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Modifying the high rate algal pond light environment and its effects on light absorption and photosynthesis

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ABSTRACT

The combined use of high rate algal ponds (HRAPs) for wastewater treatment and commercial algal production is considered to be an economically viable option. However, microalgal photosynthesis and biomass productivity is constrained in HRAPs due to light limitation. This paper investigates how the light climate in the HRAP can be modified through changes in pond depth, hydraulic retention time (HRT) and light/dark turnover rate and how this impacts light absorption and utilisation by the microalgae. Wastewater treatment HRAPs were operated at three different pond depth and HRT during autumn. Light absorption by the microalgae was most affected by HRT, significantly decreasing with increasing HRT, due to increased internal self-shading. Photosynthetic performance (as defined by P_{max}, E_k and α), significantly increased with increasing pond depth and decreasing HRT. Despite this, increasing pond depth and/or HRT, resulted in decreased pond light climate and overall integrated water column net oxygen production. However, increased light/dark turnover was able to compensate for this decrease, bringing the net oxygen production in line with shallower ponds operated at shorter HRT. On overcast days, modelled daily net photosynthesis significantly increased with increased light/dark turnover, however, on clear days such increased turnover did not enhance photosynthesis. This study has showed that light absorption and photosynthetic performance of wastewater microalgae can be modified through changes to pond depth, HRT and light/dark turnover.

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1. Introduction

Wastewater treatment ponds rely on microalgal photosynthesis and growth to assimilate dissolved nutrients and to provide the necessary oxygen to drive aerobic bacterial degradation of organic compounds (Oswald, 1988). Conventional pond systems are used worldwide but often have limited capacity to remove nutrients and pathogens due to low light availability and microalgal biomass, often resulting in poor effluent quality (Craggs et al., 2013). High rate algal ponds (HRAPs) have long been recognised for their superior wastewater treatment and higher microalgal productivity over conventional wastewater treatment ponds (Faleschini et al., 2012). There has been renewed interest in their use because of increased legislative requirements to reduce nutrient loading from wastewater discharges into receiving waters (Hu et al., 2008; Rawat et al., 2011). HRAPs are shallow (typically <500 mm deep), raceway-style ponds, that allow for the proliferation of microalgal biomass which can be harvested and used for production of fertiliser, protein-rich feed and biofuel (Craggs et al., 2014). While photobioreactors are capable of producing microalgal biomass at much higher concentrations than in HRAPs, earth-lined HRAPs are considered a more viable option for commercial-scale biofuel production due to their more simple design and construction as well as reduced capital and operational costs (Hadiyanto et al., 2013). Light limitation is regarded as one of the main controllers of microalgal performance in HRAPs and its availability impacts on both the rate and efficiency of photosynthesis and ultimately productivity (Grobbelaar, 2009; Beardall and Raven, 2013). Microalgal productivity in a full-scale wastewater HRAP was correlated to the daily mean irradiance a microalga was exposed to when carbon was not limiting (Sutherland et al., 2013). While nutrients can be stored and recycled by the cell, photons can only be absorbed once and have to be instantaneously transformed into chemically bound energy, or dissipated out of the cell again (Diehl et al., 2002). In order to maximise productivity it is important to understand how the operation of HRAP affects both the availability of light as well as the efficiency of light absorption and utilisation by the microalgae. The amount of light available to the microalgae is governed by both the degree of attenuation within the pond and internal self-shading within the cell. Light passing through the water column declines exponentially with depth as the microalgae absorb or scatter the light. Over 80% of the light entering an HRAP is absorbed by the microalgae and the high biomass leads to strong light attenuation, resulting in up to one third of the water column receiving insufficient light to support net photosynthesis (Sutherland et al., 2013).

Depth modifies the light climate within the pond both directly, through changes in the light path length, and indirectly, through biomass mediated light attenuation. Shallow ponds shorten the light path length within the pond and the result is higher microalgal biomass concentrations, which results in higher light attenuation (Sutherland et al., 2014a). In an experiment comparing pond depths, the higher light attenuation in 200 mm deep HRAPs off-set the shorter light path, resulting in vertically mixed cells experiencing the same sum total of irradiance as those in 400 mm deep HRAPs (Sutherland et al., 2014a). While biomass concentrations are typically higher in shallower ponds, deeper ponds offer greater areal productivity and volumetric nutrient removals. 400 mm deep HRAPs had significantly greater areal productivity and treated larger volumes of wastewater to the same effluent water quality standard throughout the year, compared to 200 mm deep HRAPs (Sutherland et al., 2014a). However, deeper ponds can result in increased harvesting costs due to the increased pond volume (Grobbelaar, 2013).

High attenuation in the shallow ponds can be off-set directly through changes in biomass concentration, or indirectly, through changes in the frequency of the light/dark cycle a cell experiences. Biomass concentration can be modified by altering hydraulic retention time (HRT), as well as culture depth, and light/dark cycles modified through turnover rate. Modifications to the pond's light field may also affect the light absorption capacity of the microalgal cells, which can adapt to environmental conditions by changes in pigment composition (Nelson et al., 1993). The paper examines the role of pond depth and HRT on the pond light climate, microalgal light absorption and photosynthesis and how medium frequency (seconds to minutes) light/dark cycles can further modify photosynthetic rates.

2. Methods

2.1. *High rate algal pond operations and environmental variables*

The study was conducted outdoors during autumn at the Ruakura Research Centre Hamilton, New Zealand (37°47′S, 175°190′E). Operational treatments of three pond depths and three hydraulic retention times (HRT) were established in identical HRAPs that were 2.2 m long and 1 m wide, with a surface area of 2.23 m^2. The paddlewheels were set to a rotational speed that resulted in a linear velocity of 0.2 m s^{-1}. The HRAPs received primary settled domestic wastewater which was pumped into the ponds every 4 h over a 24 h period. Supplementary carbon was added to the ponds in the form of 1% CO_2 gas. The CO_2 addition system consisted of a CO_2 gas cylinder, gas regulator, air pump, gas flow meter and gas diffusers. The CO_2 was bubbled into the bottom of the ponds at a flow rate of 1.6 L min^{-1}. This was sufficient to maintain the daytime pH between 7.6 and 7.9 in all HRAPs. Pond temperature over the course of the experiment ranged from 13.4 to 15.1 °C. At the start of the experiment, the HRAPs were inoculated with wastewater algae from an adjacent pilot-scale HRAP, which was dominated (90%) by the colonial green alga *Mucidosphaerium pulchellum* (HC Wood) C. Bock, Proschold & Krienitz.

2.2. *Organic matter and chlorophyll* a *biomass*

For organic matter, a known volume of HRAP culture was filtered through a pre-rinsed, pre-combusted and pre-weighed Whatman GF/F filter, oven dried (105 °C) and weighed, once cooled, to determine the total suspended solids (TSS) concentration. Filters were then combusted at 450 °C for 4 h, cooled in a desiccator, and re-weighed to determine the ash