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A novel strategy for sequestering atmospheric CO_2: The use of sealed microalgal cultures located in the open-oceans

Ron G. Smith[a,*], Ian J. Smith[b], Brendan D. Smith[c]

[a] Open Learning Division and Department of Biological Sciences, Thompson Rivers University, Kamloops, British Columbia, Canada V2C 0C8
[b] Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta, Canada T6G 2R3
[c] Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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ABSTRACT

Here we introduce the concept of utilizing microalgal cultures grown in sealed enclosures located in open-oceans to sequester CO_2 from both the atmosphere and flue gases. This method of sequestering CO_2 overcomes the major limitations of sequestering appreciable CO_2 using existing technologies, such as microalgae cultured in open ponds, photobioreactors, or continuous bioreactors on land or near shore. Open ponds require vast surface areas and generally have low net productivity due to light and temperature limitations during the night and winter periods. Continuous algal bioreactors are much more productive, but this comes at the expense of controlling the parameters of the bioreactors, such as light regimes and temperature. The additional energy inputs used to control the parameters of the bioreactors negate their effectiveness of sequestering CO_2 on a global scale. Near shore photobioreactors lack the capacity to be scaled up to sequester appreciable CO_2. Alternatively, we propose that atmospheric CO_2 and/or the flue gases (containing CO_2, NO_x and SO_x) can be collected and transferred to enclosed vessels or bags containing algal cultures situated in the open-oceans. The productivity of the enclosed cultures could be optimized by moving the bags to various locations in the oceans, allowing for control of temperature, irradiance, and hours of daylight.

Theoretical calculations using demonstrated CO_2 sequestration efficiencies and production rates of microalgal batch cultures suggest that 4 cylindrical enclosures, each with a diameter of 100 m and a depth of 40 m would be able to sequester the CO_2 emitted by a 500 MW coal-fired generating plant. On a grander scale, using the same CO_2 consumption rates and the enclosures described above, roughly 14,000 enclosures could reduce the CO_2 in the troposphere by 1 ppm on a yearly basis, representing half of the total CO_2 added to the atmosphere annually.

1. Introduction

It is clear from the data collected at the Mauna Loa site that atmospheric CO_2 levels are increasing exponentially, currently at a rate of about 2 ppm annually [1,2]. Noteworthy from the same data, however, is the observation that the increasing trend in CO_2 levels show an annual oscillation, with atmospheric CO_2 levels decreasing in the Northern hemisphere by about 5 ppm during the summer months, while increasing by about 7 ppm in the winter months. Given the amplitude of the annual oscillation it is conceivable that atmospheric CO_2 levels could be stabilized, or even reduced, by reducing the amount of anthropogenic CO_2 emitted coupled with increasing CO_2 sequestration from the atmosphere collectively using varying techniques throughout the year.

Estimates indicate that about 30 billion tons of CO_2 are emitted annually on a global scale. Roughly, 40–45% of these emissions are a result of point sources such as electrical generation and cement plants [3]. Several physical storages [4–6] and physio-chemical strategies have been proposed to sequester CO_2 emissions from flue gases [7,8]. Biologically, microalgal cultures have been proposed as living catalysts to sequester CO_2 from flue gases or carbonated membranes [9–14]. One major advantage of using microalgae to sequester CO_2 is that the harvested algae have economic value, used to produce, among other goods, biodiesel, ethanol, or methane [15–17], thus offsetting infrastructure and operating costs. The production and use of the abovementioned renewable energy products would also importantly reduce our dependence on fossil fuels. A second advantage to using microalgae to sequester CO_2 is that the algae can also eliminate the polluting NO_x and SO_x present in flue gases [8,18,19]. However, we are not aware of any studies suggesting that we can use the above-mentioned techniques, either solely or combined, to sequester an appreciable proportion of the CO_2 we annually emit into the atmosphere.

* Corresponding author.
E-mail address: ronsmith@tru.ca (R.G. Smith).

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In this mini-review we briefly discuss the requirements for microalgal growth, and the efficacies of two commonly referred to microalgal sequestration systems: open ponds and bioreactor systems. Importantly, we go on to introduce an adaptation to systems used for sequestering CO_2 using microalgae: situating microalgal CO_2 sequestration enclosures in the open-oceans. This novel adaptation provides an economical and scalable approach to CO_2 capture, and if implemented has the potential to sequester billions of tons of CO_2 from the atmosphere and/or flue gases on an annual basis.

2. Requirements for microalgal growth

All microalgae require CO_2, light, nitrogen (most commonly in the form of NH_4^+ or NO_3^-), PO_4^-, SO_4^- and micronutrients (notably calcium, magnesium, chloride, boron, manganese, zinc, copper, molybdenum, iron) to sustain their phototrophic growth see [19,20]. Individual species have different requirements for their optimal growth and these must be noted when designing the culturing systems used to maximize biomass production. Generally, one of the requirements listed above will limit the biomass production of a natural microalgal population or culture. Many examples of this process have been documented including algal blooms that occur with the addition of nitrogen resulting from up-welling and fertilizer runoff, and addition of phosphates from waste water. Rising seawater temperatures in temperate regions are also known to cause red tide events. In another example, pertinent to the sequestration of CO_2, the Southern Ocean and tropical waters have relatively low algal productivity due to limiting Fe levels [8,21,22]. It has been shown that Fe could be added to the oceans and the resulting algal blooms will aid in sequestering atmospheric CO_2 [8,21,22]. This is undoubtedly the case, but scaling up to be effective would be daunting and ecologically dangerous. As well, it would be difficult to harvest the microalgae from the ocean for commercialization.

Many microalgae tend to photosynthetically saturate at low irradiances but are not generally photoinhibited [23,24]. However, even microalgae like *Dunaliella tertiolecta* and *Synechocystis* sp. that exhibit low light saturation levels on the order of 100 $\mu E\, m^{-2}\, s^{-1}$ can become light-limited in dense culture [7,24]. Thus, for maximum photosynthetic efficiency and microalgal productivity the light throughout the cultures should range between 100 to over 2000 (sunlight at the equator) $\mu E\, m^{-2}\, s^{-1}$. Supplying adequate light to scaled-up large CO_2 sequestration systems is potentially the most difficult and costly hurdle. Interestingly, when light is supplied at over-saturating levels, algal productivity is not diminished when the light is supplied in short light/dark cycles. Vejrazka and colleagues [25] reported that cultures of *Chlamydomonas* attained the same growth rates when illuminated with an irradiance of 1000 $\mu E\, m^{-2}\, s^{-1}$ subjected to a light/dark cycle of 100 Hz as when illuminated with a constant irradiance of 100 $\mu E\, m^{-2}\, s^{-1}$. This allows the microalgae to be produced at maximal rates in vessels that have dark and light zones given there is optimal mixing within the cultures.

The nutrients required by algal cultures can be added to the culture vessels at the required concentrations, keeping in mind that the NO_x and SO_x present in flue gases will reduce the amount of exogenous nitrogen and sulfur required [8,19,20]. In addition, many species of cyanobacteria fix nitrogen, transforming N_2 into NH_4^+. The process results in these microalgae having relatively low C/N ratios, raising the possibility of composting the algae produced in the cultures [26]. Using the compost as fertilizer would reduce our reliance on the industrial Haber process that currently accounts for roughly 10% of the natural gas combusted annually.

Microalgal growth is typically limited by light, nitrogen, phosphate, or Fe, and not by CO_2. This is due to the naturally low levels of these required inputs and the efficiency at which microalgae take up inorganic carbon (CO_2 and HCO_3^-). For instance, microalgal species, such as the cyanobacterium *Synechococcus* sp., can concentrate inorganic carbon up to a thousand-fold in support of photosynthesis see [6,27,28]. The CO_2 concentrating mechanisms used by microalgae result in the microalgae attaining CO_2 compensation points, the CO_2 concentration of a culture where the amount of CO_2 taken up by photosynthesis is equal to that released by respiration, of 0.2 $\mu L\, L^{-1}$ in alkaline conditions and 5 $\mu L\, L^{-1}$ in acidic conditions [29]. The CO_2 concentrating mechanisms of microalgae also mitigate photorespiration caused by the high oxygen content created by the photosynthetic process. Regardless of the above, microalgal cultures are usually bubbled with air or air supplemented with added CO_2. Doing so maintains the CO_2 concentration in the culture above the compensation point and increases the productivity of the system by mixing the cultures see [9,11,30].

The CO_2 sequestered by the microalgae is transformed into sugars by the algae using the Calvin cycle. The sugars are then converted into the other carbon containing compounds needed by the microalgae to grow and divide. Excess fixed carbon is stored in the form of starch or oil depending on the species. The algae or their products can be harvested for food, biodiesel, or used to produce ethanol or CH_4. The production of biodiesel, ethanol, and CH_4 could all be used as alternatives to fossil fuels. Further, the excess fixed carbon can be metabolized via secondary metabolic pathways that produce compounds that are useful in cosmetic and pharmaceutical manufacturing [30,31]. It should be noted that microalgae can be genetically modified such that they can sequester CO_2 to an even greater extent, as demonstrated by Li and coworkers [13], or so that they produce “designer” bioproducts. O_2, the by-product of photosynthesis, can also be collected and used in commercial enterprises see [32]. Thus, as discussed briefly below, the products created during the CO_2 sequestration process can be commercialized and used to offset the costs of culturing the microalgae and reduce our demands on fossil fuels.

2.1. Open microalgal sequestration systems

Open microalgal sequestration systems involve cultivating microalgae in shallow ponds or raceway systems see [8,9,11,15,16,30]. They are a low tech, low cost approach to cultivating microalgae and sequestering CO_2 (see Table 1). These systems do not require many inputs and can sequester CO_2 at rates of almost 2 $g\, L^{-1}\, d^{-1}$ [30]. However, the practicality of using microalgal ponds to sequester appreciable CO_2 is limited by the inability to optimize most of the important parameters affecting CO_2 sequestration (irradiance and temperature), and the loss of productivity in darkness and in the winter months. As important, with regard to sequestering appreciable CO_2, the pond surface area required to obtain high CO_2 sequestration rates near point source emitters is unworkable on a world-wide scale, given that there are roughly 50,000 stacks currently operating worldwide. For instance, one 500 MW coal-fired generation plant releases on the order of 9×10^6 kg of $CO_2\, d^{-1}$ [33]. An open pond system that is 0.3 m deep with a total

Table 1
Comparisons of several attributes of open, continuous, and open-ocean enclosure systems used for sequestering CO_2 by microalgae.

	Open Systems/ Raceways (land-based)	Continuous Bioreactors (land-based)	Open-Ocean Enclosures (ocean-based)
Productivity	low	high	medium
Contamination risk	high	low	low
CO_2 and water loss	high	low	low
Process control	difficult	easy	medium
Scale up	easy	difficult	easy
Construction costs	low	high	low
Ongoing energy inputs	low	high	low
Temperature control	poor	high	high
Transportability	NA	NA	good

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