SAND2013-4478C

Spectroradiometric monitoring of open algal cultures

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Supported by the U. S. DOE's Office of Energy Efficiency and Renewable Energy (DOE/EERE)

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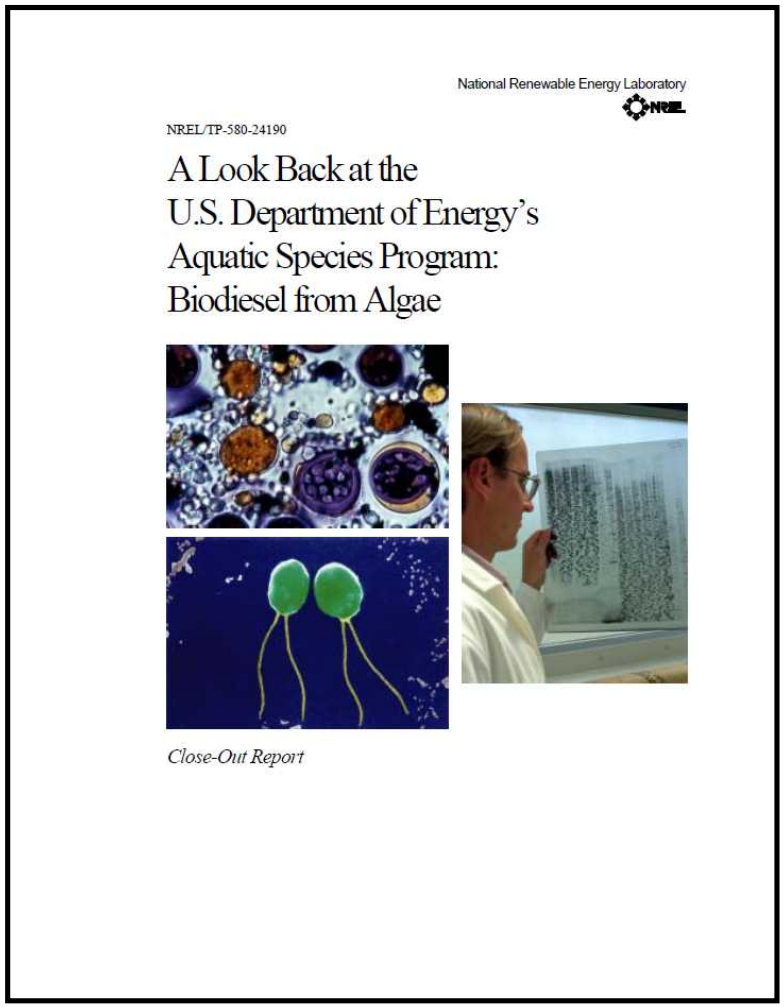
Algae and the U. S. DOE

1978-1996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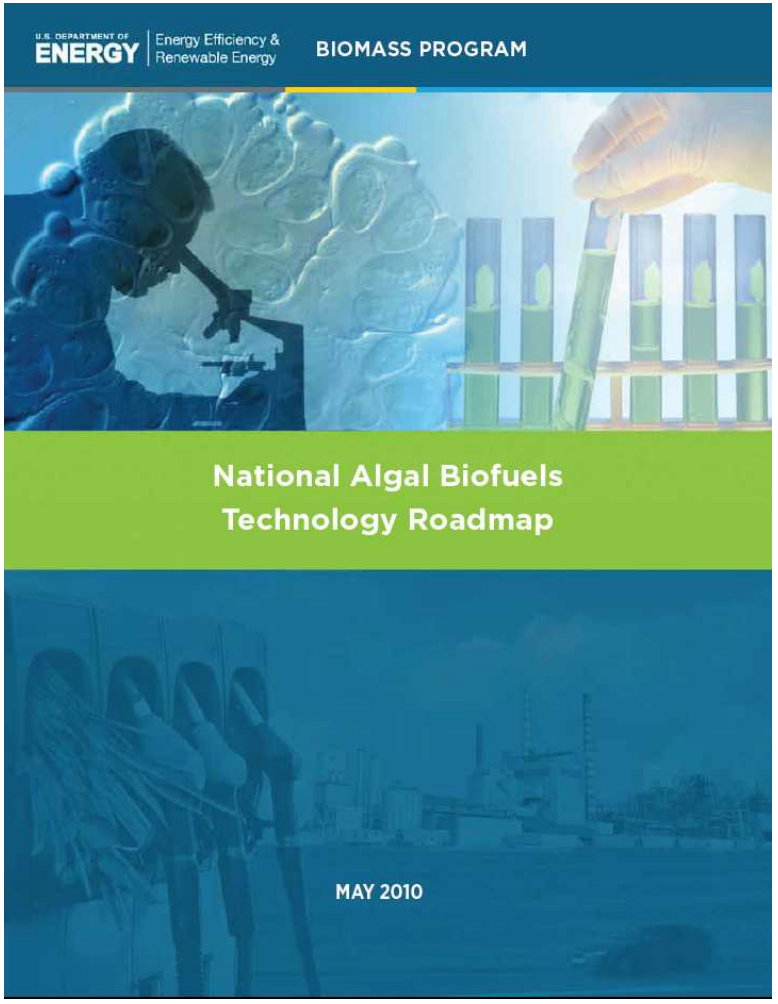
NREL/TP-580-24190

A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae

Close-Out Report

2010-future



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From Algae to Fuel

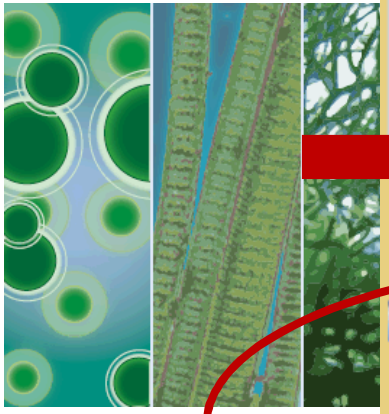
Algae feedstocks

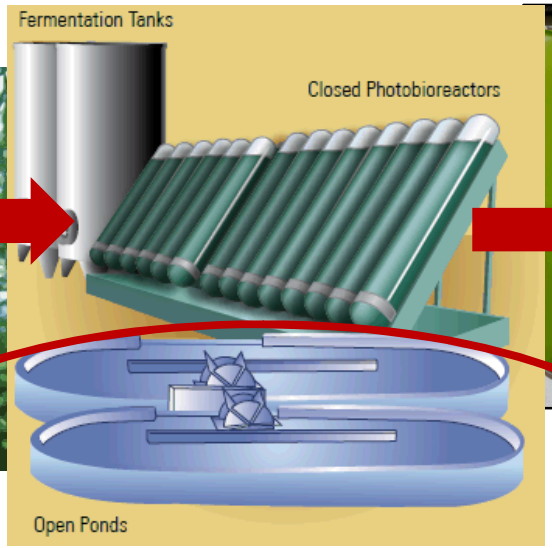
Cultivation

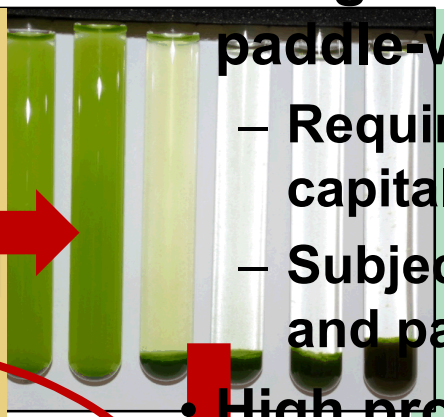
Harvesting/Dewatering

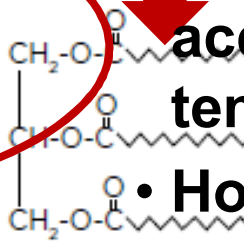
Extraction

Conversion









- Typically a raceway design circulated by a paddle-wheel
  - Requires the least capital cost
  - Subject to predators and pathogens
- High productivity accompanied by high temporal variability
- Hours versus days

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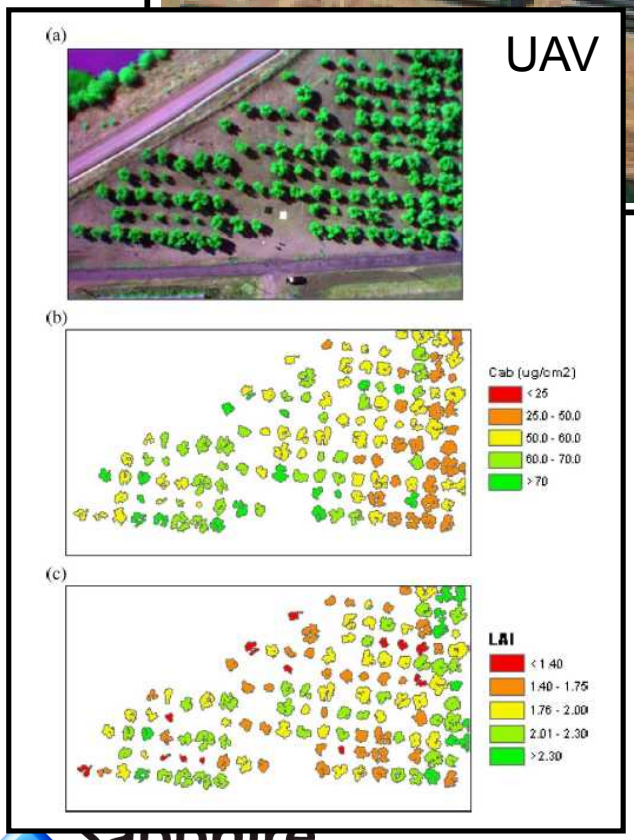
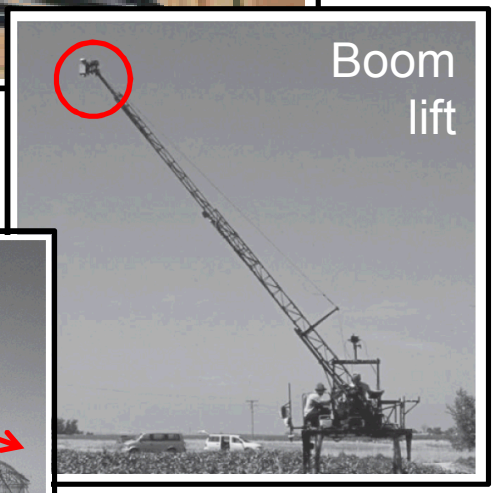
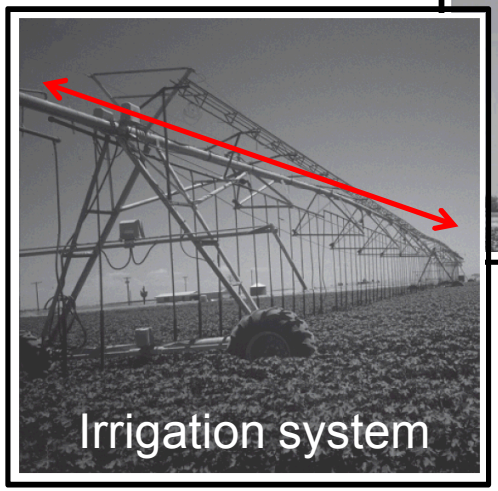
Rapid, broad-area assessment of growth and conditions in open systems



J. A. J. Berni et al, IEEE Trans. Geosci .& Rem. Sens. **47**, 2009.





S. Moran et al., Photogrammetric Eng. & Rem. Sens., June 2003, 705-718.

Aquaculture Pond Monitoring

- **A. Gitelson et al. (Ben-Gurion Univ. of the Negev)**
  - "Optical properties of dense algal cultures outdoors and their application to remote estimation of biomass and pigment concentration in Spirulina platensis (cyanobacteria)," J. Phycol. **31** (1995).
  - "Quantitative near-surface remote sensing of wastewater quality in oxidation ponds and reservoirs: a case study," Water Environ. Res. **69** (1997).
  - "Comparative reflectance properties of algal cultures with manipulated densities," J. Appl. Phycol. **11** (1999).
  - "Optical characteristics of the phototroph *Thiocapsa roseopericina* and implications for real-time monitoring of the bacteriochlorophyll concentration," Appl. & Environ. Microbiology, **65**, (1999).
  - "Optical properties of *Nannochloropsis* sp and their application to remote estimation of call mass," Biotech. & Bioeng. **69** (2000).
- **Recent demonstration by group at Univ. of Florida (Gainesville/Wimauma)**

A. Abd-Elrahman et al., IPRS Journal of Photogrammetry and Remote Sensing 66, 463-472 (2011).

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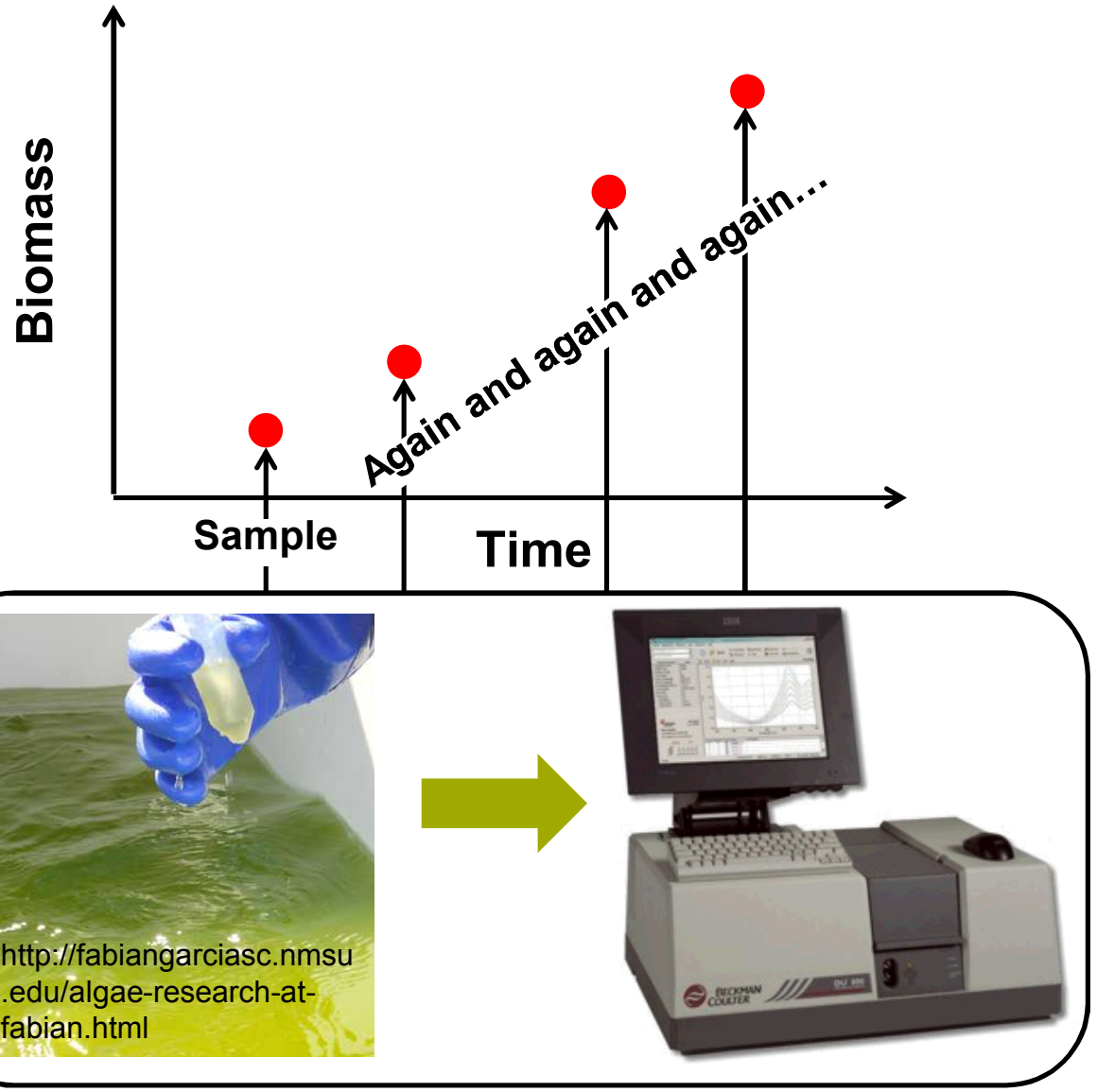
Specific question: Can biomass be measured without sampling the culture?



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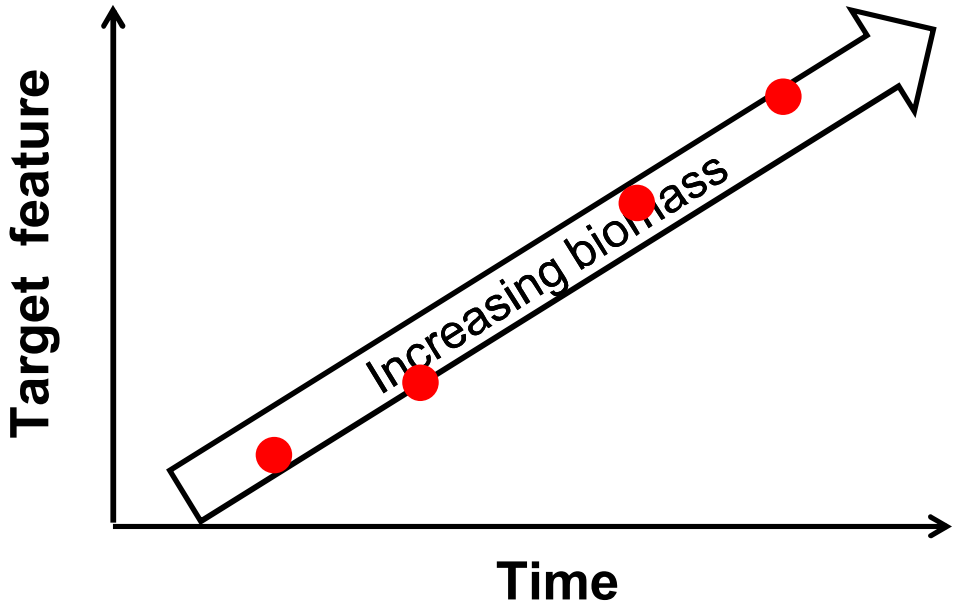

- Target feature based on collection of light
- Change in feature requires change in optical properties
- 3 effects: scattering, absorption, and re-emission (fluorescence)

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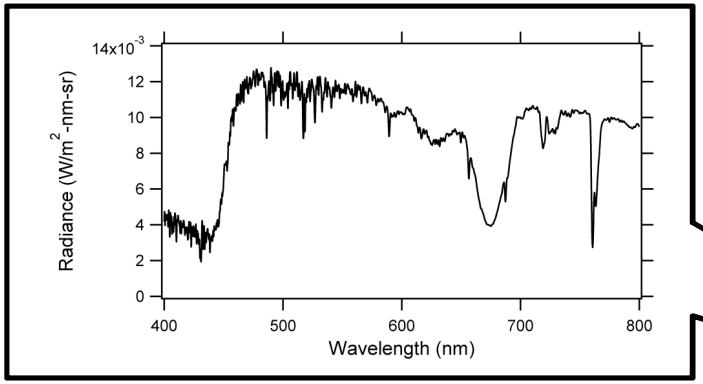
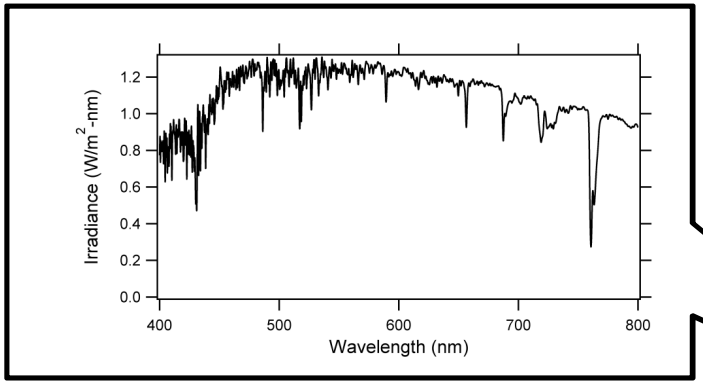
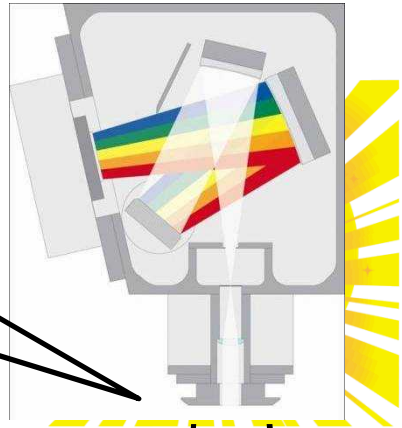
Discussion Topics

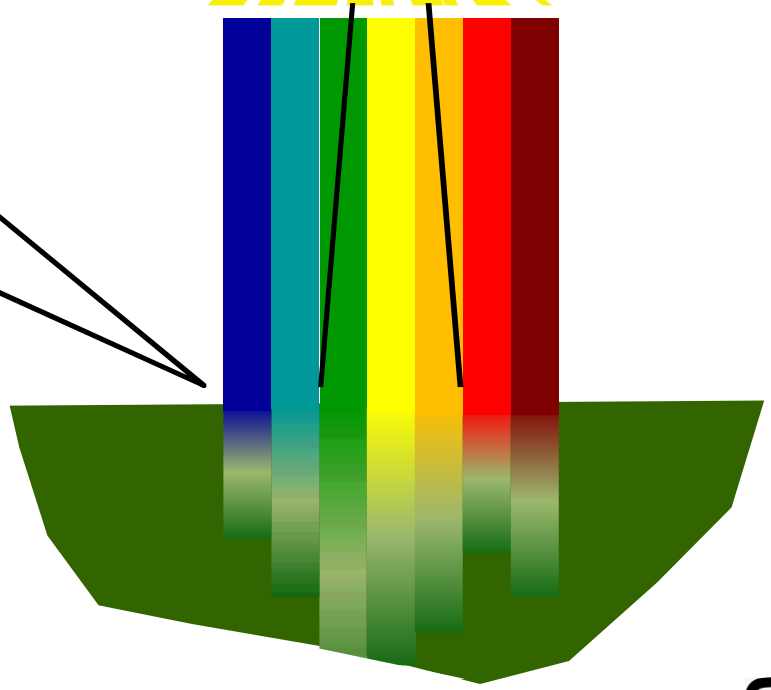
- Basics of spectroradiometric monitoring
- Field deployment at Sapphire Energy's Las Cruces, NM, facility
- Reflectance model to extract culture properties from data
- Application of reflectance model to our field deployment data

Spectroradiometric Monitoring









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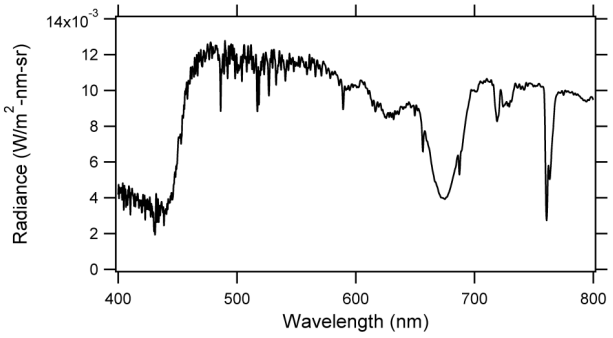
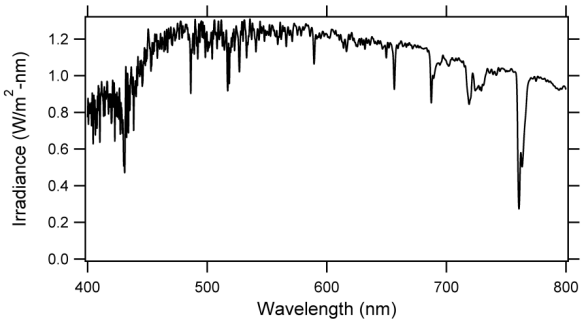
Spectroradiometric Monitoring





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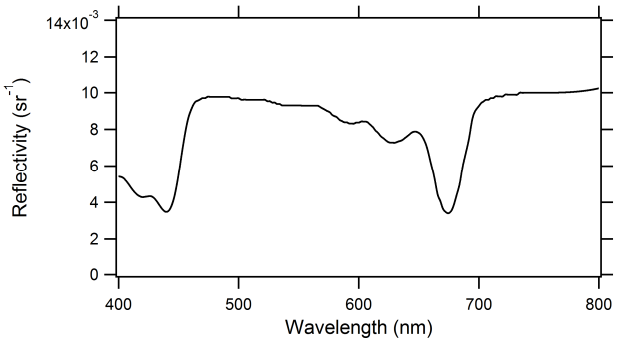

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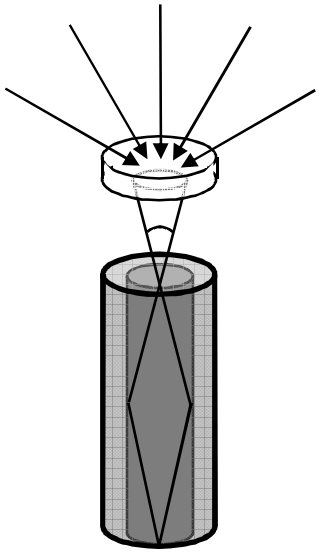
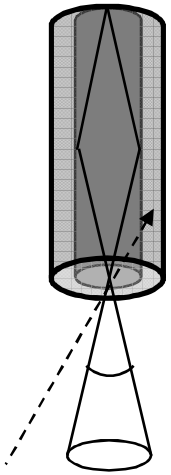
Dual-Channel Spectroradiometer

- Diffuser randomizes the direction of incoming light
- Fiber captures light from all downwelling angles



- Refractive indices of core and cladding limit field-of-view to 25° cone of light



Escapes into cladding

Trapped by core

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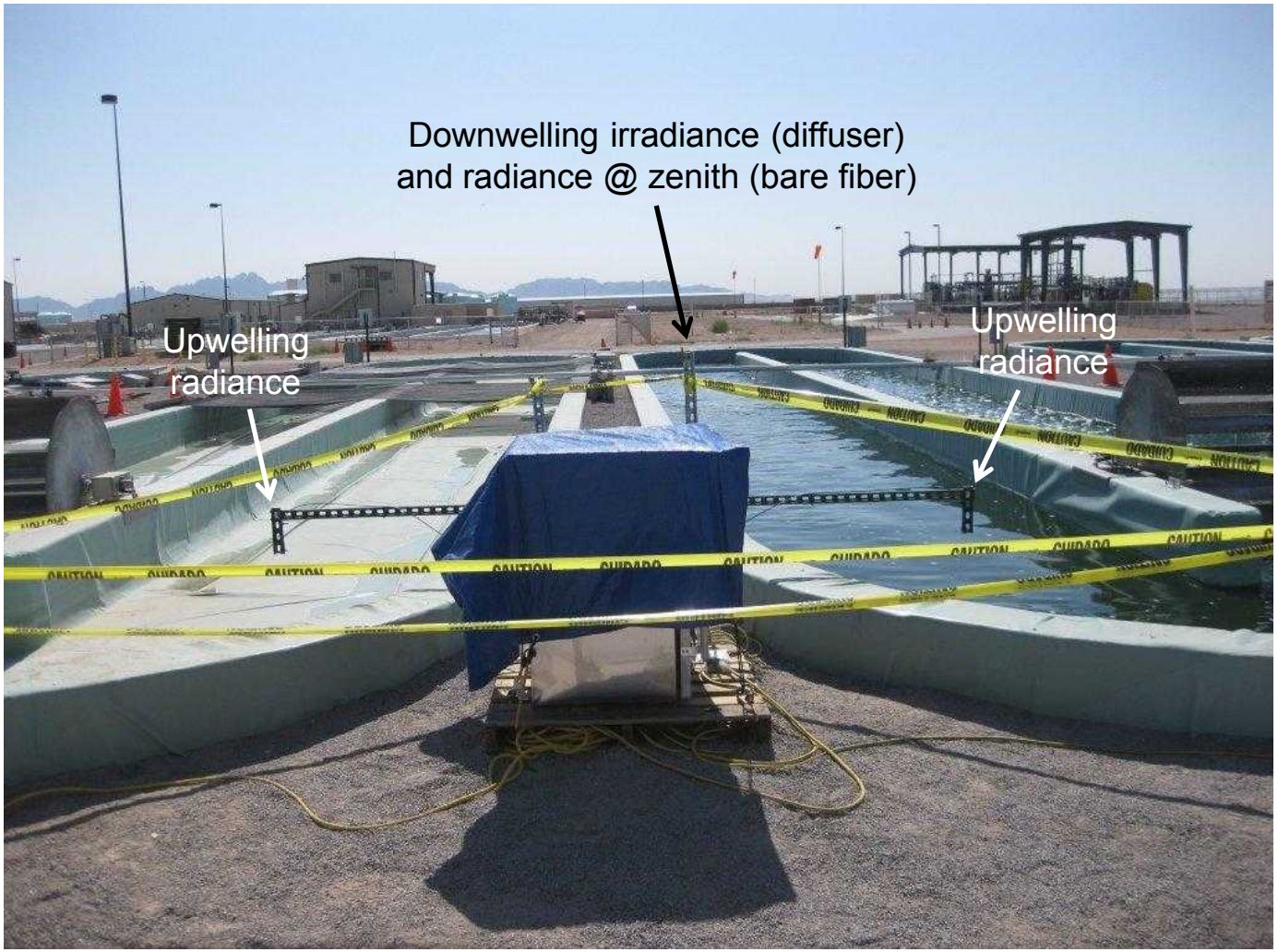
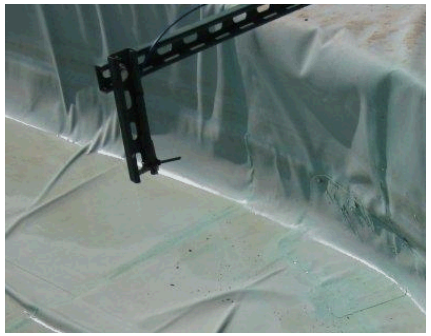
Deployed at Sapphire Energy (Las Cruces, NM)





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Temperature stability achieved in refrigerated container

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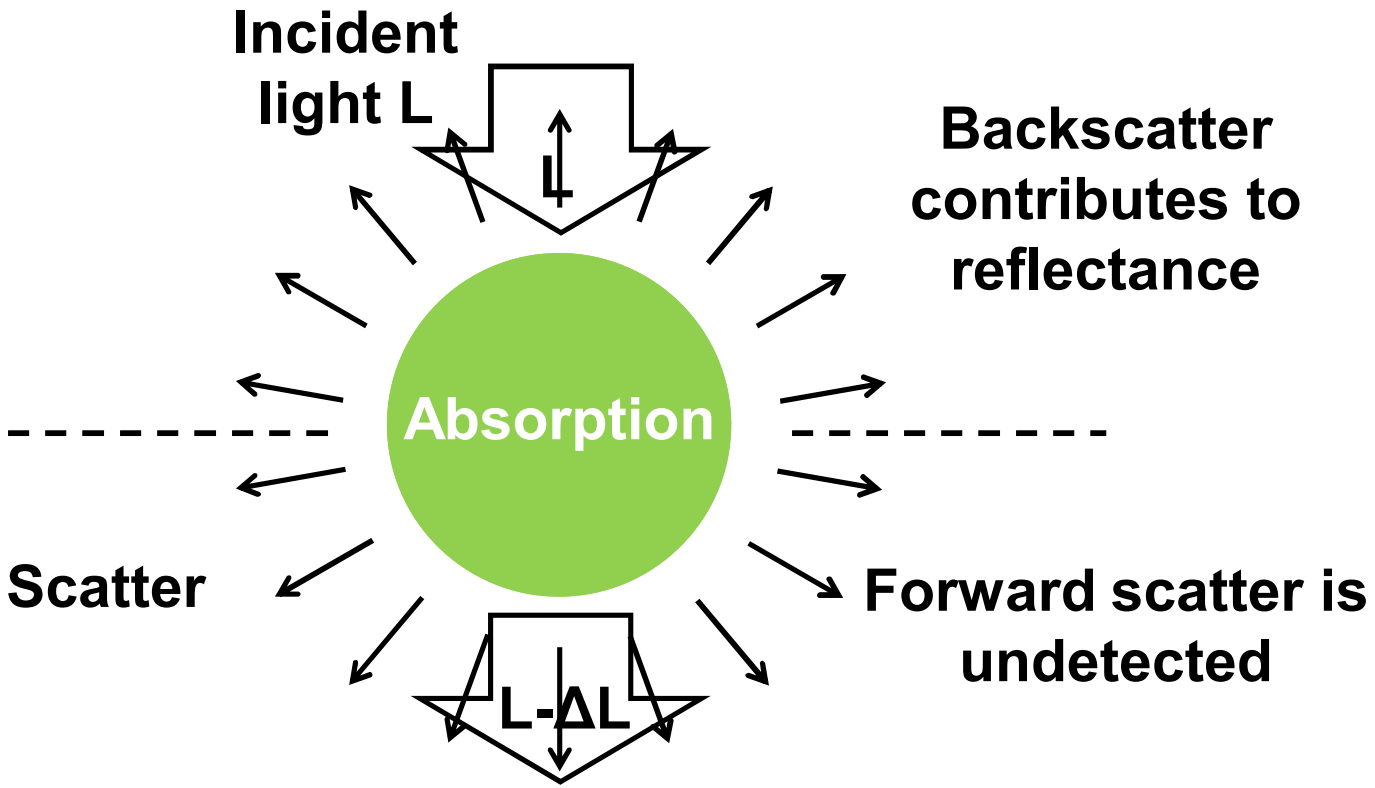
Reflectance depends on *single backscattering albedo* (u)

$$u(\lambda) = \frac{\text{Backscatter}(\lambda)}{\text{Backscatter}(\lambda) + \text{Absorption}(\lambda)} = \frac{b_b(\lambda)}{b_b(\lambda) + a(\lambda)}$$



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Reflectance Model of Z. Lee et al.

- **Multiple scattering**
  - $r(\lambda) = (G_1 + G_2 u)u$
- **Angular effects also included**
- **$u(\lambda)$: absorption a(λ) and backscatter b(λ)**

An inherent-optical-property-centered approach to correct the angular effects in water-leaving radiance

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[5]UMR-EPOC 5805, CNRS, Université de Bordeaux 1, Talence, 33405, France

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Received 12 January 2011; revised 29 March 2011; accepted 6 April 2011; posted 19 April 2011 (Doc. ID 141059); published 22 June 2011

Remote-sensing reflectance (R_{rs}), which is defined as the ratio of water-leaving radiance (L_w) to downwelling irradiance just above the surface ($E_d(0^+)$), varies with both water constituents (including bottom properties of optically-shallow waters) and angular geometry. L_w is commonly measured in the field or by satellite sensors at convenient angles, while $E_d(0^+)$ can be measured in the field or estimated based on atmospheric properties. To isolate the variations of R_{rs} (or L_w) resulting from a change of water constituents, effects of R_{rs} (or L_w) need to be removed. This is also a necessity for the calibration measurements. To reach this objective, for optically-deep waters a system centered on water's inherent optical proper and offers an alternative to the

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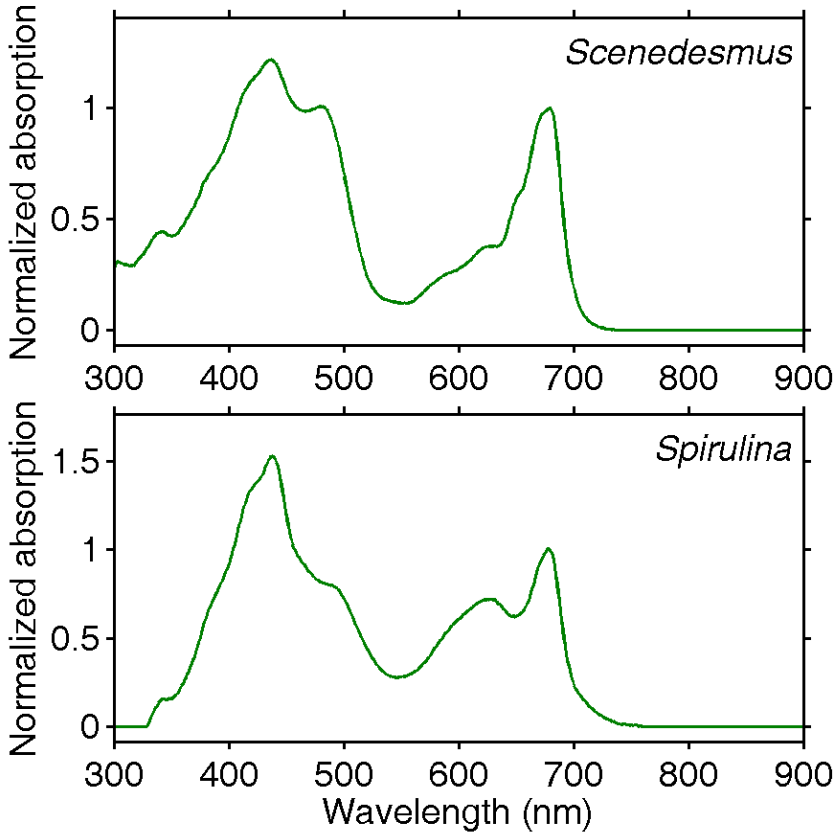
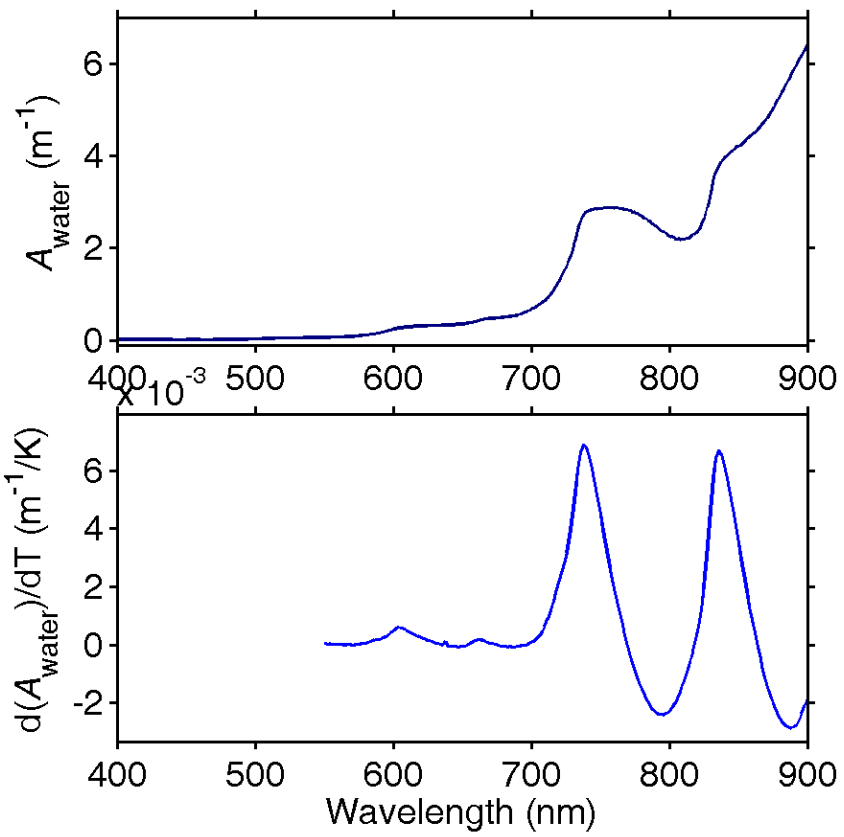
Absorption *a*





- **Dissolved organic matter: $A_{DOM} = \exp[- 0.015 (\lambda - 440\ nm)]$**
- **$a = C_1 A_{culture} + A_{water}(22^oC) + dA_{water}/dT \times (T\text{-}22^oC) + C_2 A_{DOM}$**

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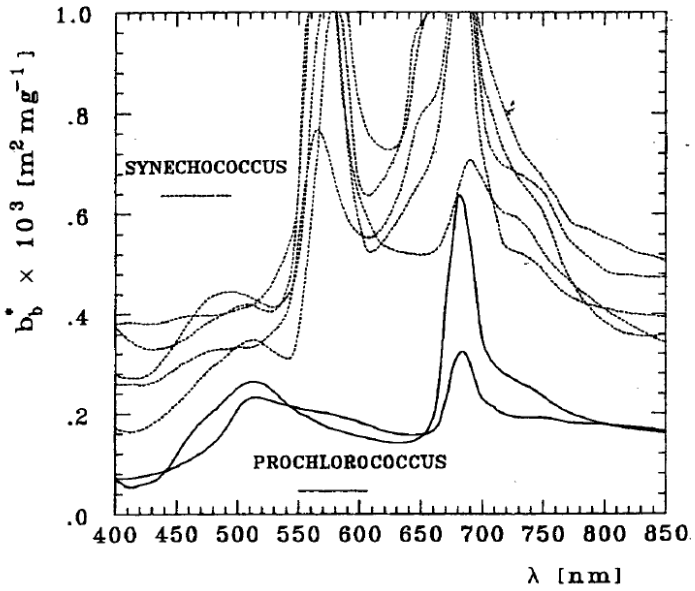
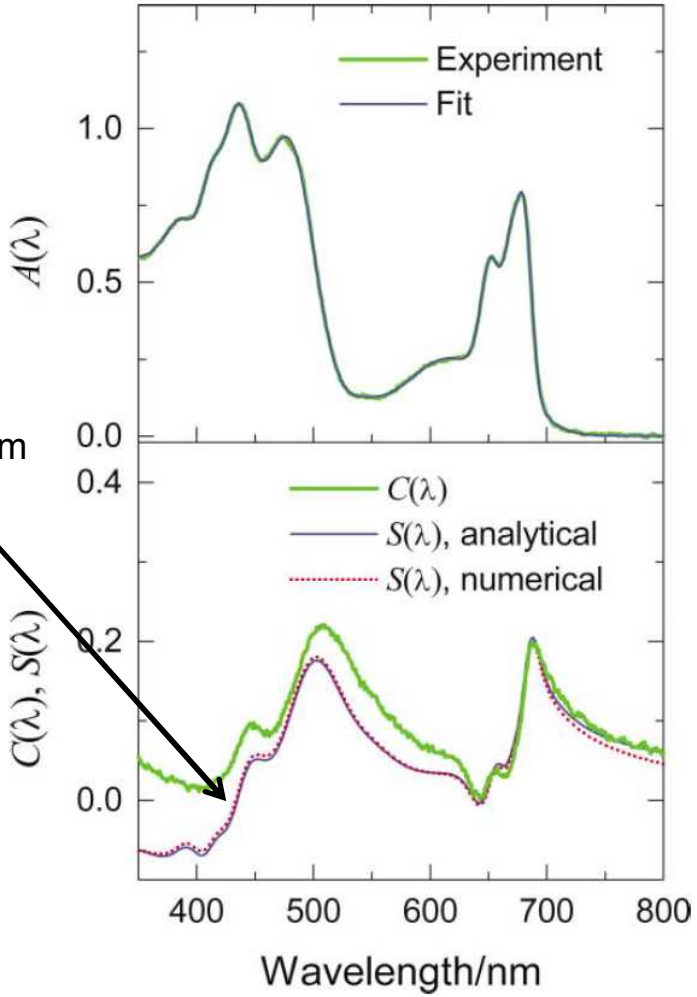
Backscatter *b*

- **Backscattering spectrum**



A. Morel et al., J. Marine Res. **51**, 617-649 (1993).



Hilbert transform of absorption spectrum

K. R. Naqvi, Photochem. Photobio. Sci. **3**, 132-137 (2004).

- **Absorption affects imaginary and real components of the refractive index**
- $b = C_3 + C_4 \times H_A(\lambda)$

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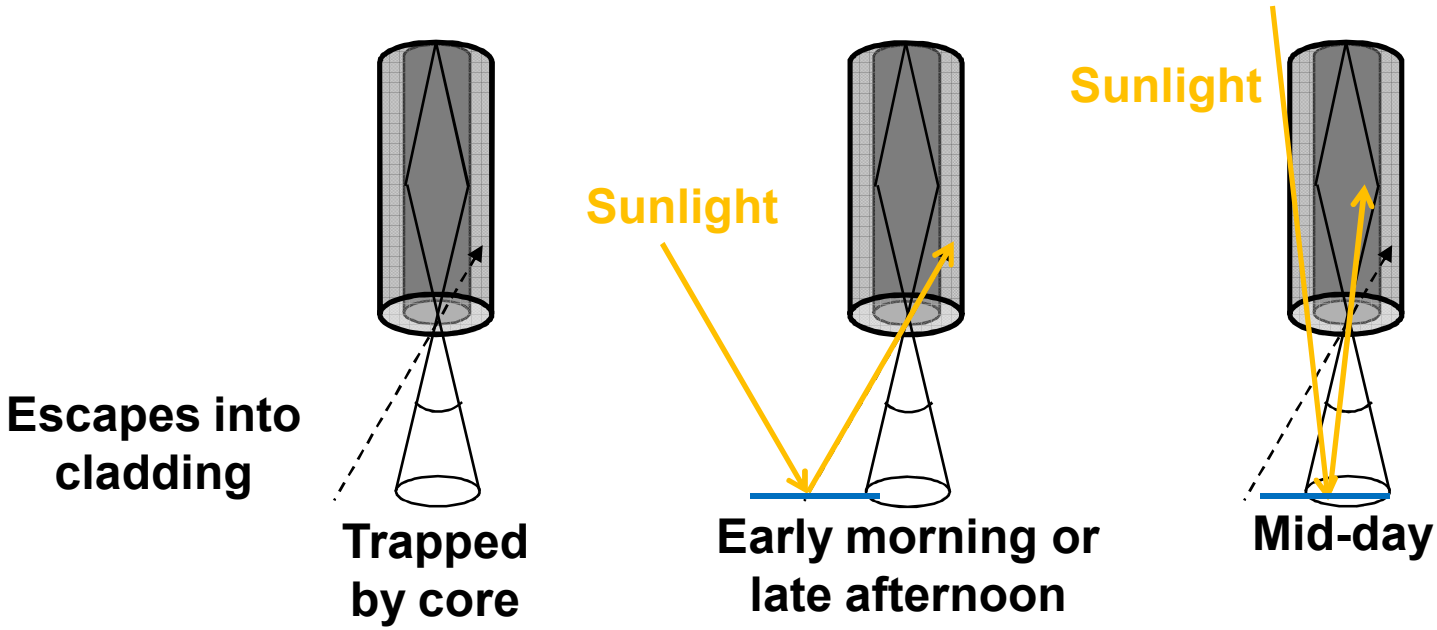
Additional Terms are Required

- Variable position of the sun → C_5



- Add specular (mirror-like) reflection term C_5

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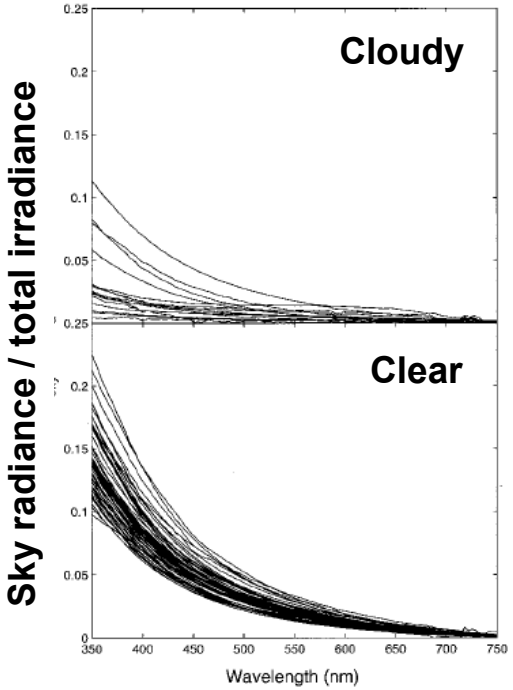
Additional Terms are Required

- Variable position of the sun → C_5
- Different downwelling light fields from the sun and sky → C_6

D. A. Toole et al., Appl. Opt. **39**, 456-469 (2000).



- The diffuse skylight is spectrally shifted to shorter λ
- Impacts water-surface reflection
- Divide downwelling irradiance into two components

Water surface reflection = $C_5 + C_6\lambda^{-4}$ (Rayleigh scattering approx.)

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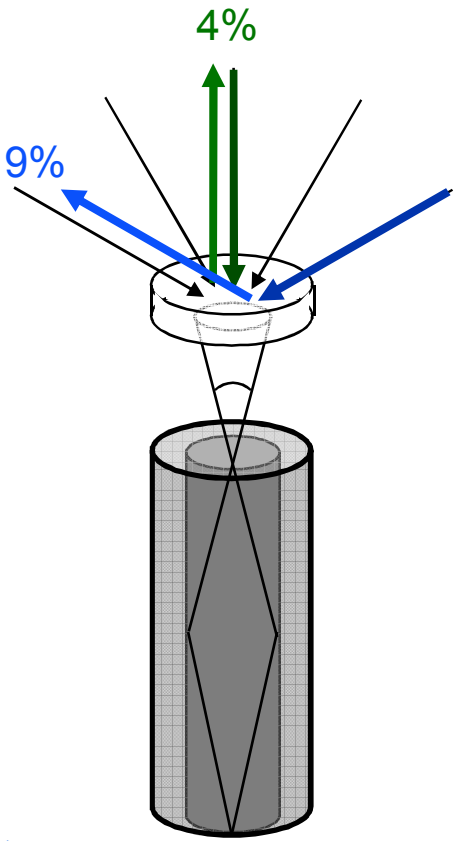
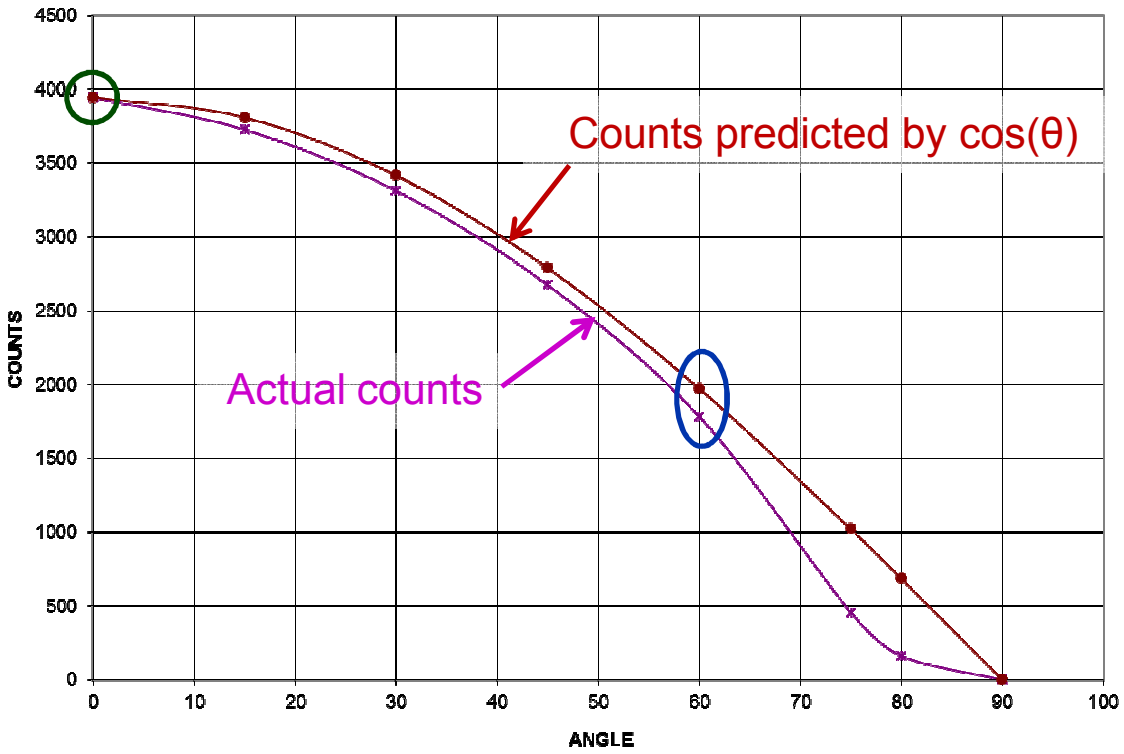
Additional Terms are Required

- Variable position of the sun → C_5
- Different downwelling light fields from the sun and sky → C_6
- Angular sensitivity, variable clouds, and sensor fouling → C_7





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Additional Terms are Required

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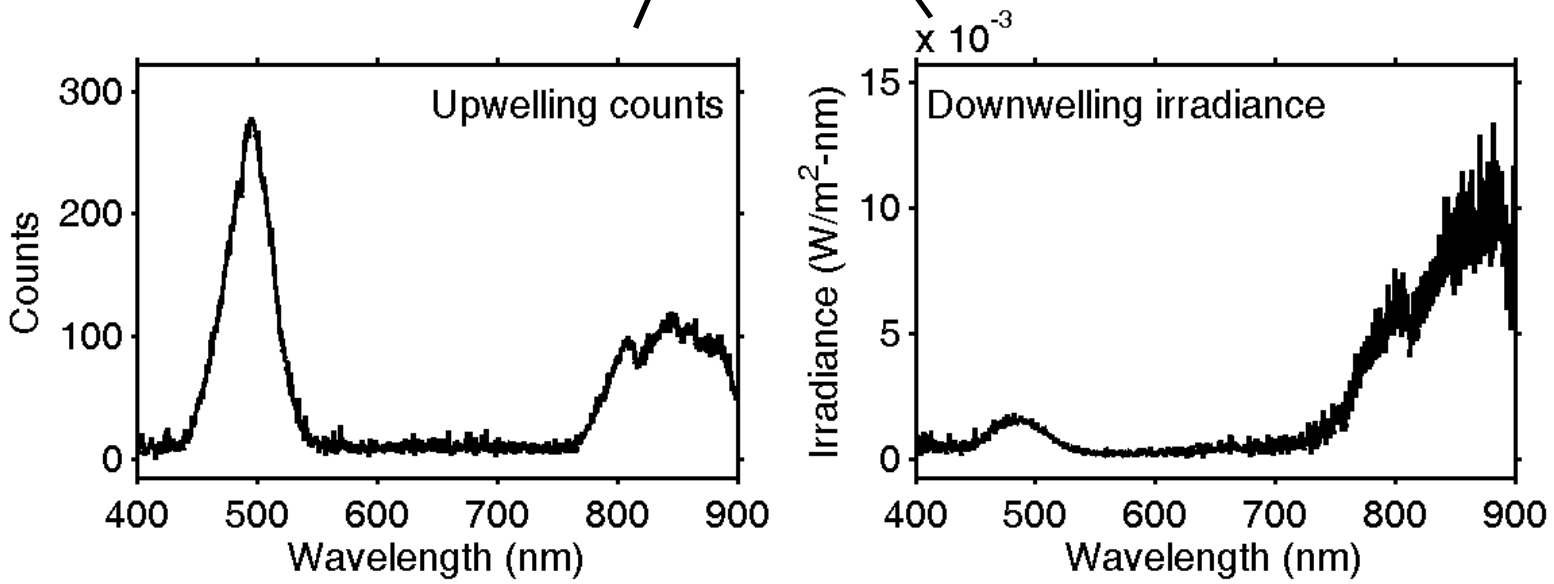
- Angular sensitivity, variable clouds, and sensor fouling → C_7
- Light leakage into fibers → C_8, C_9



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Additional Terms are Required

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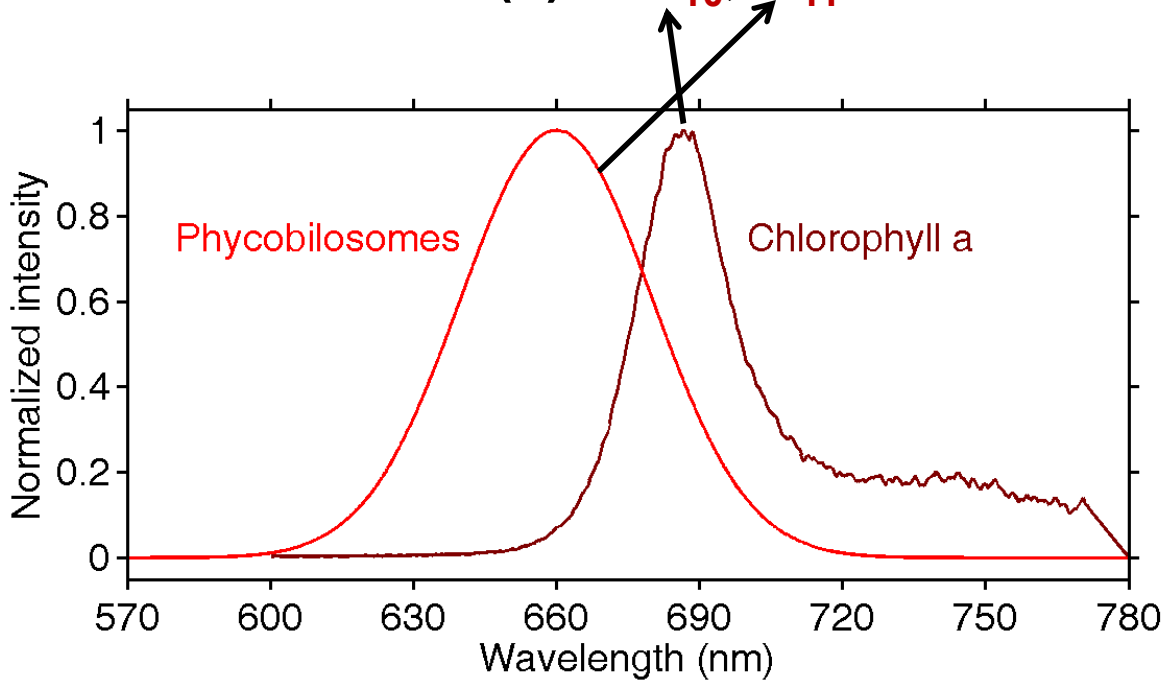
- Different downwelling light fields from the sun and sky → C_6
- Angular sensitivity, variable clouds, and sensor fouling → C_7
- Light leakage into fibers → C_8, C_9
- Fluorescence contribution(s) → C_{10}, C_{11}



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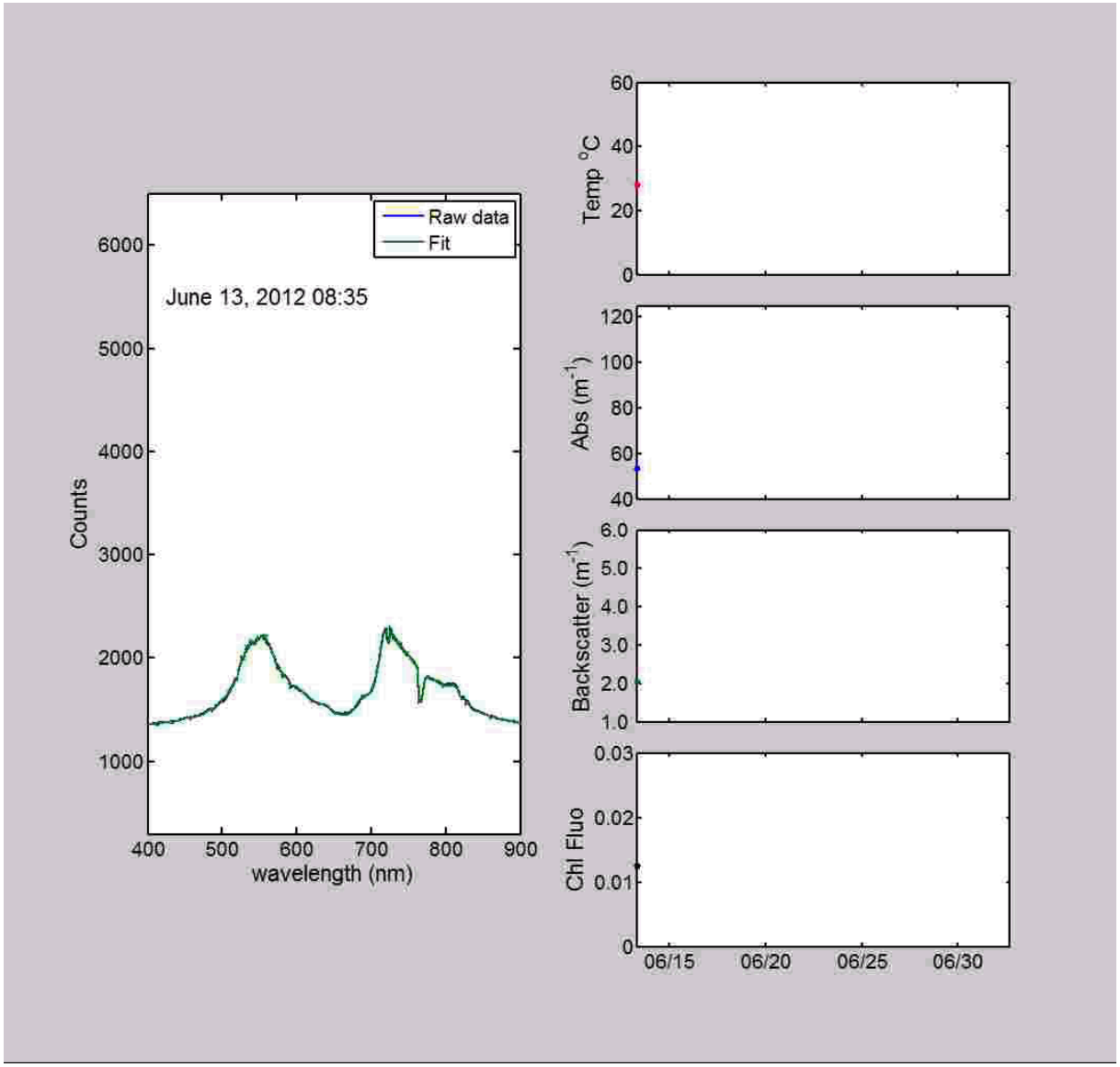
Fitting Parameters for Green Algal Culture



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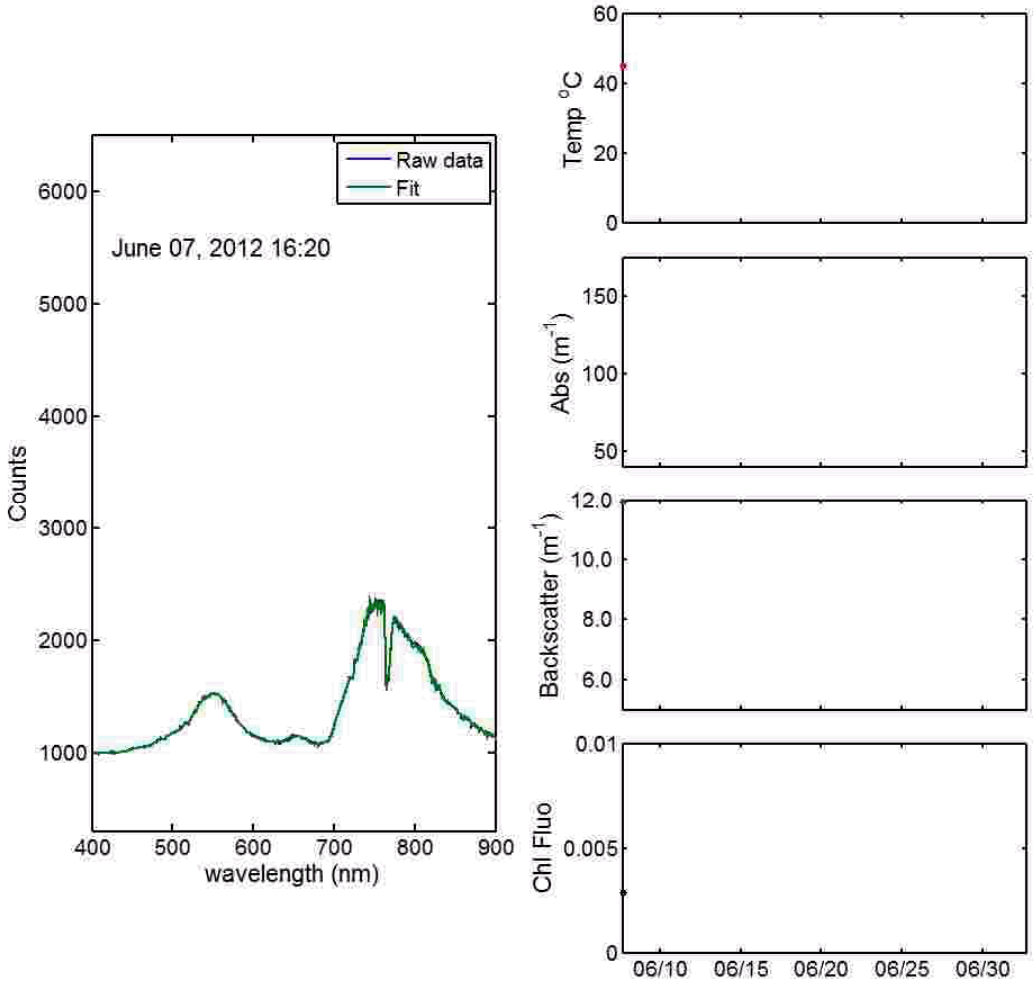
Fitting Parameters for Cyanobacterial Culture



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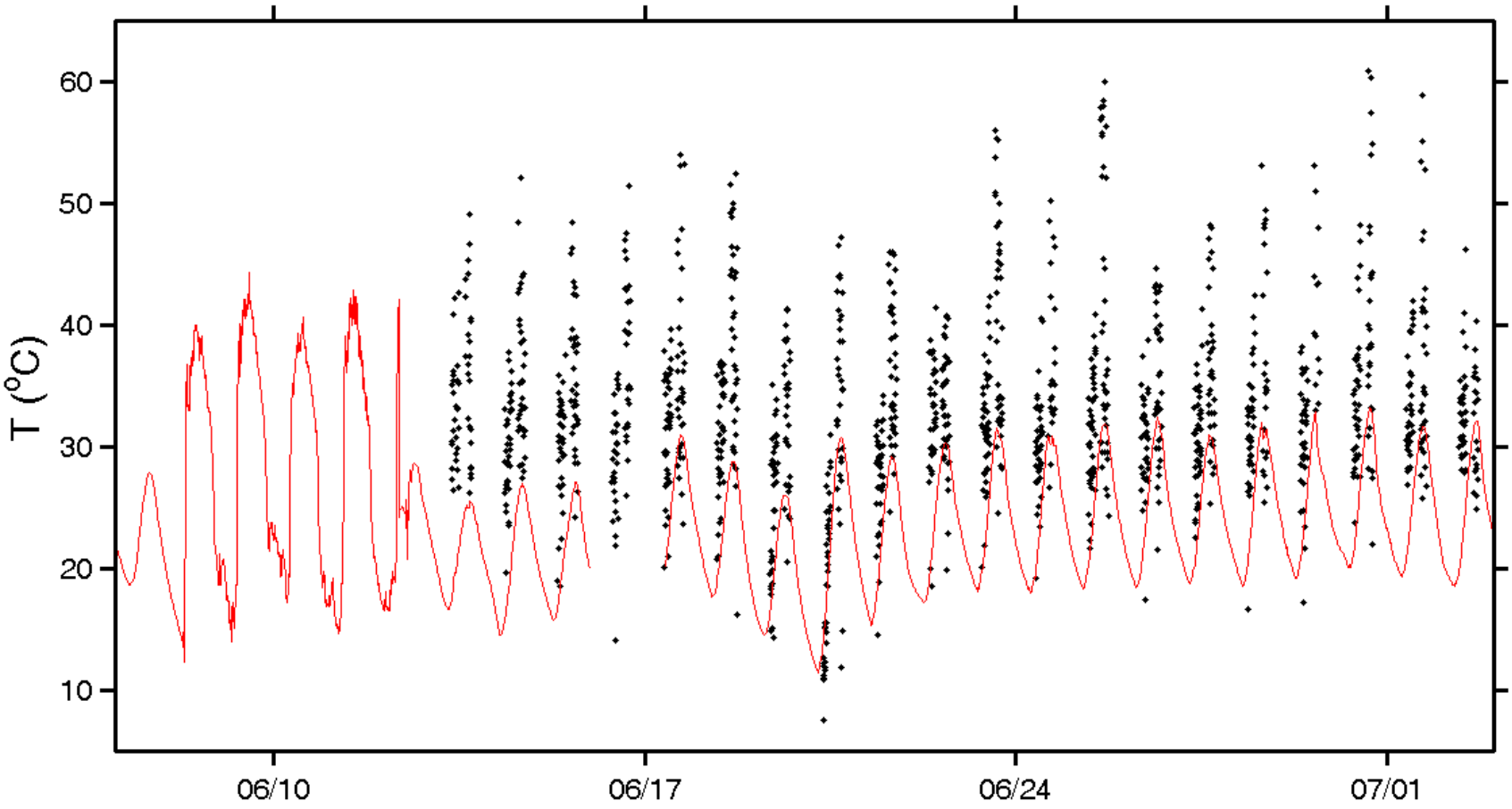
Temperature Comparison for Green Algal Culture



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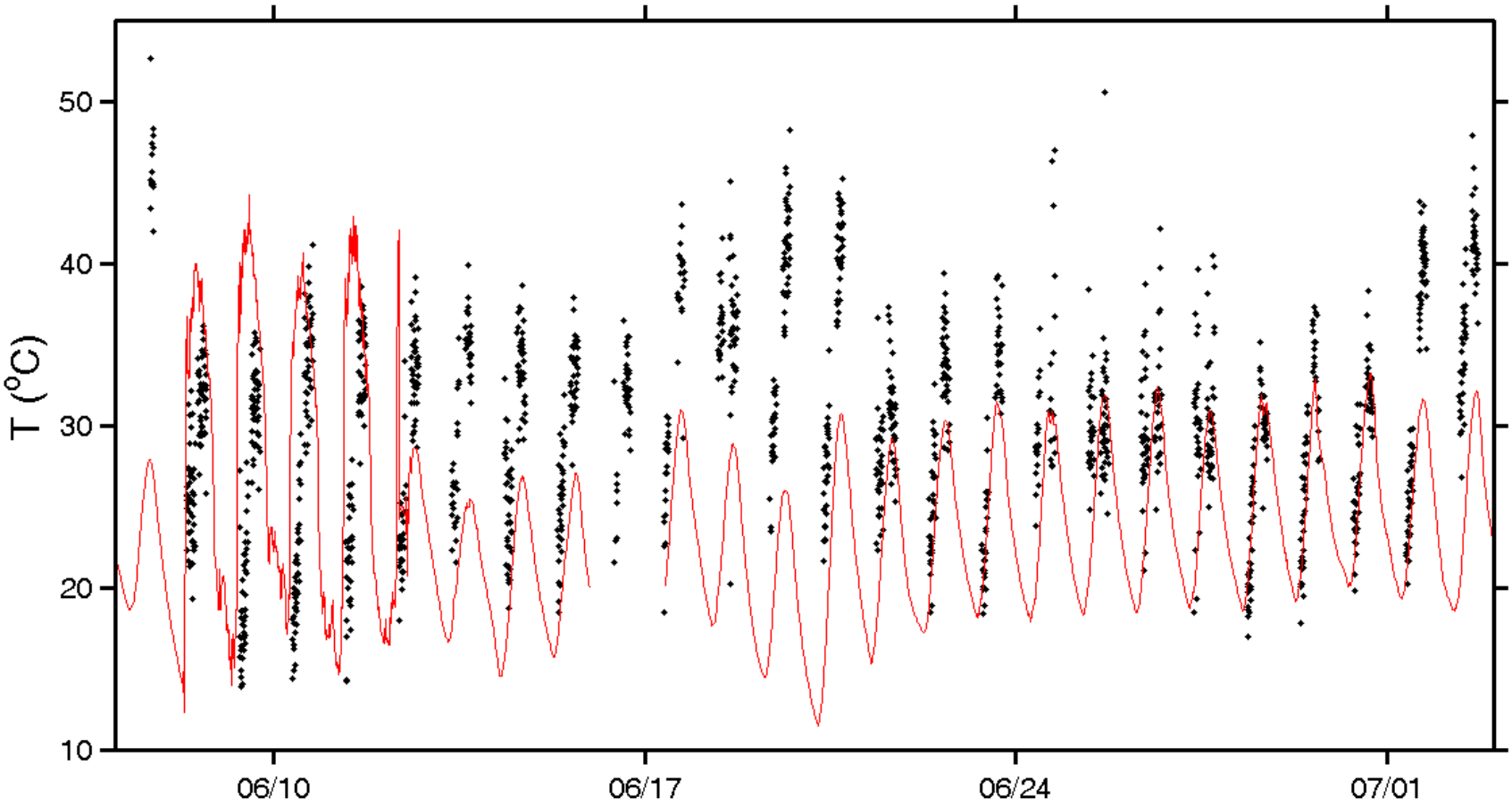
Temperature Comparison for Cyanobacterial Culture



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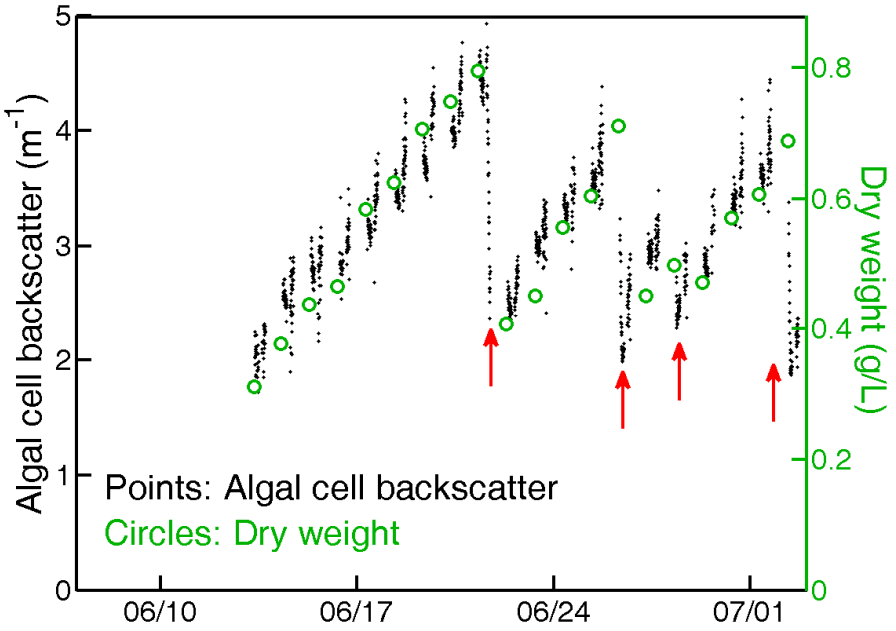
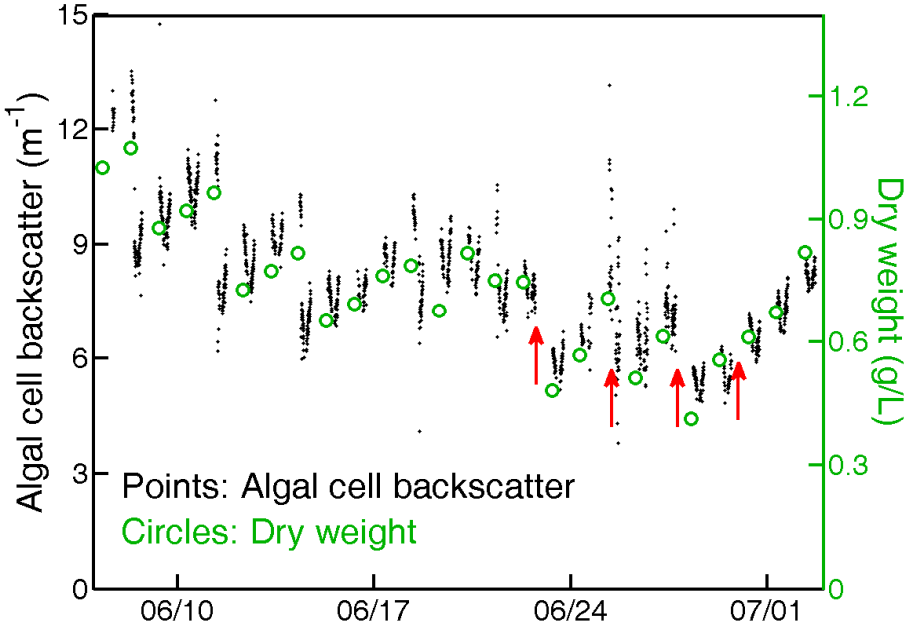
Backscatter and Biomass

Green algae



Cyanobacteria



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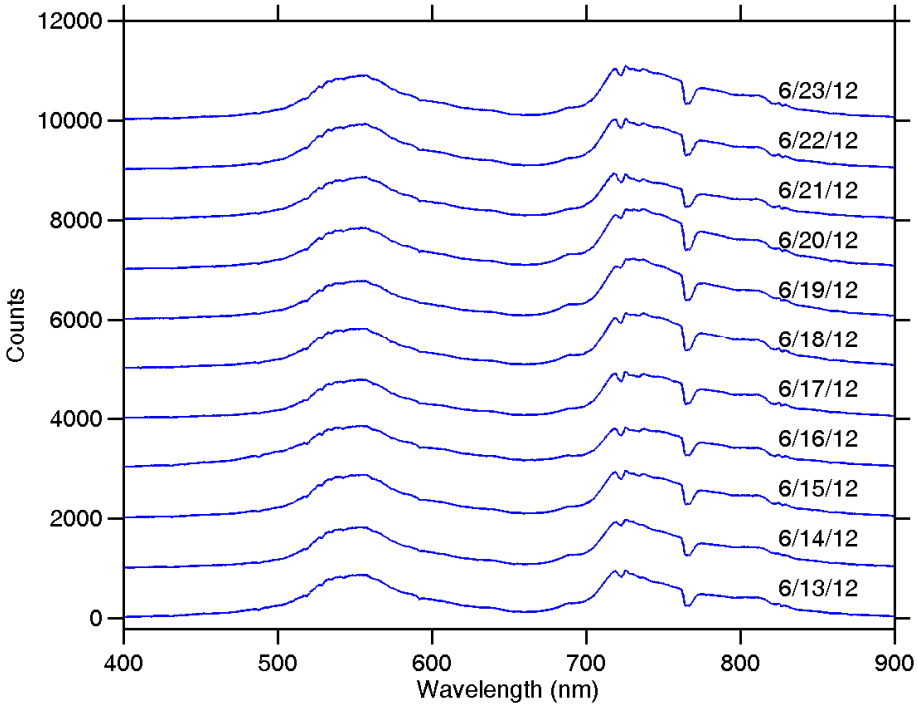
Summary

- Provides *in-situ* measurement of biomass and pigment optical activity
  - Extremely rapid (~5-min) measurement times
- Non-sampling
  - No laboratory facility required
- Integrates rigorous light transport physics into the data analysis
  - No extensive pre-calibration required
- Non-contact
  - Avoids instrument fouling
- Fully autonomous operation
  - Deployed over several months in the field

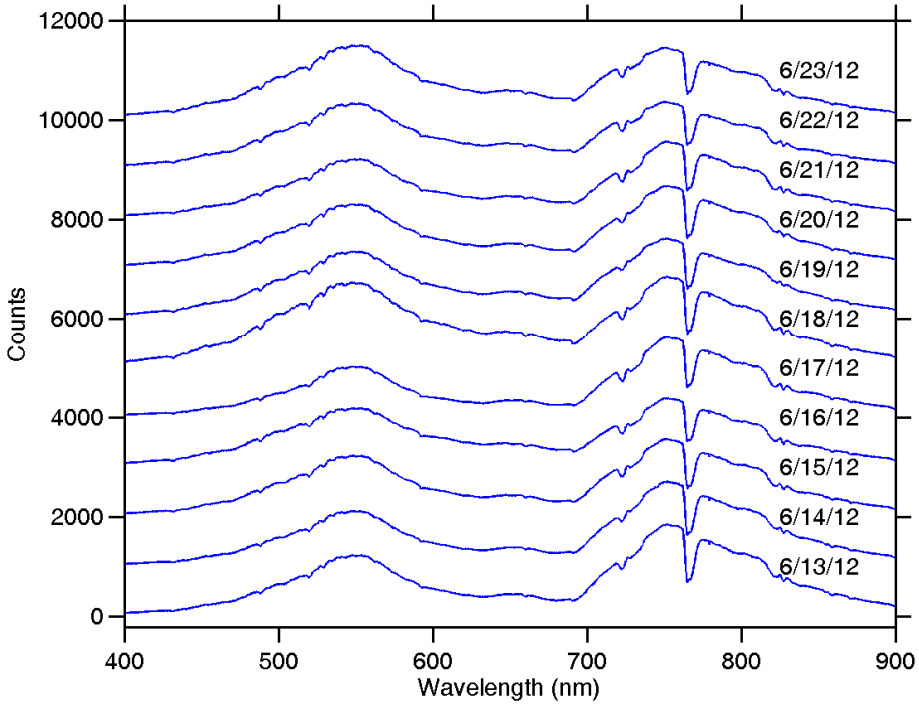
Backup Viewgraphs

Example data acquired at ~8:30 AM

Green algae



Cyanobacteria



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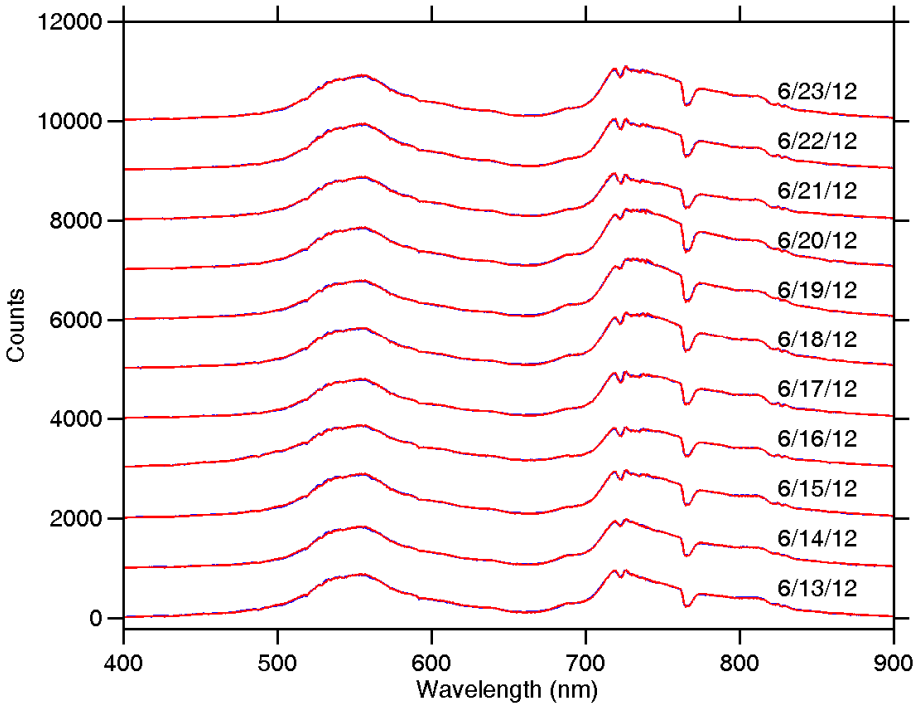
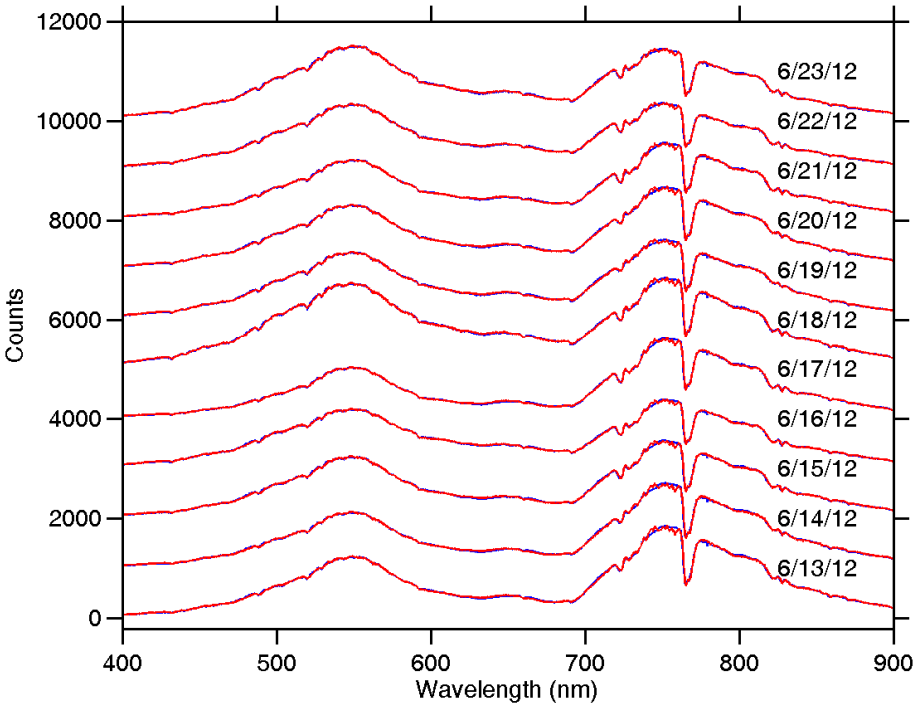
Example fitting results

Green algae



11 fitting parameters

Cyanobacteria



12 fitting parameters

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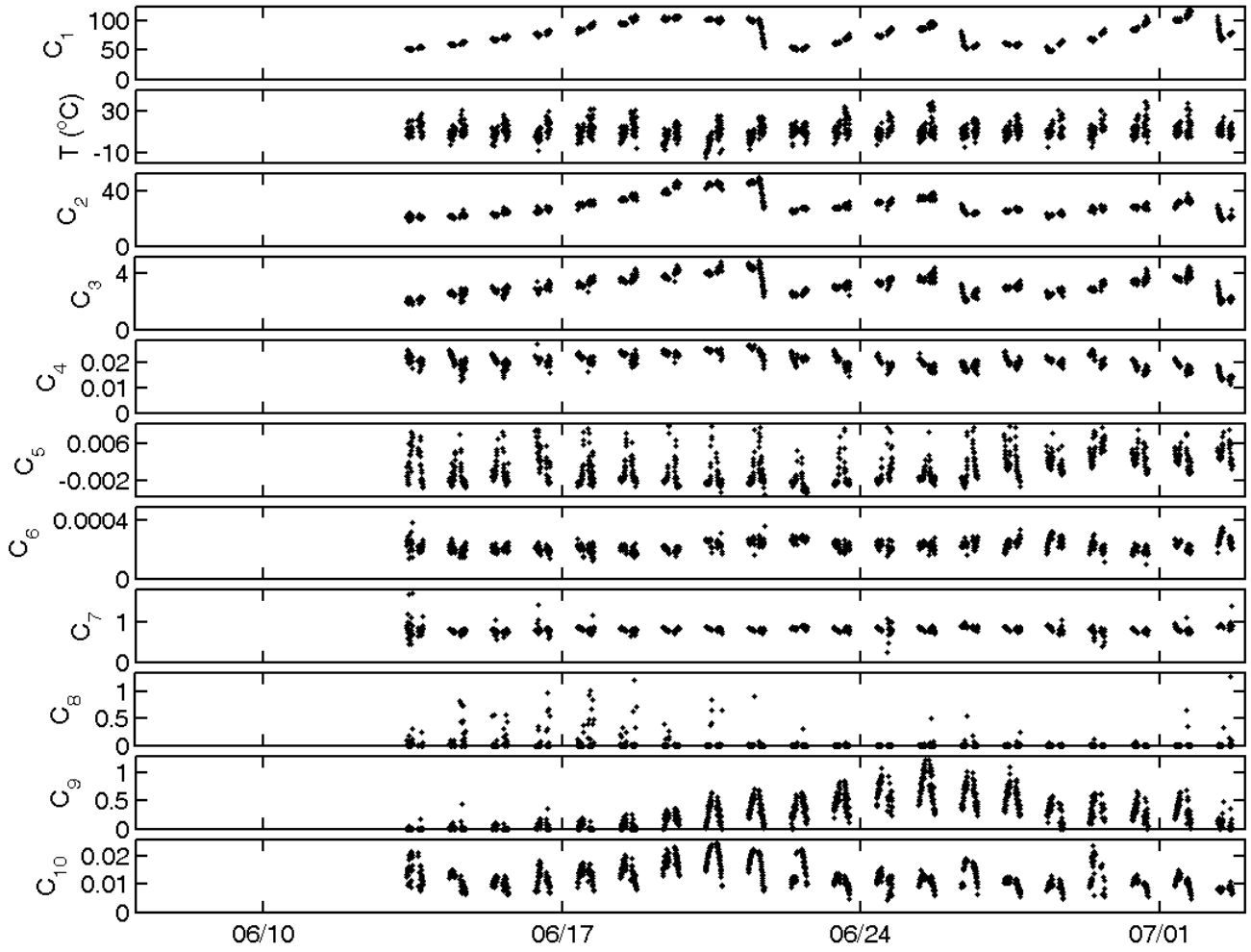
Fitting Parameters for Green Algal Culture



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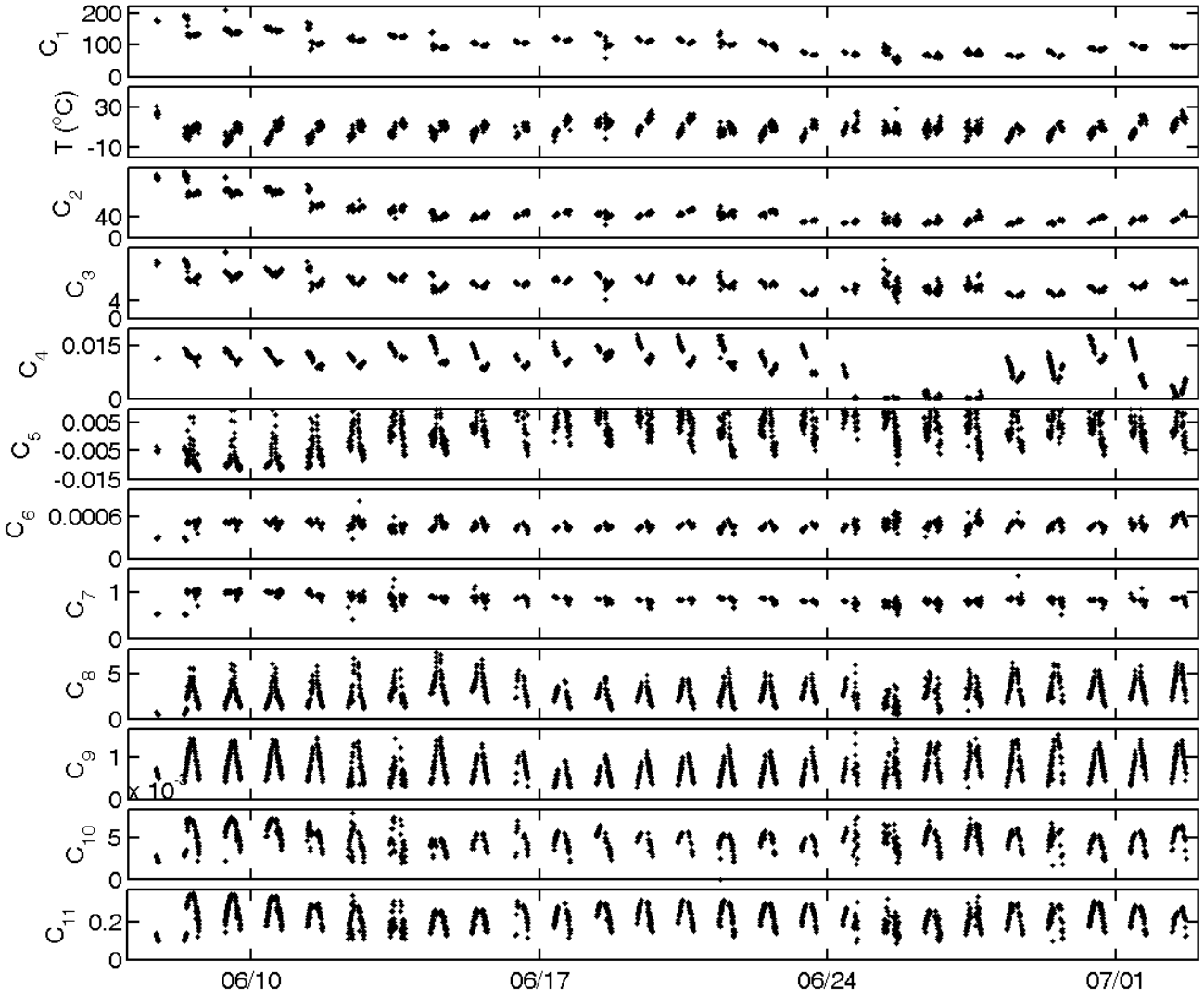
Fitting Parameters for Cyanobacterial Culture



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