive and negative effects on parameters that affect algal productivity. Bed turbulence directly affects the light availability through induced motion of the algal filaments, reducing self-shading by the algal community. Bed turbulence inversely affects the thickness of the diffusive boundary layer at both the turf and filament scale, thereby increasing the availability of nitrogen to the algal filaments. Increased availability of light and nitrogen increase the algal productivity and thus standing algal biomass increases. Bed turbulence also directly influences scour, however, which inversely affects algal productivity by removing productive biomass from the algal bed. Increased biomass density

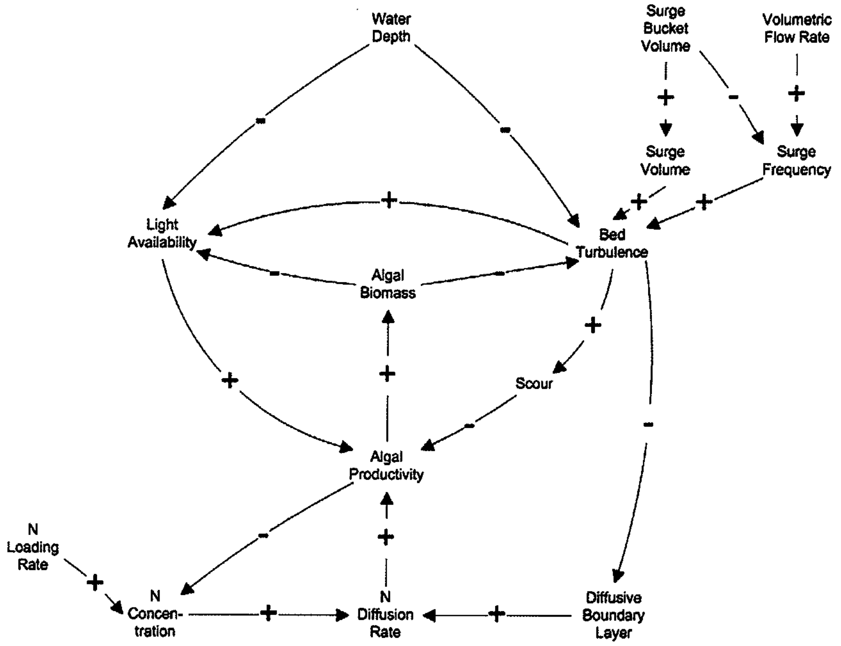

**Fig. 5.** A causal relationship model of the environmental and design parameters in an algal turf scrubber that affect algal productivity, showing the role of turbulence on diffusion rates and scour. A "+" indicates a direct relationship (for example, an increase in light availability causes an increase in algal productivity); and a "−" indicates an inverse relationship (for example, an increase in water depth causes a decrease in light availability).

inversely affects light availability, through self-shading within the algal canopy, and on the bed turbulence itself, through dampening and dissipation of the wave surge energy.

These relationships have implications for the optimization of the ATS process for algal production for water treatment through uptake and removal of dissolved pollutants, as optimization can be done with strategic modification of the wave surge. The engineering efficiency of the ATS process as a water treatment option favors the highest algal productivity at the lowest expenditure of energy. Therefore, design of the ATS process favors a peak production at lower volumetric flow rates, as volumetric flow translates directly to pumping power expended. Results of this research show that algal production can be maximized at lower wave surge volumes through optimization of the wave surge frequency, presumably providing a subsidy through the combined effects of increased light availability (through the reduction of self-shading) and through increased nitrogen availability (through the reduction of the diffusive boundary layer surrounding the turf), meanwhile reducing the potential for scour and loss of algal biomass from the system. With a major cost of large-scale systems potentially coming from requirements for pumping and providing flow turbulence, these results have implications for refining the design of ATS installations to improve efficiency and reduce cost of operation.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.algal.2013.01.001.

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