Chapter 4: Scaling and Integration

Extrapolating Lab Scale Results to Full Scale Systems

Convener: Michael Huesemann

Discussion:

- It is very difficult to use currently published microalgae growth data obtained from laboratory studies to predict how strains will perform in large outdoor ponds. There are several reasons:
    - First, laboratory studies are generally performed under controlled conditions (i.e., constant and relatively low light intensity using an artificial light source with spectrum different from that of sunlight, constant temperature, perfect mixing) that are not representative of outdoor ponds (i.e., variable and relatively high sun light intensity, variable temperature, imperfect mixing). In addition, the geometry of laboratory culture vessels is often very different from the structure of large outdoor pond cultures.
    - Second, while it is relatively straightforward to predict the performance of large-scale cultures from small-scale experiments of heterotrophic (glucose, starch, etc.) fermentations (i.e., as long as there is good mixing and gas mass transfer, scale has little impact on the fermentation kinetics and yields), this is not possible for photoautotrophic cultures since light is limiting biomass growth and light attenuation is affected by both the properties of the cells (i.e., extinction coefficient) and the geometry of the culturing system (i.e., pond depth or photo bioreactor thickness).
- There are currently two approaches for using laboratory culturing data to predict the productivity performance in large-scale ponds.
    - The first approach is biomass growth modeling, where a microalgae strain is characterized in the laboratory and the resulting physiological data (i.e., the effects of light and temperature on the specific growth rate and biomass loss rate in the dark, light attenuation characteristics) serve as model input parameters to predict the performance of large outdoor pond cultures. The best models are those that integrate biomass growth equations with nutrient (CO_2, nitrate, phosphorus) uptake and fluid dynamics (mixing, laminar versus turbulent flow, stagnant areas).
    - The second approach is to run laboratory-scale outdoor pond simulators under conditions that simulate the light intensity and water temperature fluctuations encountered in outdoor ponds at the chosen geographic location and season. The problem is the growth performance of microalgae strains in these laboratory-scale pond simulators has not been validated against their performance in real outdoor ponds. Compared to a biomass growth model that can be used to predict the performance of outdoor ponds under any conditions (i.e., geographic location and time of year), a pond simulator experiment can only predict the performance of a

single hypothetical outdoor pond at a given time (i.e., pond simulators generate much more limited data).

- One company indicated that they are using both approaches for scaling up from laboratory cultures. They have indoor pond simulators that are used to predict the performance of their outdoor ponds. Furthermore, they also extensively characterize promising strains and use the resulting physiological parameters to predict the growth performance in outdoor ponds. Their scale-up predictions do not include biotic challenges (such as invasive species or predators) or imperfect pond mixing. Both of these problems will result in suboptimal growth performance in large outdoor ponds.
- A key concern at the recent BETO Peer Review[6] was the rather limited evidence of improved biomass productivities that are needed to make microalgae biofuels cost-competitive. How can these scale-up models be used to actually improve biomass productivity in outdoor ponds? Models can help in improving biomass productivity in outdoor ponds in at least three ways:
    - First, a sensitivity analysis of a validated growth model can inform experimentalists which physiological properties have the greatest impact on biomass productivity. For example, if the model indicates that cells with smaller light extinction coefficients have greater biomass productivities, experimentalists could work on reducing the chlorophyll light antennae responsible for light absorption and light attenuation. Similarly, if the model predicts that biomass losses in the dark have a profound effect on overall biomass productivity in outdoor ponds, experimentalists could work on strategies for minimizing or inhibiting biomass loss overnight. Furthermore, if the model indicates that high biomass productivities in outdoor ponds located in southern states can only be achieved by strains that are tolerant to high temperatures, experimentalists could create temperature-tolerant strains.
    - Second, a biomass growth model in conjunction with the biomass assessment tool (BAT) can be used to identify the outdoor pond location(s) for the given strain that results in the optimum annual biomass productivity.
    - Third, a biomass growth model can also be used to identify the pond culture operation strategy (i.e., pond depth, dilution rate, choice of harvesting time) that results in the highest achievable biomass productivity.
- There has to be better interaction between modelers and experimentalists. Modelers, in the absence of experimentalist collaborators, create models that are populated with limited experimental data, often taken from the literature. Experimentalists, in the absence of modeling collaborators, generate large quantities of experimental data, but much of it may not be useful to modelers. Therefore, a close collaboration between modelers and experimentalists is necessary, where the model informs what experimental parameters should be measured and the experimental pond culture data inform where the model has to be improved.
- The importance of strain-specific (rather than generic) biomass growth models was stressed.

[6] For information on the 2013 Bioenergy Technologies Office Peer Review and to download the Final Report, please visit bioenergy/peer_review2013.html

- The need for scale-up (growth, harvesting, extraction, HTL) models was also stressed.
- It is not only important to determine the biomass productivity of a given strain but also the cost of production. This is important for the down-selection of strains and processes.
- The need for fully instrumented, ideally automated, large scale ponds was mentioned so that sufficient data can be collected for validating and testing models. For example, light, temperature, pH, fluid flow velocity, and even biomass concentration (by turbidity meter or reflectance spectroscopy) could potentially be measured automatically and logged via computer.
- It would also be useful to devise laboratory-scale systems for testing down-stream processes such as harvesting, extraction, or HTL, since these processes are likely to be influenced by variable feedstock characteristics. There was some agreement that scale-up of these abiotic processes is easier to predict than biotic processes (such as growth in ponds and photobioreactors) since they are traditionally treated as "unit processes/operations" in chemical engineering. However, feedstock variability has to be taken into account, possibly by establishing a feedstock tolerance range for these downstream processes.

Guiding Questions:

1. What is the time horizon for this topic or issue; will this impact algal biofuel production in the near, mid, or long term?
    - The time frame is short term to medium term for these research needs.
2. Has this topic been included in the National Algal Biofuel Technology Roadmap; and if not, should it be?
    - The issues of scale-up and predicting large pond performance from laboratory scale data, was not mentioned in the previous DOE Roadmap and is very important.
    - Scale-up issues were only mentioned in relation to strain robustness but not in terms of predicting biomass productivity in outdoor ponds from laboratory studies, as on page 9 of the Roadmap: "Previous studies revealed that algae strains tested in the laboratory do not always perform similarly in outdoor mass cultures (Sheehan et al., 1998). Therefore, to determine a strain's robustness, small-scale simulations of mass culture conditions will need to be performed. The development of small-scale but high-throughput screening technologies is an important step in enabling the testing of hundreds to thousands of different algal isolates."
3. What is the BETO Algae Program role in furthering this topic or addressing this issue?
    - The role of DOE should be to fund collaborative biomass growth modeling and pond simulator studies, perhaps using outdoor pond data collected by existing research consortia (e.g., ATP3, RAFT) and by microalgae companies (e.g., Sapphire, Heliae). DOE should emphasize the need for close collaboration between modelers and experimentalists.

Poster:

(Short term = S, Medium term = M)

LARGE SCALE	LAB SCALE
Cultivation models (S-M)	Physiological input parameters
Energetic plus economic models (S)	Hydrodynamic model
Lab-scale pond simulator validations (S)	Physio-chemical parameters
Cost-effective culture monitoring system (M)	Biomass composition
Close collaboration between models and experimentalists needed (S)	Pond observations (sensors)
Standard testing systems for downstream processing technologies to allow for system integration (S)	

Integration (Coal, Natural Gas, CO_2)

Convener: Paul Woods

Discussion:

Federal agencies need to coordinate on CO_2 as it relates to algae cultivation. There is conflicting federal interaction on this issue. DOE researches carbon capture and storage (CCS), while EPA is currently blocking permitting algae CCS. The DOE needs to work with the EPA to develop pathways to algae CCS.

The DOE could help by instituting a standard CCS Technology Readiness Level (TRL) for the industry. Currently, the industry uses Exxon’s standards.

Increased collaboration between EPA and DOE could lead to reuse of CO_2 by algae. The agencies could issue a joint Request for Information (RFI) or Funding Opportunity Announcement (FOA) on CO_2 delivery and reuse. An RFI could get best industry information to regulatory agencies along the entire pathway, and could help to mobilize the community and algae industry. This would also aid researchers in getting out of the lab and exploring integration and addressing GMO concerns. A joint FOA, however, may provide too many requirements on the process, making it difficult for applicants.

The DOE should integrate the Fossil Energy (FE) Office and EERE to work on CO_2 emissions and beneficial reuse issues. These issues are integrated within DOE BETO (i.e. Thermochemical Conversion Program working with the Algae Program). The Commercial Aviation Alternative Fuels Initiative (CAAFI) (USDA, DOE) could also play a role in algae to jet fuel pathway approval.

Guiding Questions:

1. What is the time horizon for this topic or issue; will this impact algal biofuel production in the near, mid, or long term?
    - The timeframe for this issue is 5 years ago. Near term is the time horizon.
2. Has this topic been included in the National Algal Biofuel Technology Roadmap; and if not, should it be?
    - The Algae Roadmap refers to the unclear regulatory framework, and this still has not changed, so clarifying regulations among agencies should be explored in greater depth.
3. What is the BETO Algae Program role in furthering this topic or addressing this issue?
    - DOE should increase interagency cooperation and coordination on CO_2 regulation issues.

Poster:

1. Integrate FE and EERE
    a. Get Fossil Energy Office to work on algae (coal to algae to liquids)
2. Pathway approval
3. Coordinated effort between EPA and DOE
    a. RFI/FOA
    b. Form relationship is most important outcome between EPA and DOE
4. TRL Standardization