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A computational model of algal growth integrating mixing

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In order to make production of algal biofuels fuels more economically feasible and environmentally friendly, steps must be taken to optimize algal growth for higher yields as a function of design, environmental, and water quality parameters. Laboratory scale experiments have shown a positive correlation between mixing and growth rate suggesting this could be a promising way to increase productivity. However, these experiments can be time and capital intensive making them ill suited to large-scale factorial experiments. Development of computational models of algal growth in open ponds could serve as an invaluable tool for prediction and optimization of biomass production based on factors such a environmental conditions, algal species, and mixing. A biologically based model of algal growth utilizing finite difference to analyze the effect of mixing on algal growth. The model was used to simulate a full factorial design with factors of temperature, solar irradiation, and mixing rate. A statistical analysis was then conducted to analyze the effects and interactions of key variables on algal growth. Results indicate that mixing has a statistically significant effect of biomass production. This model could be used for optimization of mixing based on algal species, weather conditions, and pond design.

Introduction

Increasing biomass yields is a key step in making algal biofuels more economically favorable. Mixing has been shown, through experimentation at the bench and pilot scale, to have an affect on algal growth and could be used to increase algal yields on the commercial scale. However, due to the complex interactions of variables affecting growth, experimental results are not always consistent. Computational modeling could be used to better understand these interactions and optimize mixing in order to increase growth rates.

Methods

Algal growth was modeled using a finite difference model of heat and species transport. The governing equations can be described as:

$$\frac{k}{\rho C_p}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)=\frac{\partial T}{\partial t} \qquad q"=[f(rad)f(conv)f(evap)]$$

$$D_{AB}\left(\frac{\partial^2 c_A}{\partial x^2}+\frac{\partial^2 c_A}{\partial y^2}\right)+\dot{n}_A=\frac{\partial c_A}{\partial t} \qquad \dot{n}_A=P_m[f(T)f(I)]$$

- Algal growth was modeled as a function of maximum growth rate, light, and temperature.
- The heat flux at the surface of the pond was modeled as a function of radiation, convection, and evaporation.
- Temperature was modeled as a cosine function and solar intensity as a step function.
- Mixing time is the time for algae to complete one clockwise rotation through the domain, see figure 1.
- A full factorial design for three levels of light and temperature and six levels of mixing was simulated, see table 1.
- ANOVA and post-ANOVA means comparison (Tukey's method) were used to analyze the data, see table 1 and figures 2 and 3.

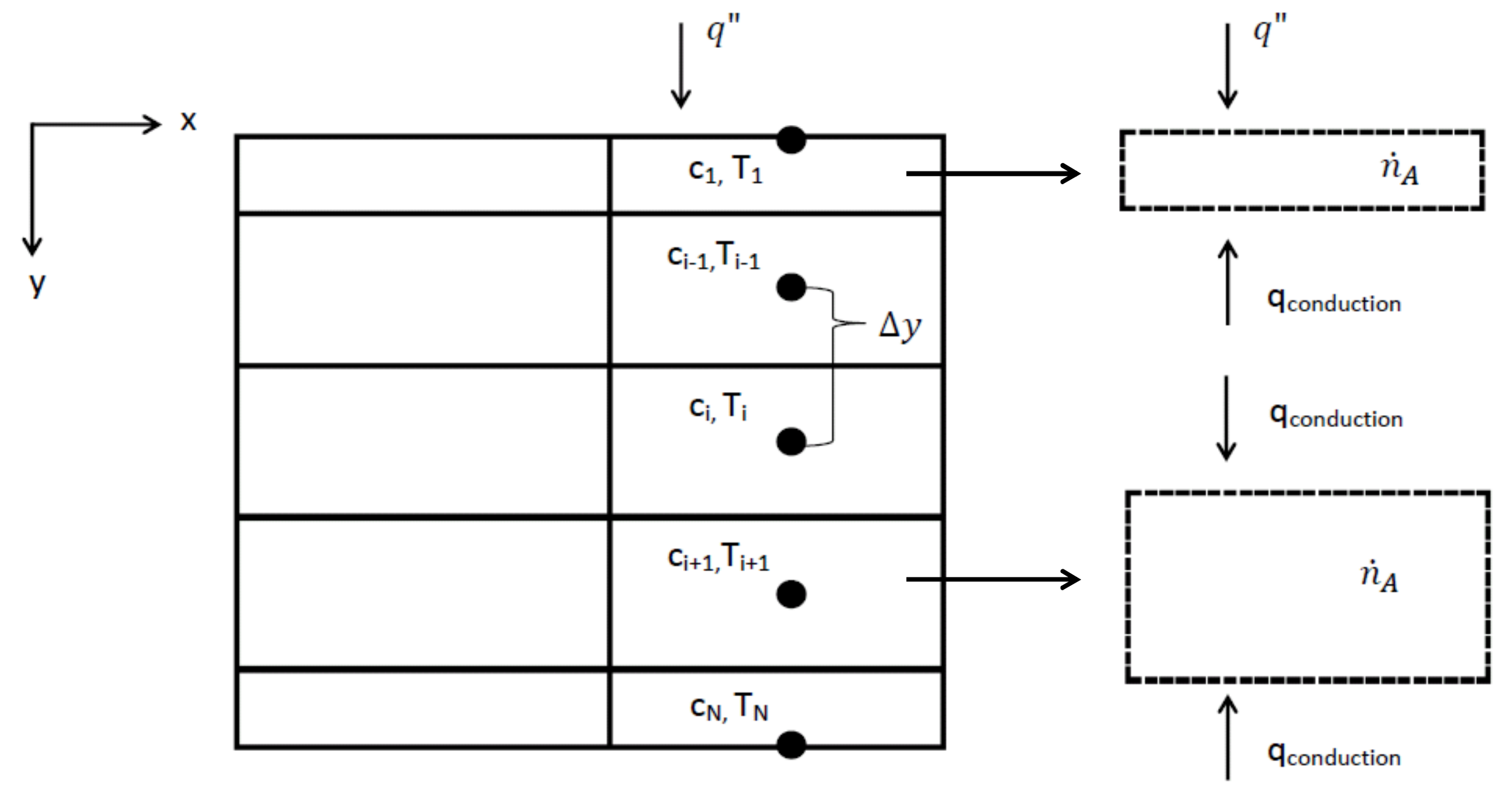

Figure 1: Computational domain and boundary conditions for the 2D finite difference model.

Table 1: Parameters used in full factorial design.

	Low	Medium	High
Temperature [C]	12 ± 2	22 ± 2	32± 2
Intensity [W m^{-2}]	300	600	900
Mixing time	30 s (A)	30 min (B)	1 h (C)
Mixing time	2 h (D)	4 h (E)	unmixed (F)

Results

Table 2: Least squares means (LSMEAN) value for biomass concentration [g m^{-3}] at day seven for the full factorial design, all factors and interactions were found to be significant with α=0.05. The key for temperature, solar intensity and mixing levels are presented in table 1.

Temperature	Solar Intensity	Mixing level	LSMEAN	Temperature	Solar Intensity	Mixing level	LSMEAN	Temperature	Solar Intensity	Mixing level	LSMEAN
mid	mid	C	563.8	low	mid	E	433.1	mid	mid	F	324.9
mid	mid	B	562.2	high	low	A	428.3	high	mid	F	312.9
mid	mid	D	561.7	high	mid	A	423.2	low	mid	F	300.6
mid	mid	A	550.9	low	high	B	419.0	mid	low	E	299.1
mid	high	A	550.3	mid	high	D	418.3	low	mid	B	279.8
mid	low	A	549.7	high	high	A	417.9	high	high	E	277.6
mid	mid	E	548.1	high	low	D	404.9	low	high	E	262.3
mid	high	B	540.9	low	mid	D	403.7	mid	high	E	260.5
high	low	B	540.2	mid	low	C	384.3	low	low	A	185.4
high	mid	D	539.5	low	high	E	382.9	low	mid	A	185.4
high	mid	E	537.3	high	high	B	373.0	low	high	A	185.2
high	mid	C	529.0	mid	high	E	366.1	high	low	F	178.9
high	mid	B	504.7	high	high	C	350.3	mid	low	F	178.1
high	low	C	482.0	low	mid	C	350.1	low	low	B	174.1
mid	high	C	480.2	high	low	E	344.4	low	low	C	169.3
low	high	C	465.0	mid	low	D	335.3	low	low	D	165.7
mid	low	B	447.5	high	high	D	334.4	low	low	E	164.3
low	high	D	437.8	high	high	E	332.7	low	low	F	147.2

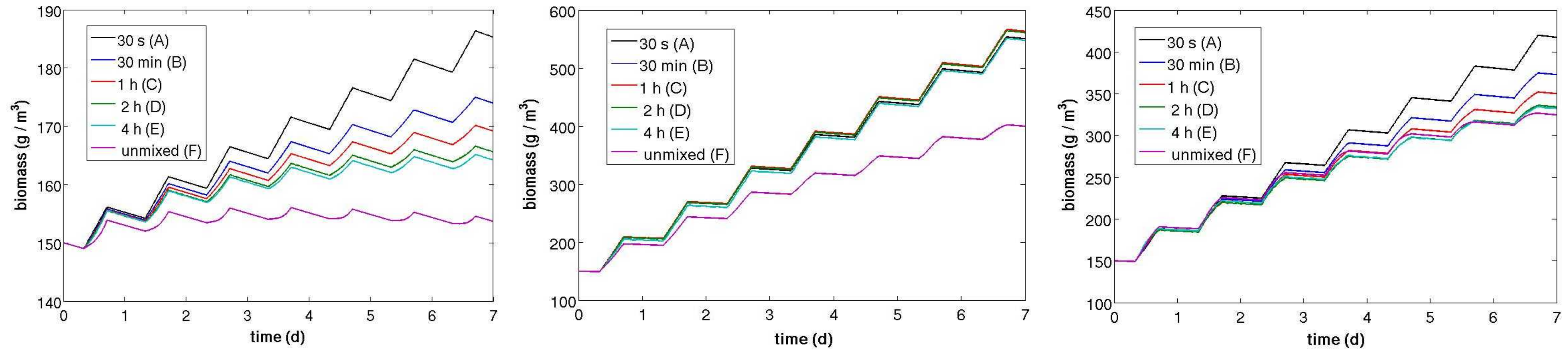

Figure 2 a, b, c: Biomass concentration as a function of time with both temperature and light held at low, medium, and high levels, respectively for ease of visualization. The key for temperature, solar intensity and mixing levels are presented in table 1.

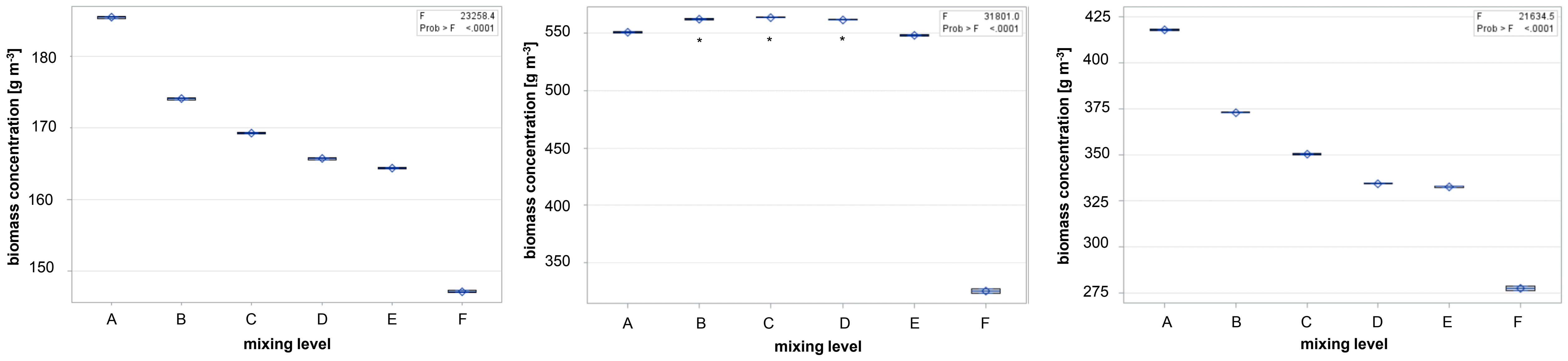

Figure 3 a, b, c: Biomass concentration as a function mixing rate at day seven with both temperature and light held at low, medium, and high levels, respectively. Levels with asterisks are not significantly different using Tukey's method of post ANOVA means comparison. The key for temperature, solar intensity and mixing levels are presented in table 1.

Conclusion

- The model indicates that mixing can increase biomass production under certain environmental conditions.
- Under non-ideal conditions, high and low levels of solar intensity and temperature, mixing increases biomass production
- Under ideal conditions, mid level of solar intensity and temperature, low levels of mixing produce the highest biomass concentrations.
- Mixing does not appear to have a significant effect while biomass concentration is low
- More advanced computational models could be used to optimize systems for higher biomass yields based on mixing and environmental conditions.

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