Vertical Distribution of Phytoplankton

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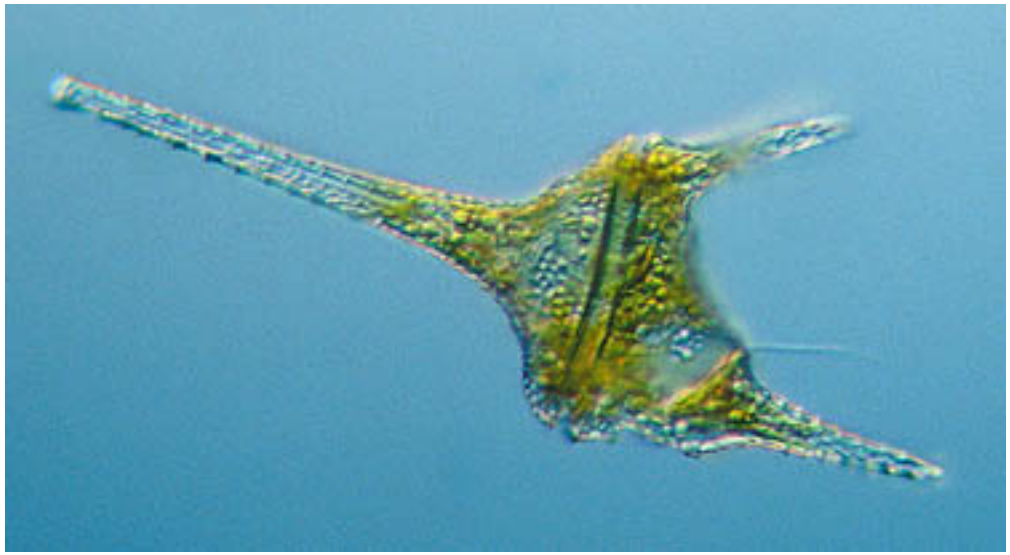
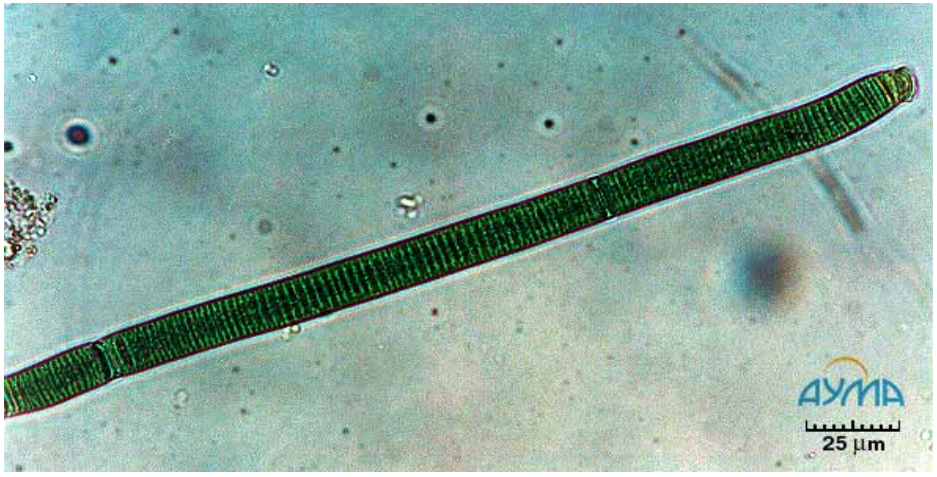
Phytoplankton

- Microscopic photosynthetic organisms at the base of most aquatic food webs
- Name derived from the Greek word **πλαγκτος**, meaning **wanderer**

Cryptophytes



Dinoflagellates



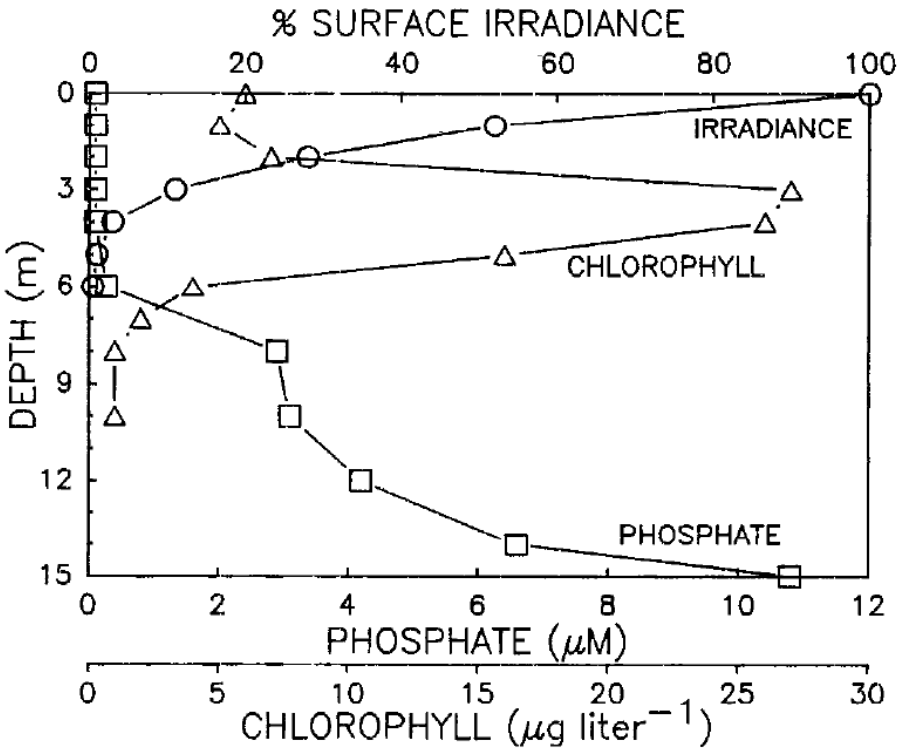
Cyanobacteria

Diatoms

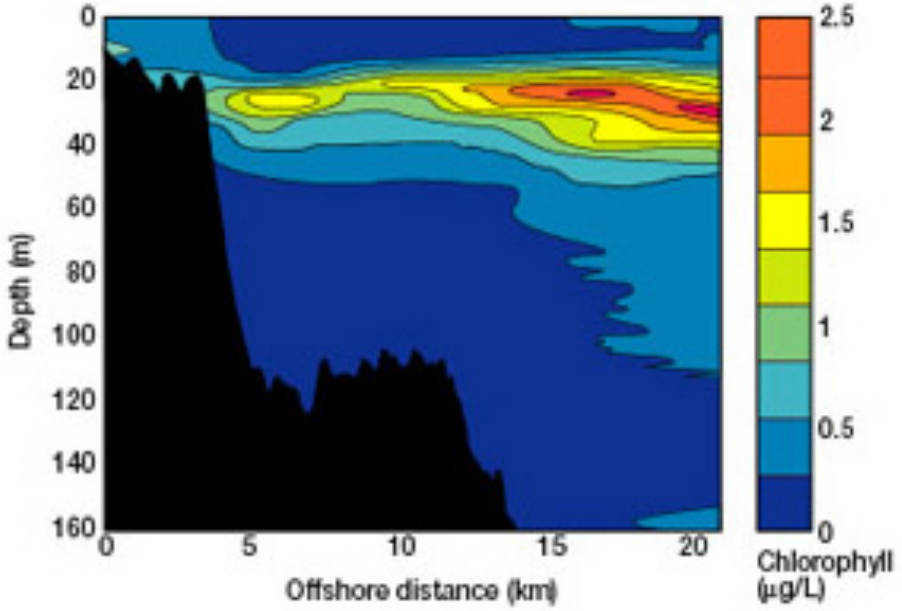
Vertical Distribution of Phytoplankton

- Opposing gradients of 2 essential resources:
  - Light supplied from above
  - Nutrients (N, P, Si) supplied from below
- Many phytoplankton can regulate their depth
- In poorly mixed water columns, these depth-regulating phytoplankton form thin layers

Deep chlorophyll maximum (DCM)



(Konopka 1989)



Surface Scum

Benthic Layer

Questions

- What determines layer type?
- What determines layer location?

b – phytoplankton biomass

$$\frac{\partial b}{\partial t} = gb + D\frac{\partial^2 b}{\partial z^2} + \frac{\partial}{\partial z}\left(v\left(\frac{\partial g}{\partial z}\right)b\right)$$

$$= \left[\text{growth - loss}\right] + \begin{bmatrix}\text{passive}\\ \text{movement}\end{bmatrix} + \begin{bmatrix}\text{active}\\ \text{movement}\\ = \text{auxanotaxis}\end{bmatrix}$$

$$g = \min\left(f_R(R), f_I(I)\right) - m$$

$$\left(D\frac{\partial b}{\partial z} + v\left(\frac{\partial g}{\partial z}\right)b\right)\Bigg|_{z=0} = 0, \quad \left(D\frac{\partial b}{\partial z} + v\left(\frac{\partial g}{\partial z}\right)b\right)\Bigg|_{z=z_b} = 0$$

(Klausmeier and Litchman 2001)

R – nutrient

$$\frac{\partial R}{\partial t} = -\frac{b}{Y}\min\left(f_R(R), f_I(I)\right) + D\frac{\partial^2 R}{\partial z^2}$$

$$= -[\text{uptake}] + [\text{mixing}]$$

$$\left.\frac{\partial R}{\partial z}\right|_{z=0} = 0, \quad \left.\frac{\partial R}{\partial z}\right|_{z=z_b} = h\left(R_{\text{in}} - R(z_b)\right)$$

(Klausmeier and Litchman 2001)

I – light

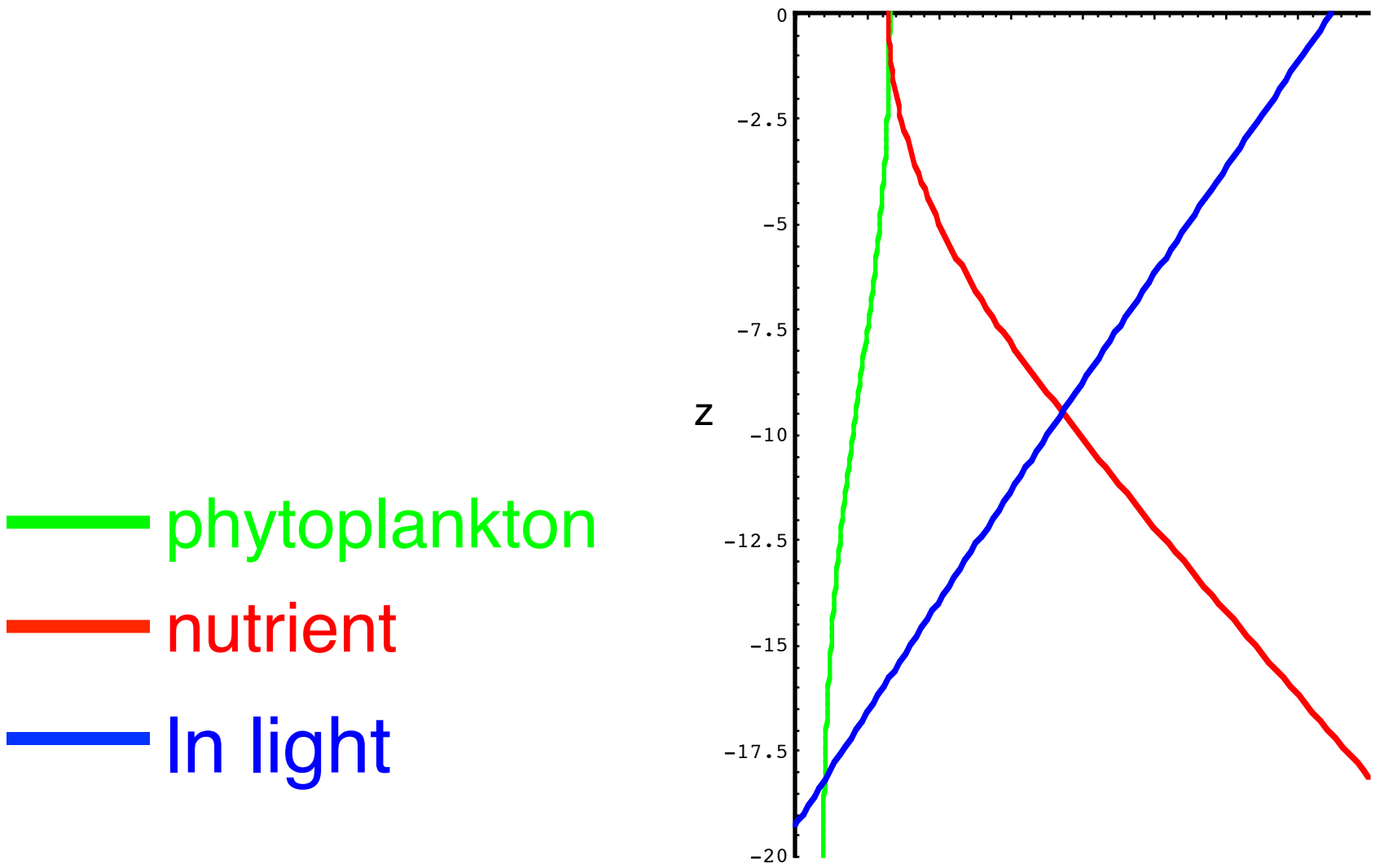
$$I(z) = I_{\text{in}} e^{-\int_0^z \left(a_{\text{bg}} + ab(Z)\right) dZ}$$

$$\log I(z) = \log I_{\text{in}} - a_{\text{bg}} z - a \int_0^z b(Z) dZ$$

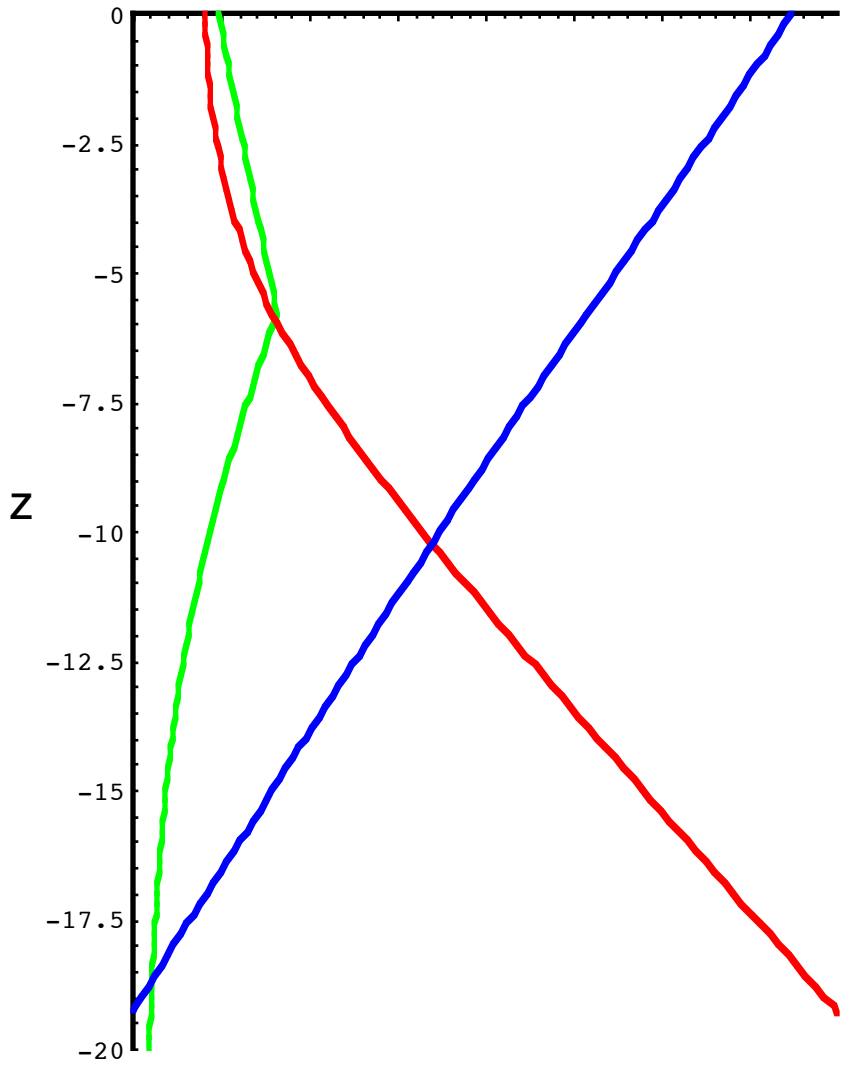
$$= \begin{bmatrix}\text{incoming} \\ \text{light}\end{bmatrix} - \begin{bmatrix}\text{background} \\ \text{attenuation}\end{bmatrix} - \begin{bmatrix}\text{algal} \\ \text{attenuation}\end{bmatrix}$$

(Klausmeier and Litchman 2001)

$v_{max}=0$



v_{max}=1 m/day

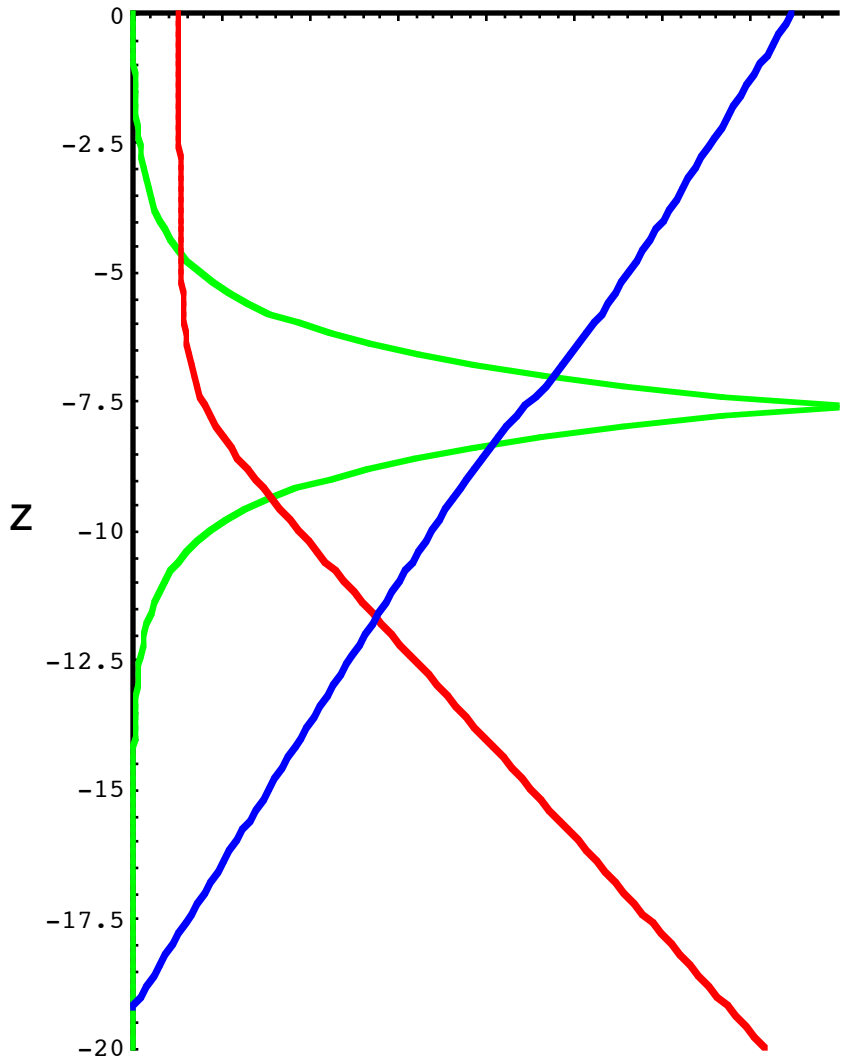


phytoplankton

nutrient

In light

v_{max}=10 m/day

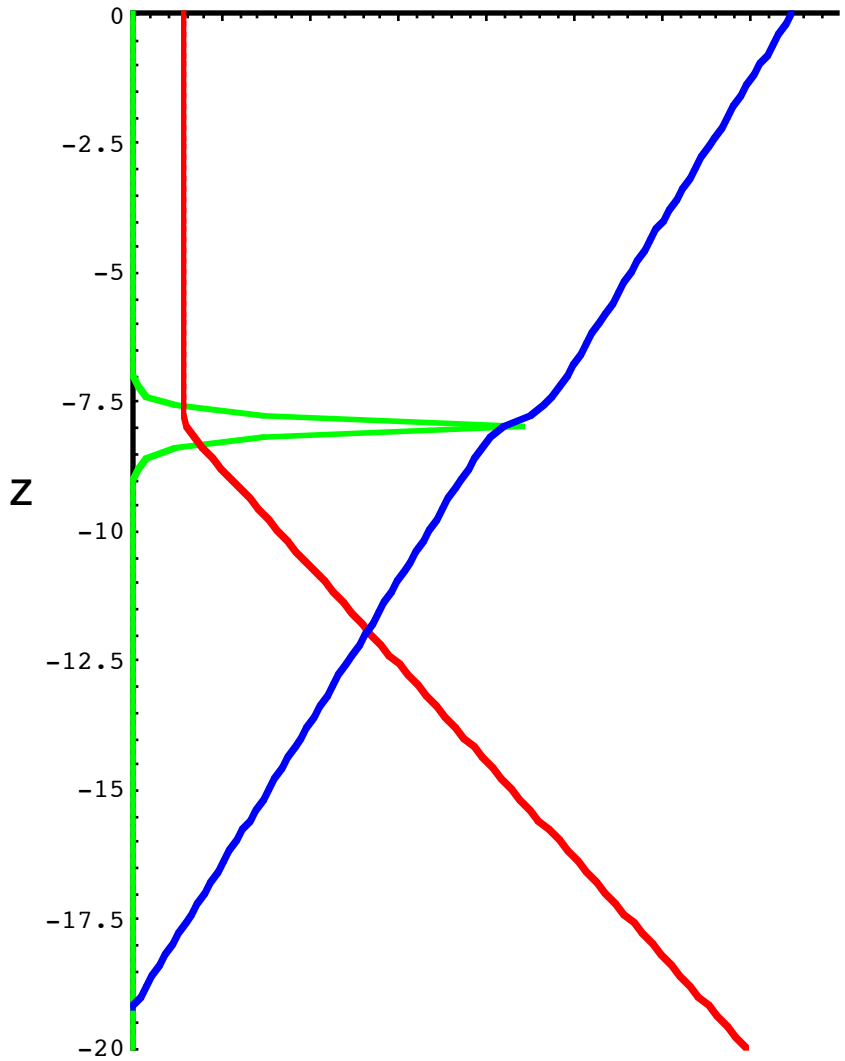


phytoplankton

nutrient

In light

v_{max}=100 m/day

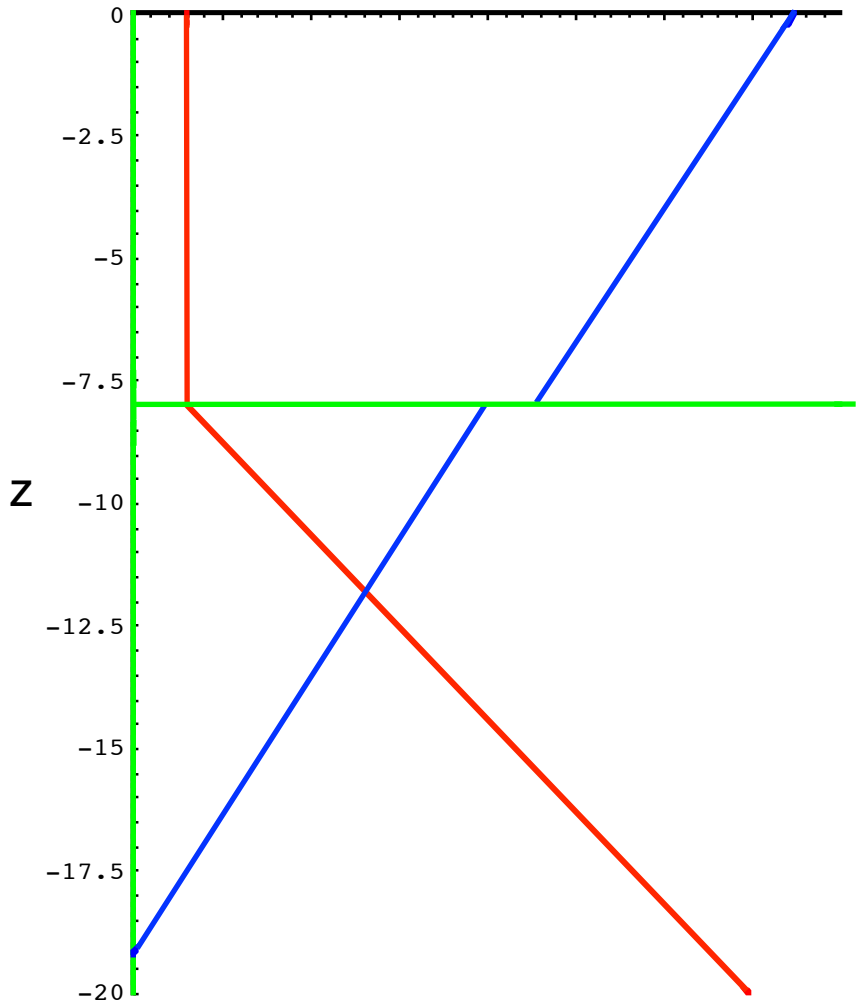


phytoplankton

nutrient

In light

$v_{max} = \infty$



phytoplankton

nutrient

In light

$$v_{max} = \infty$$

SIAM J. MATH. ANAL.
Vol. 40, No. 4, pp. 1419–1440

CONCENTRATION PHENOMENA IN A NONLOCAL QUASI-LINEAR PROBLEM MODELLING PHYTOPLANKTON I: EXISTENCE*

YIHONG DU† AND SZE-BI HSU‡

SIAM J. MATH. ANAL.
Vol. 40, No. 4, pp. 1441–1470

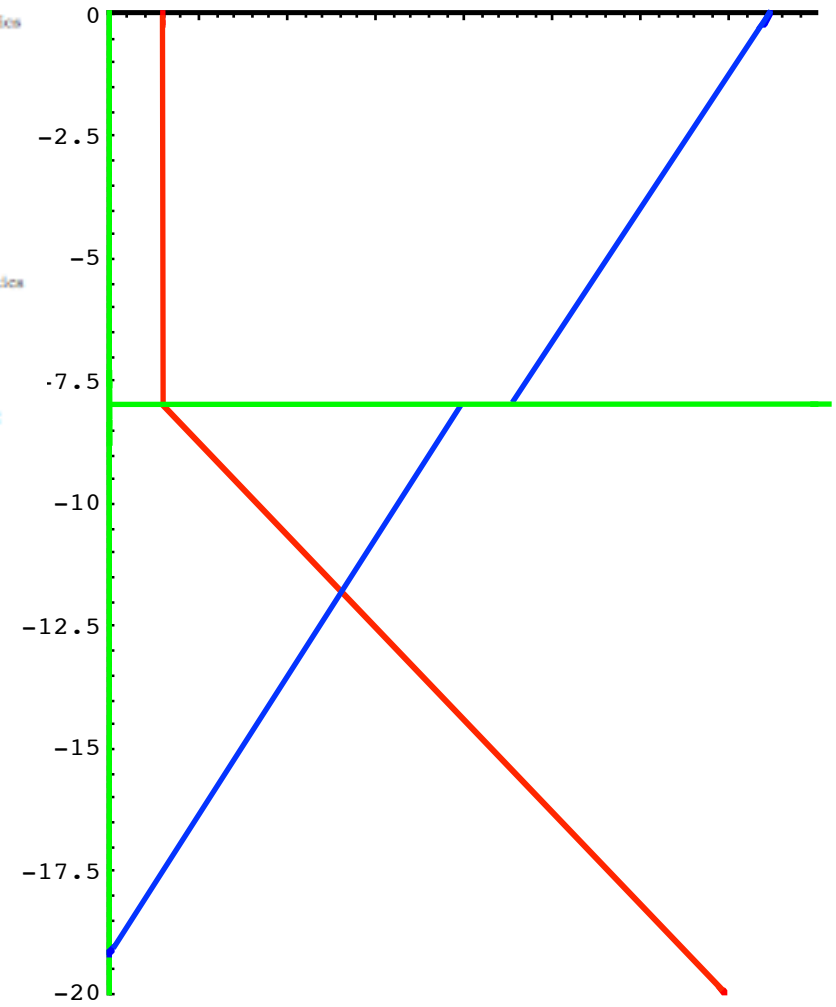
CONCENTRATION PHENOMENA IN A NONLOCAL QUASI-LINEAR PROBLEM MODELLING PHYTOPLANKTON II: LIMITING PROFILE*

YIHONG DU† AND SZE-BI HSU‡

phytoplankton

nutrient

In light

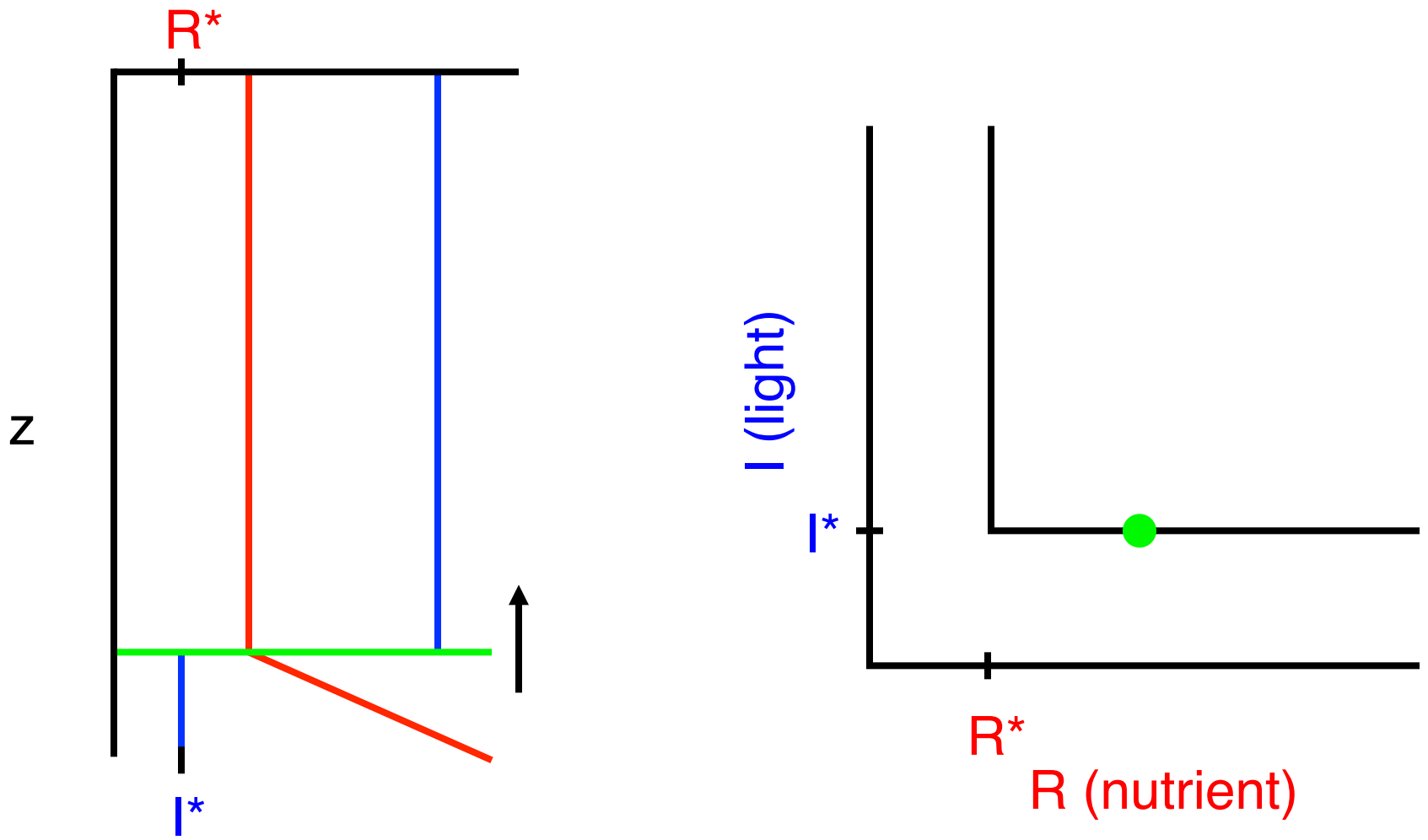


Game Theoretical Approach

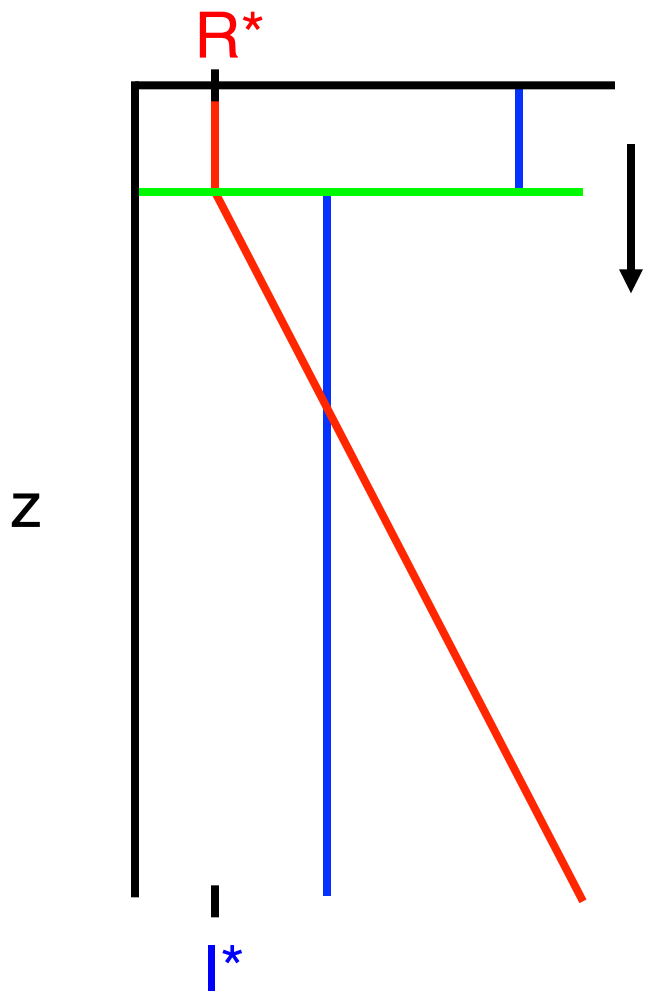
- Assume phytoplankton form thin layer
- Strategy: depth of layer, z_l
- Given layer at z_l, determine equilibrium profile of nutrients and light
- Look for strategy z^* that prevents growth everywhere else (ESS)

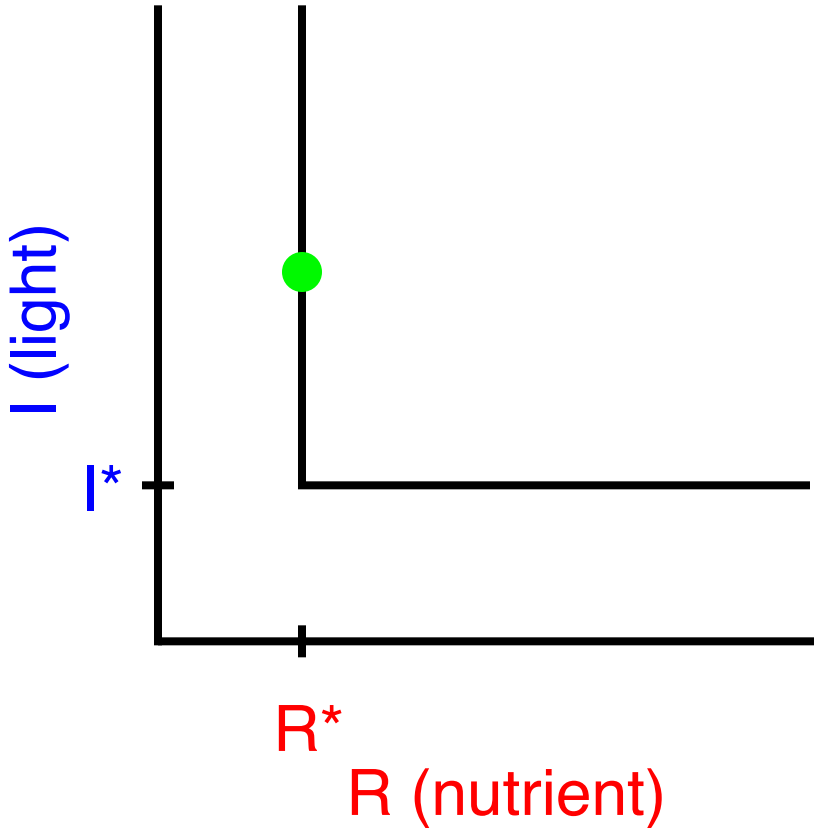
(Klausmeier and Litchman 2001)

Too Deep – Light-Limited



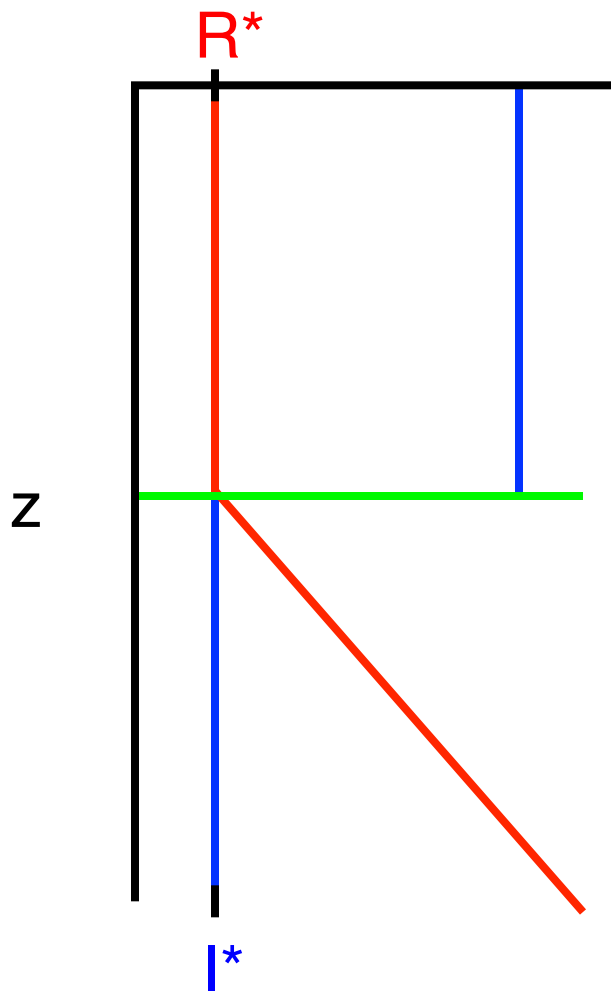
Too Shallow – Nutrient-Limited

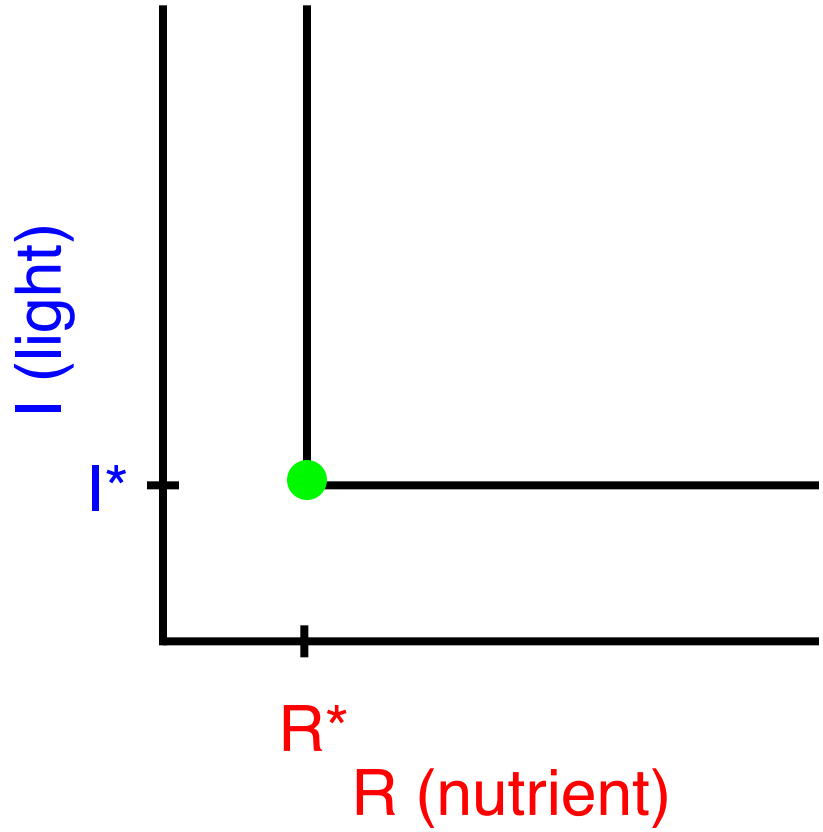




Just Right – Co-Limited

"where there is light, no nutrients are left, and where nutrients remains, there is no light" - Margalef (1978)





ESS Depth, z*

$$\frac{\log I_{\text{in}} - \log I^*}{a} - \frac{a_{\text{bg}}}{\text{a}} z^* = \frac{YD\left(R_{\text{in}} - R^*\right)}{m\left(1-\varepsilon\right)\left(z_b + 1/h - z^*\right)}$$

$$\begin{bmatrix}\text{light - limited} \\ \text{biomass}\end{bmatrix} = \begin{bmatrix}\text{nutrient - limited} \\ \text{biomass}\end{bmatrix}$$

Effect of Model Parameters

- Increase light supply / competitive ability
  - Increase Iin
  - Decrease abg, a
  - Decrease I*

➔ Move layer down (increase z*)

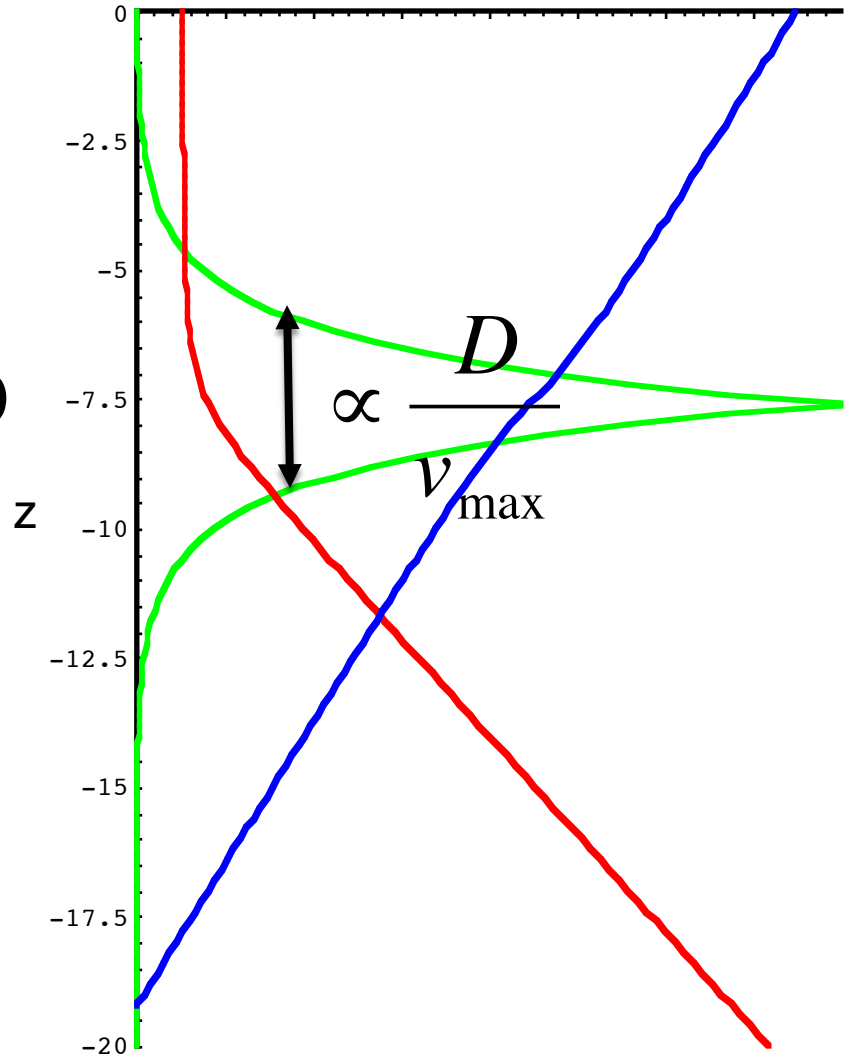
- Increase nutrient supply / competitive ability
  - Increase Rin
  - Decrease R*

➔ Move layer up (decrease z*)

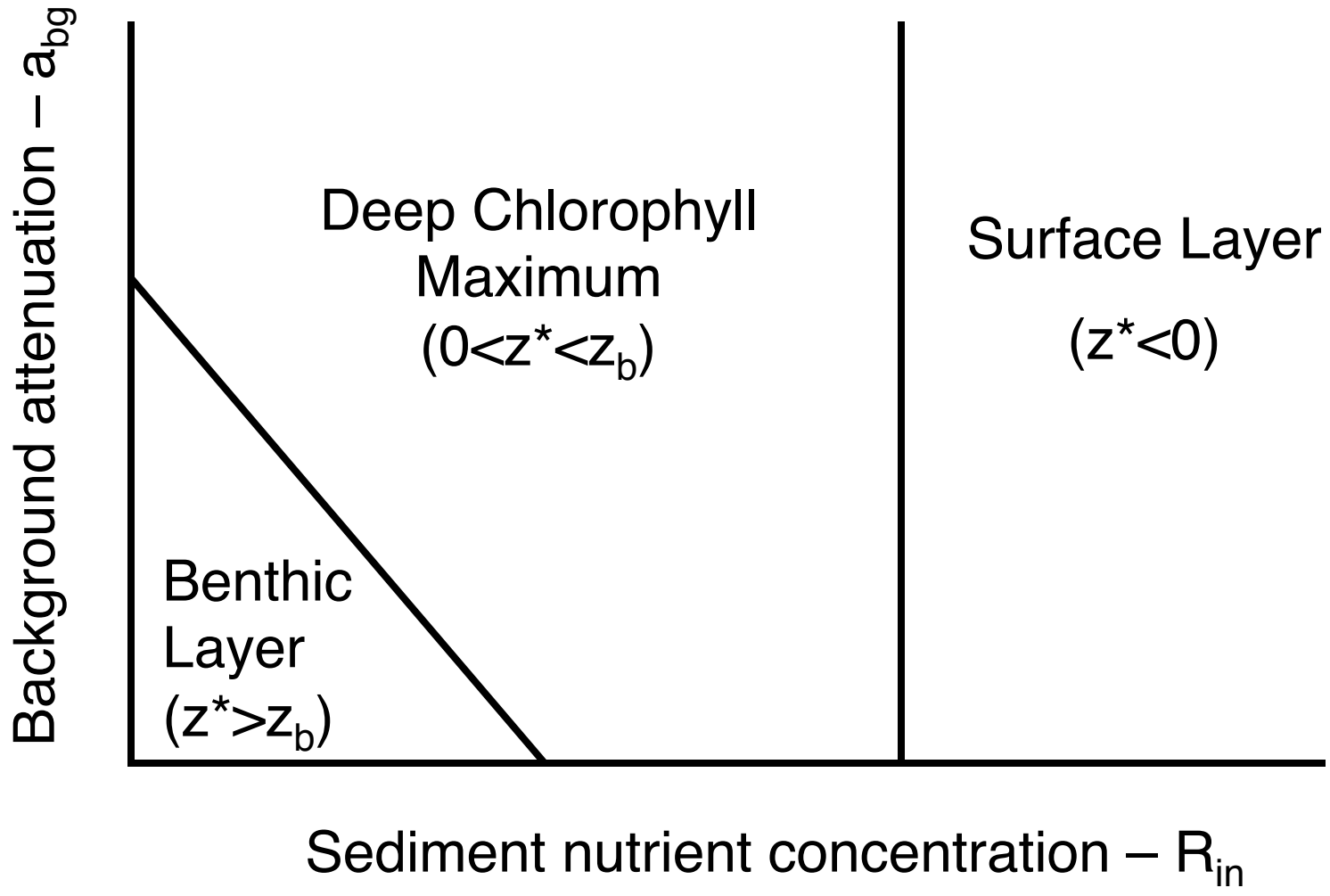
Width of layer

$$\frac{\partial b}{\partial t} = D\frac{\partial^2 b}{\partial z^2} + \frac{\partial}{\partial z}\begin{cases} -v_{\max} b, & z < z^* \\ v_{\max} b, & z > z^* \end{cases} = 0$$

$$= \begin{bmatrix} \text{passive} \\ \text{movement} \end{bmatrix} + \begin{bmatrix} \text{active} \\ \text{movement} \end{bmatrix}$$



Overview of Outcomes

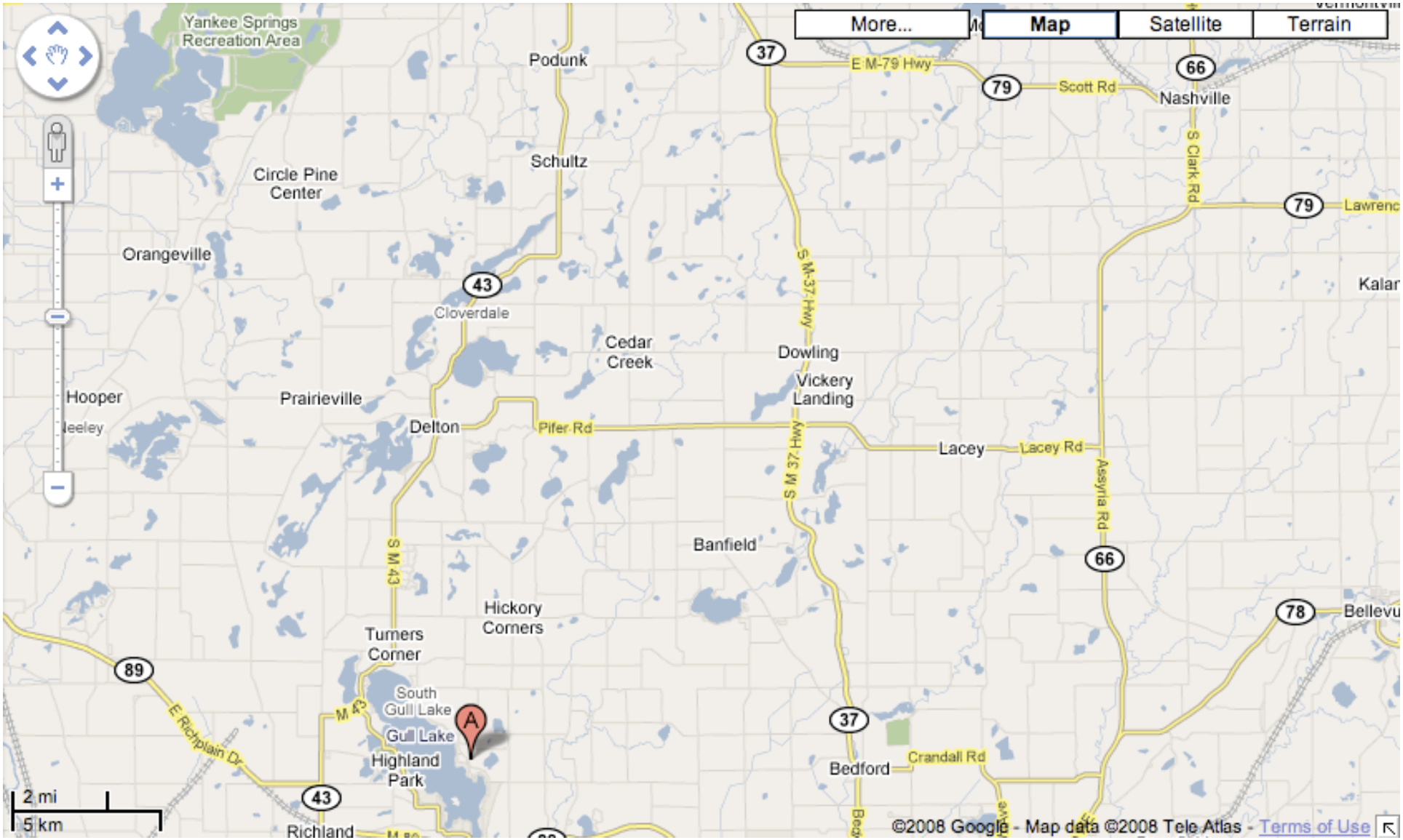


Extending this research…

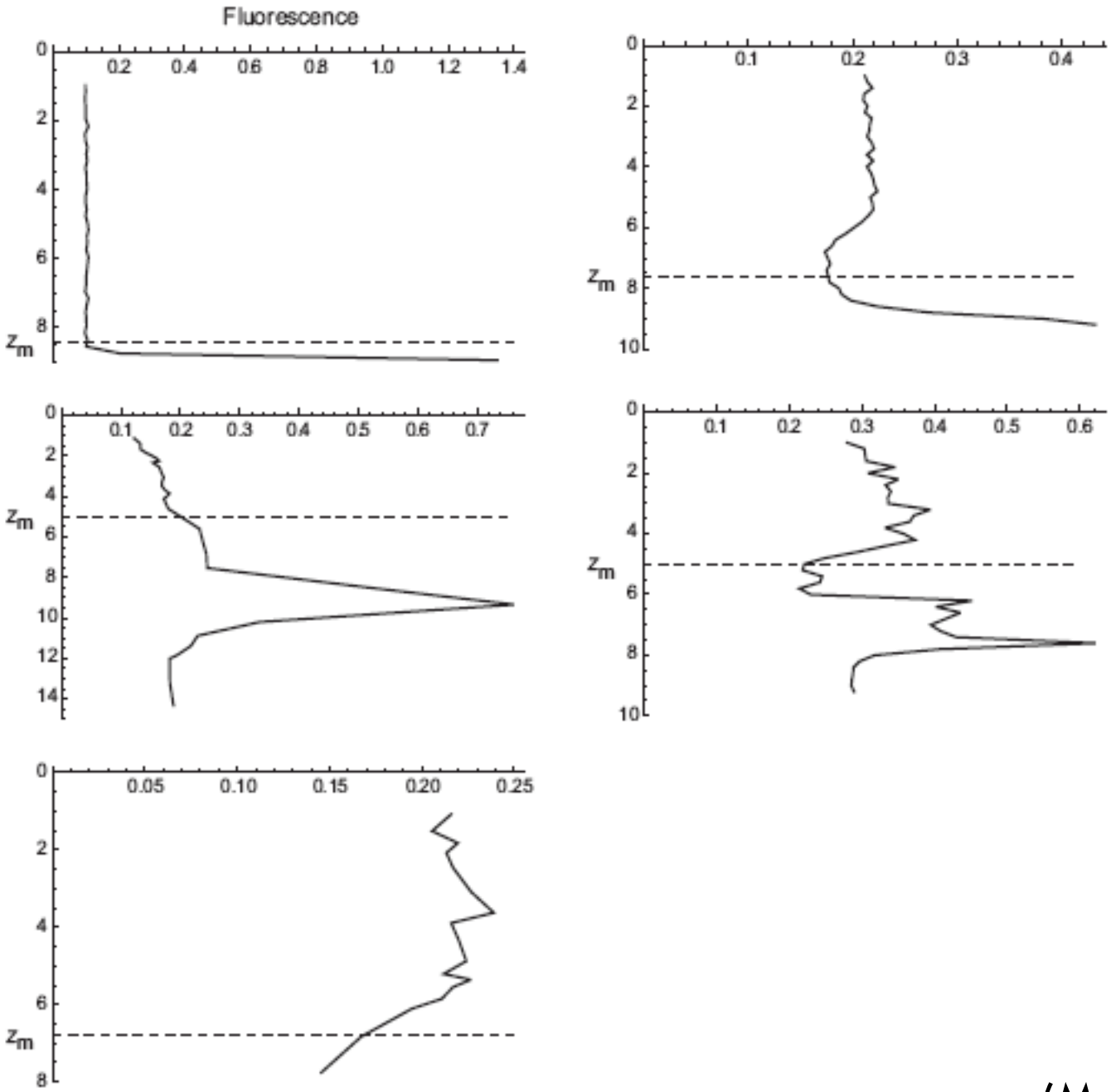
Jarad Mellard [GS] Kohei Yoshiyama [PD]

Laboratory mesocosms

(Mellard et al 2012 Ecological Monographs)



(Mellard et al. *in prep.*)



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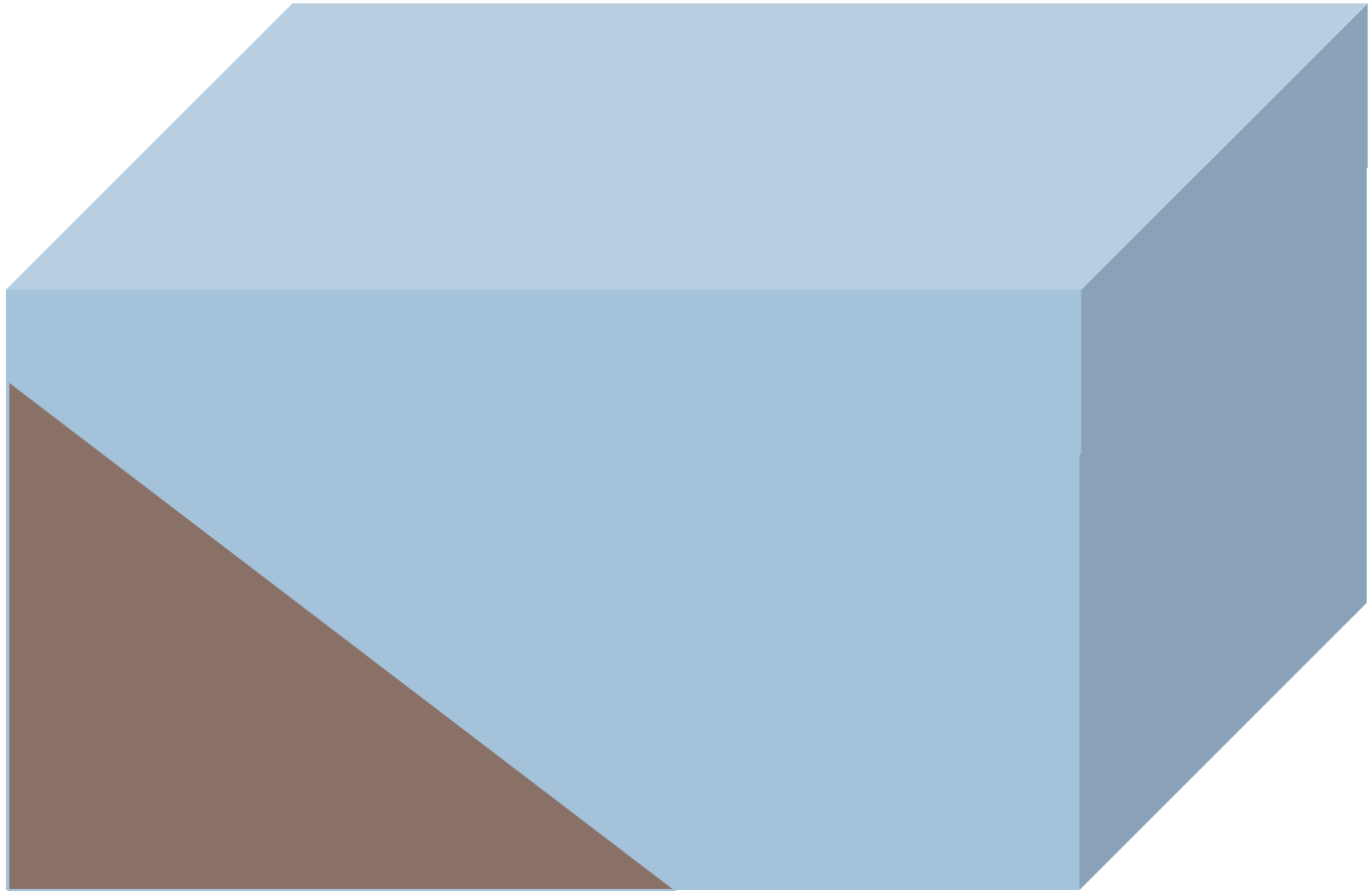
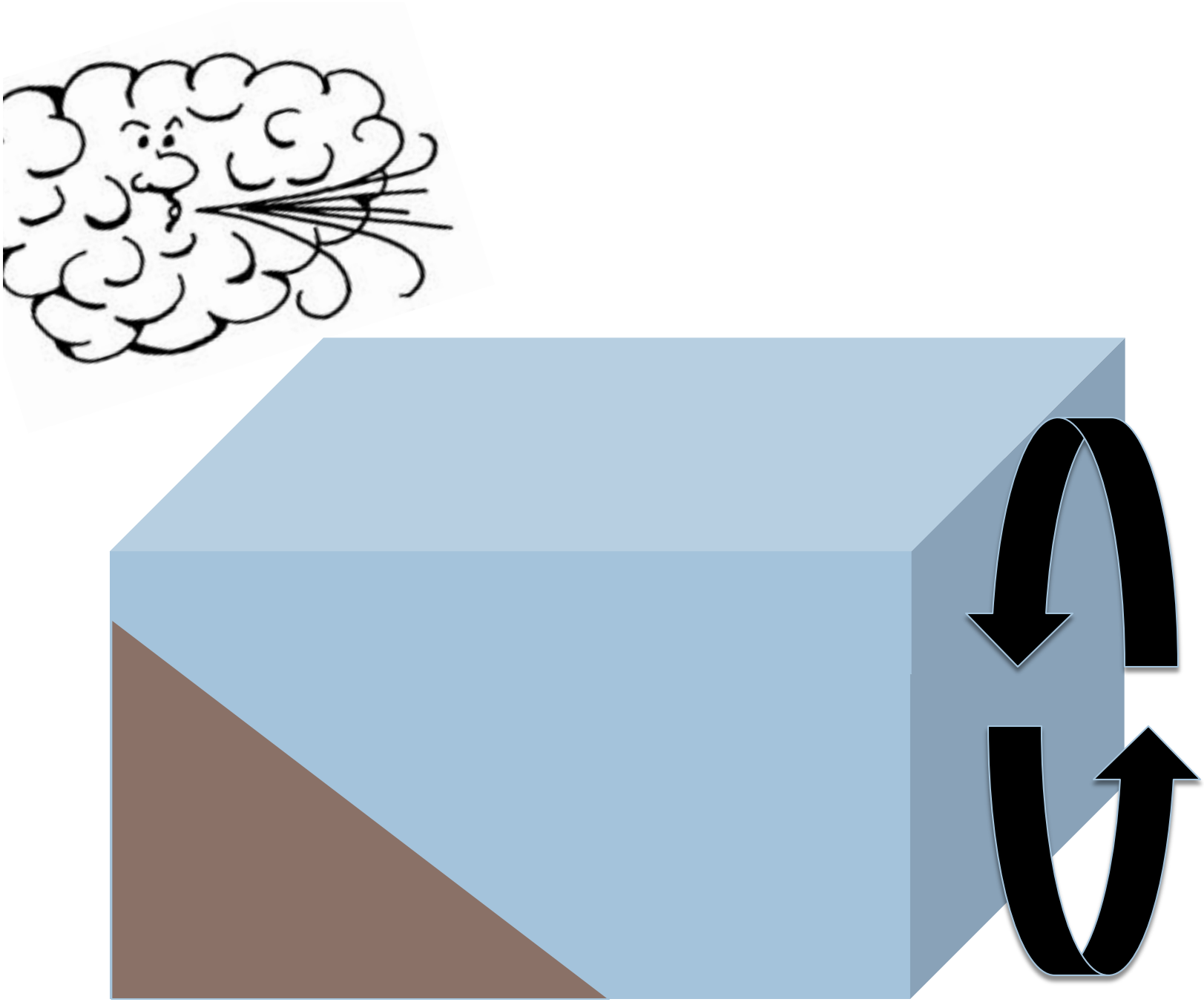
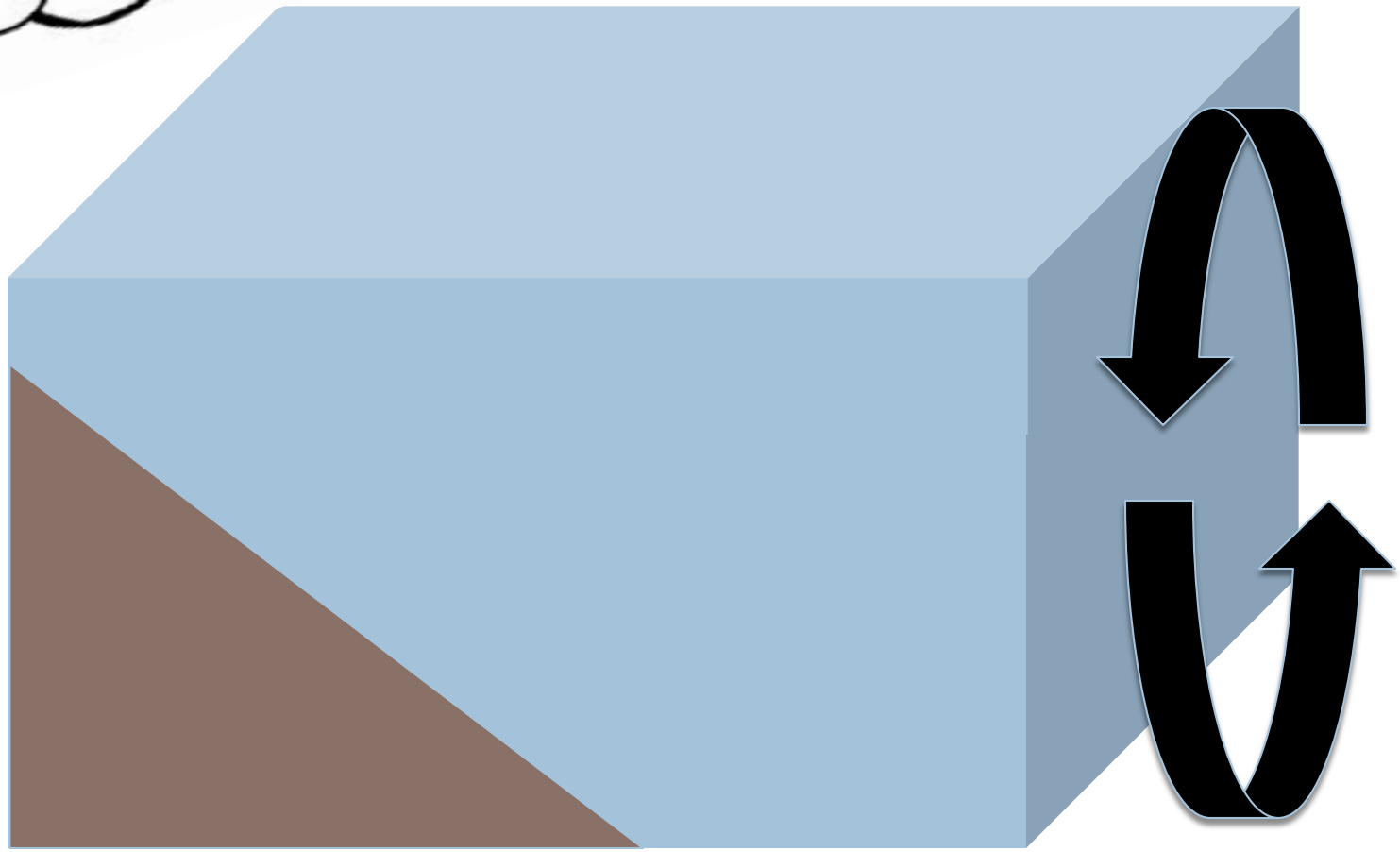






Model Results

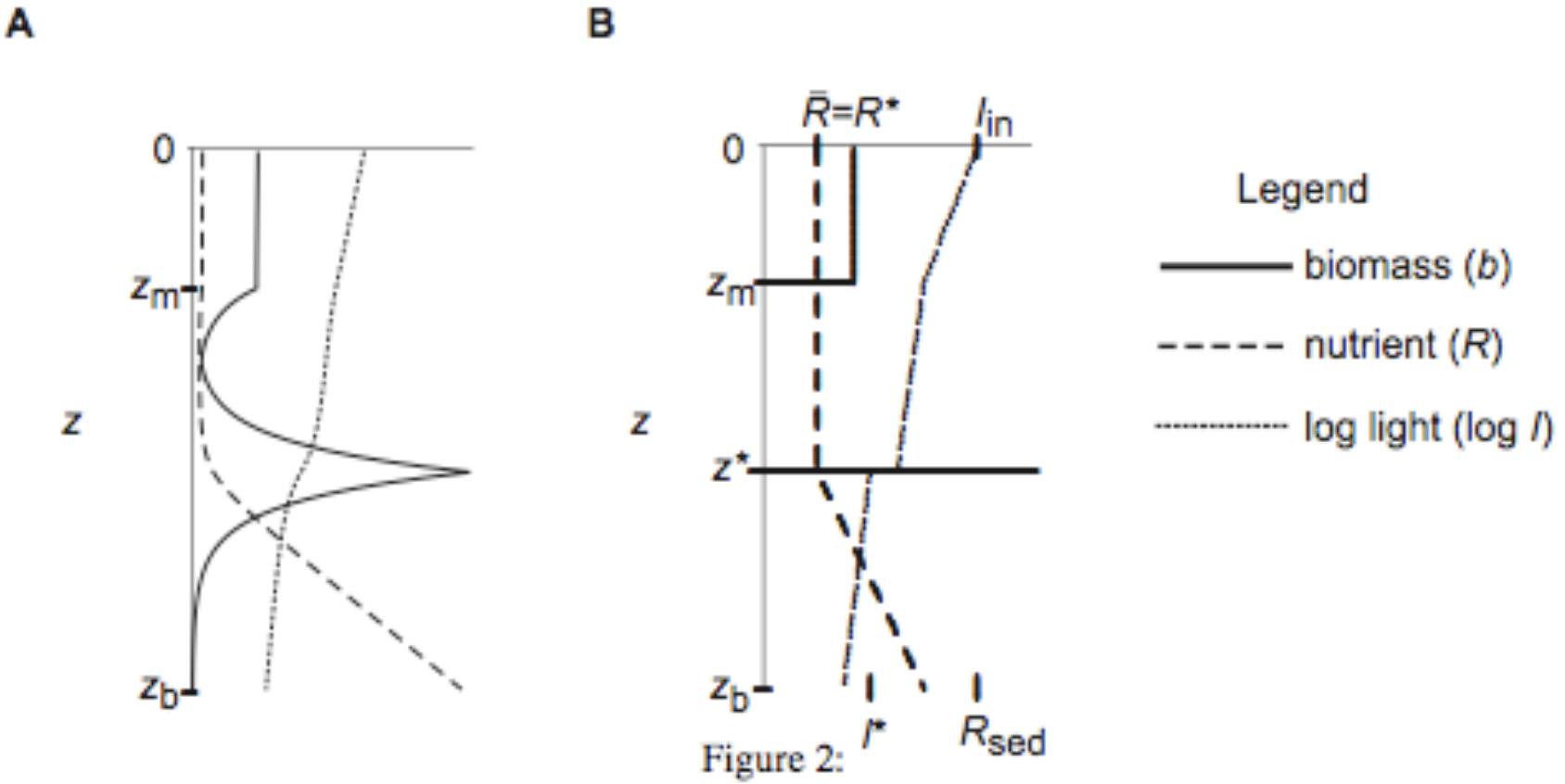
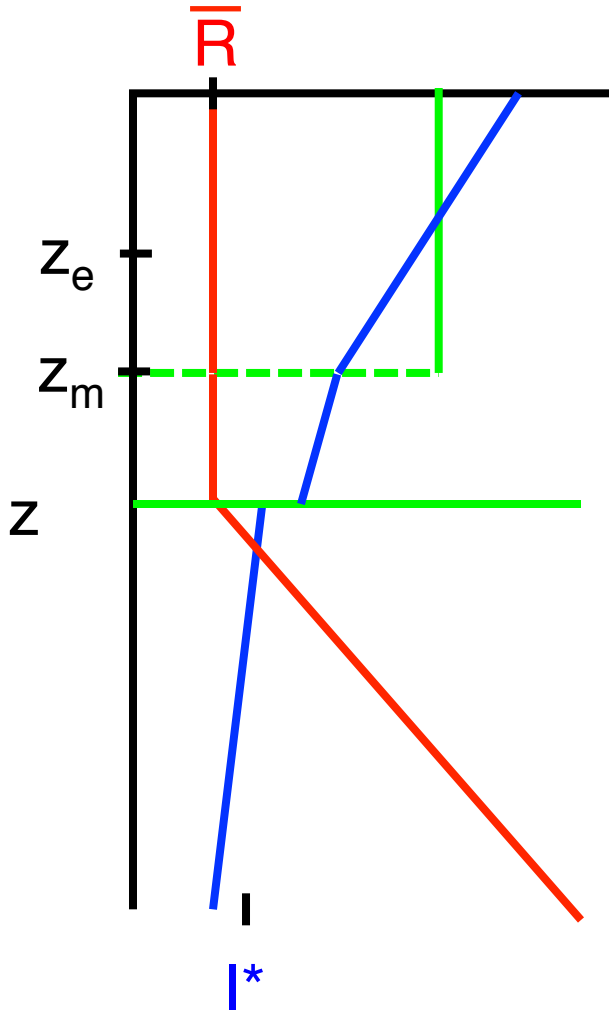


Figure 2:

(Mellard et al JTB 2011)

Simplified model: stratified

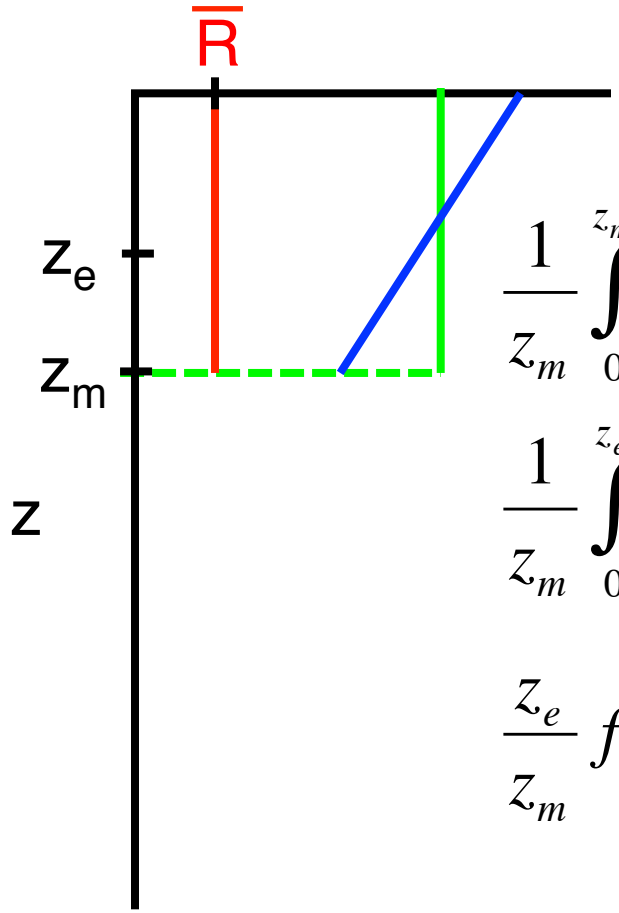


Huisman and Weissing 1994, 1995

Klausmeier & Litchman 2001

(Mellard et al JTB 2011)

Simplified model: mixed layer colimited case



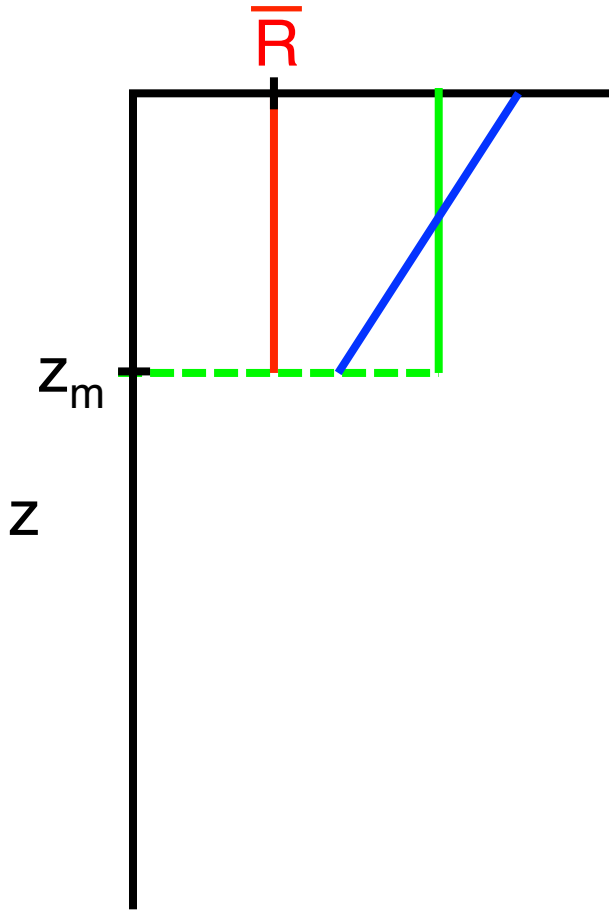
Huisman and Weissing 1994, 1995

$$\frac{1}{z_m}\int_0^{z_m} \min(f_R(\overline{R}), f_I(I(z))dz - m = 0$$

$$\frac{1}{z_m}\int_0^{z_e} f_R(\overline{R})dz + \frac{1}{z_m}\int_{z_e}^{z_m} f_I(I(z))dz - m = 0$$

$$\frac{z_e}{z_m} f_R(\overline{R}) + \frac{r}{a_{bg} z_m + aB_{ML}} \log\left(\frac{K_I + I(z_e)}{K_I + I(z_m)}\right) - m = 0$$

Simplified model: mixed layer light-limited case



Huisman and Weissing 1994, 1995

$$\frac{1}{z_m}\int_0^{z_m} \min(f_R(\bar{R}), f_I(I(z))dz - m = 0$$

$$\frac{r}{a_{bg}z_m + aB_{ML}}\log\left(\frac{K_I + I_{in}}{K_I + I(z_m)}\right) - m = 0$$

Model Results

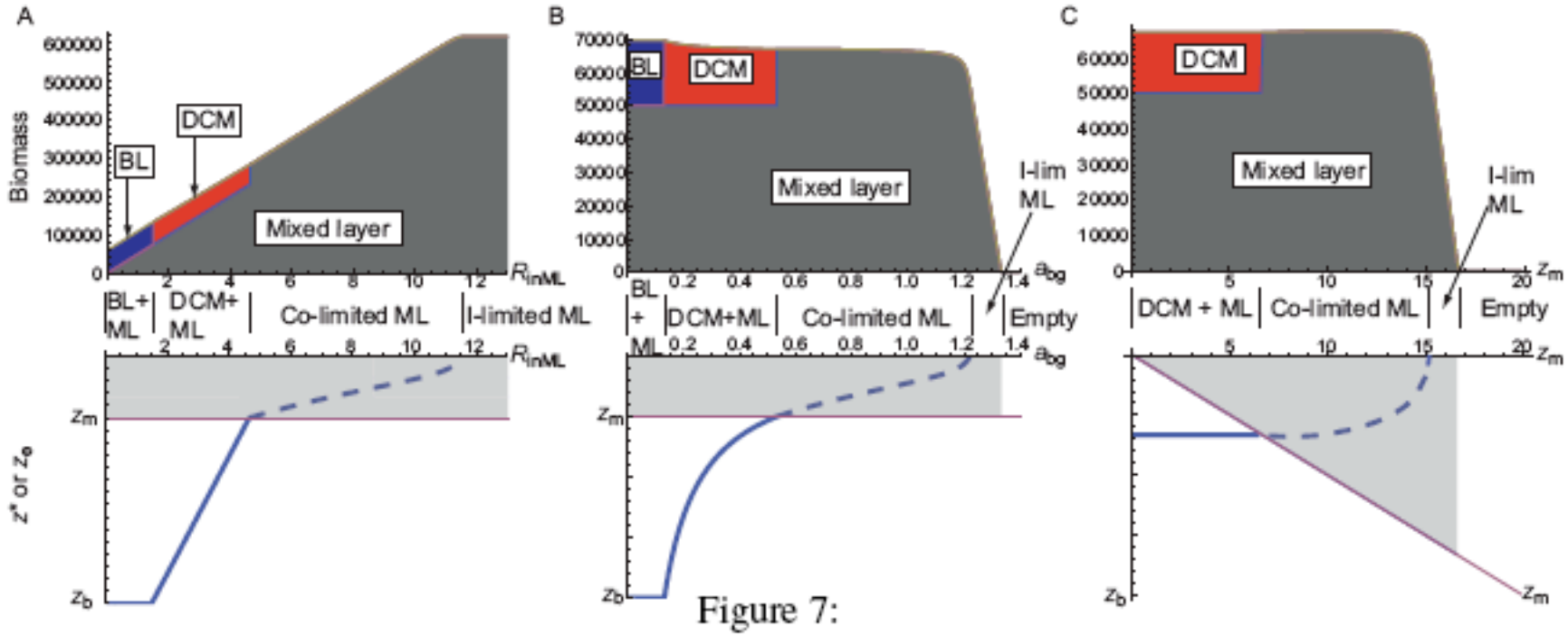


Figure 7:

(Mellard et al JTB 2011)

Model Results

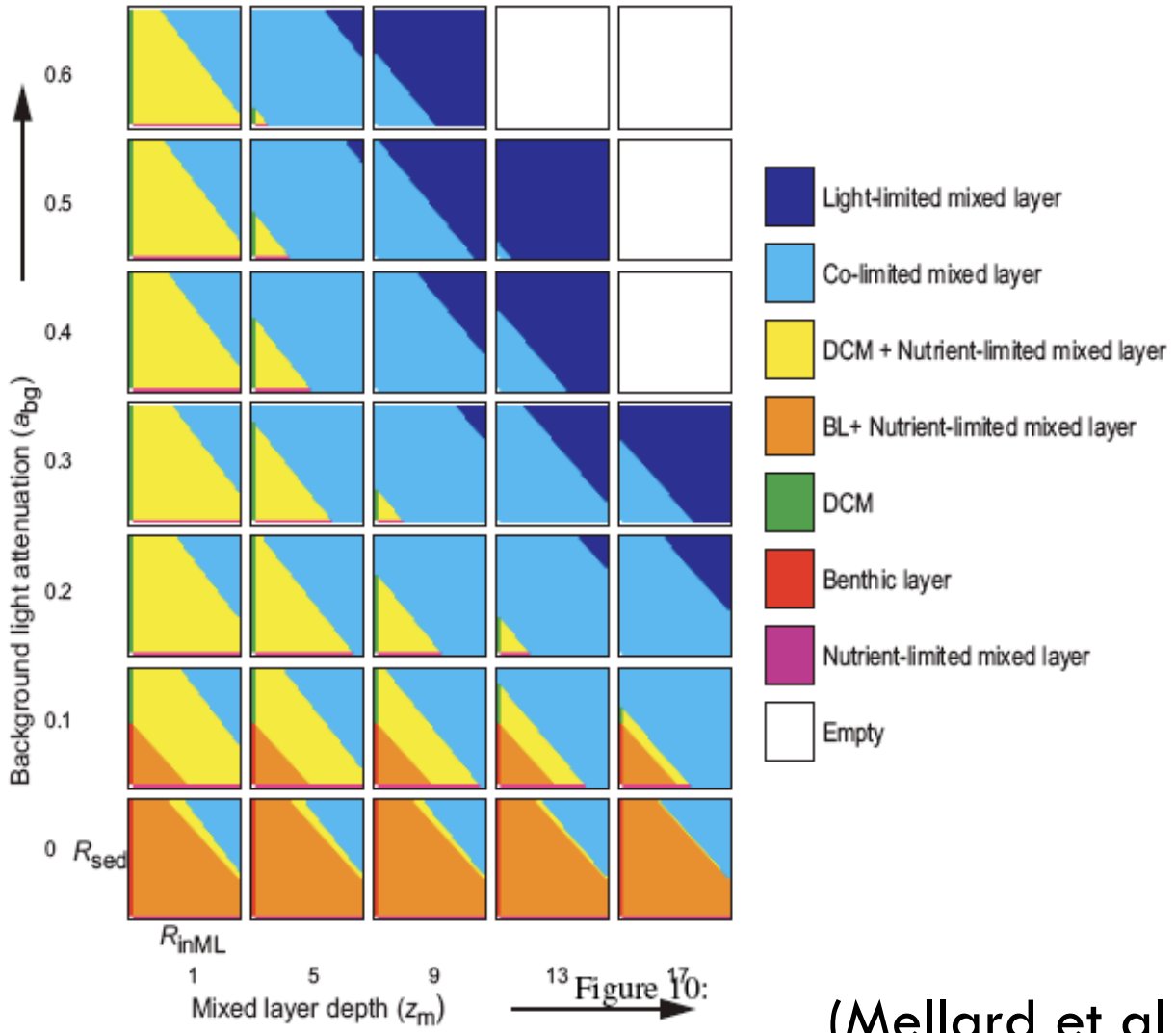
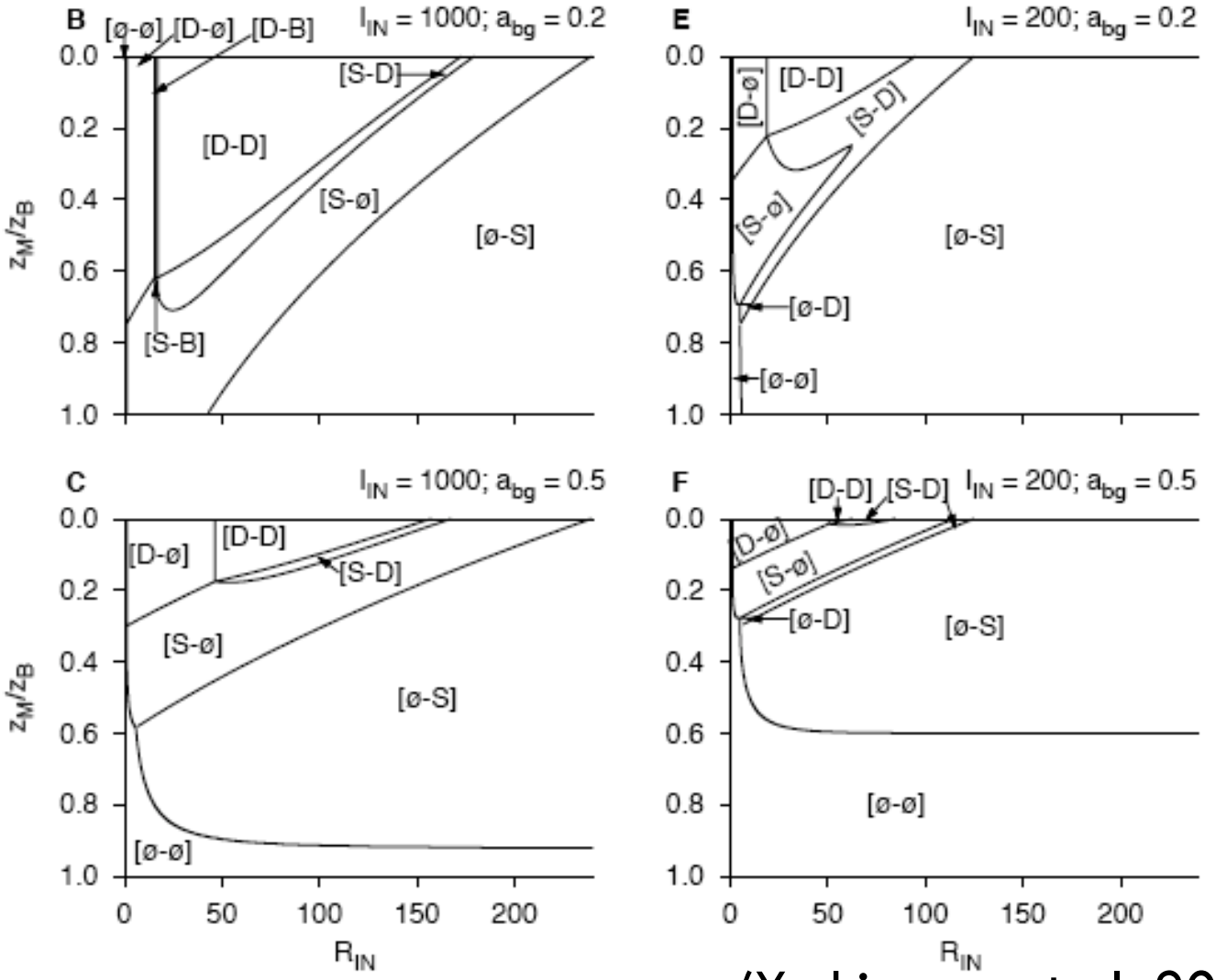


Figure 10:

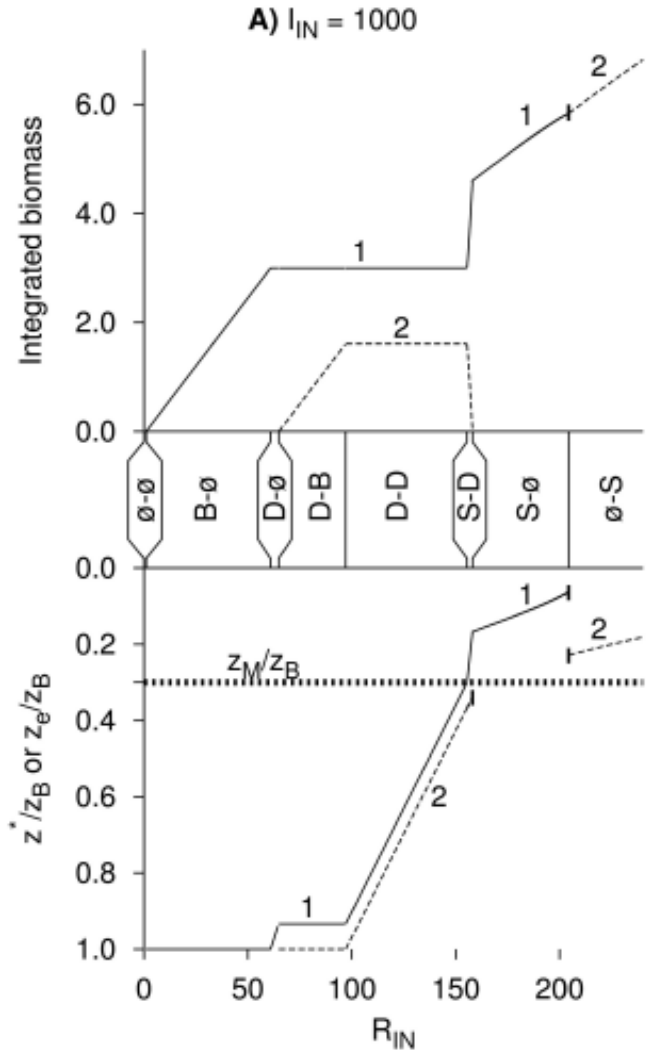
(Mellard et al JTB 2011)

Two competitors, stratified



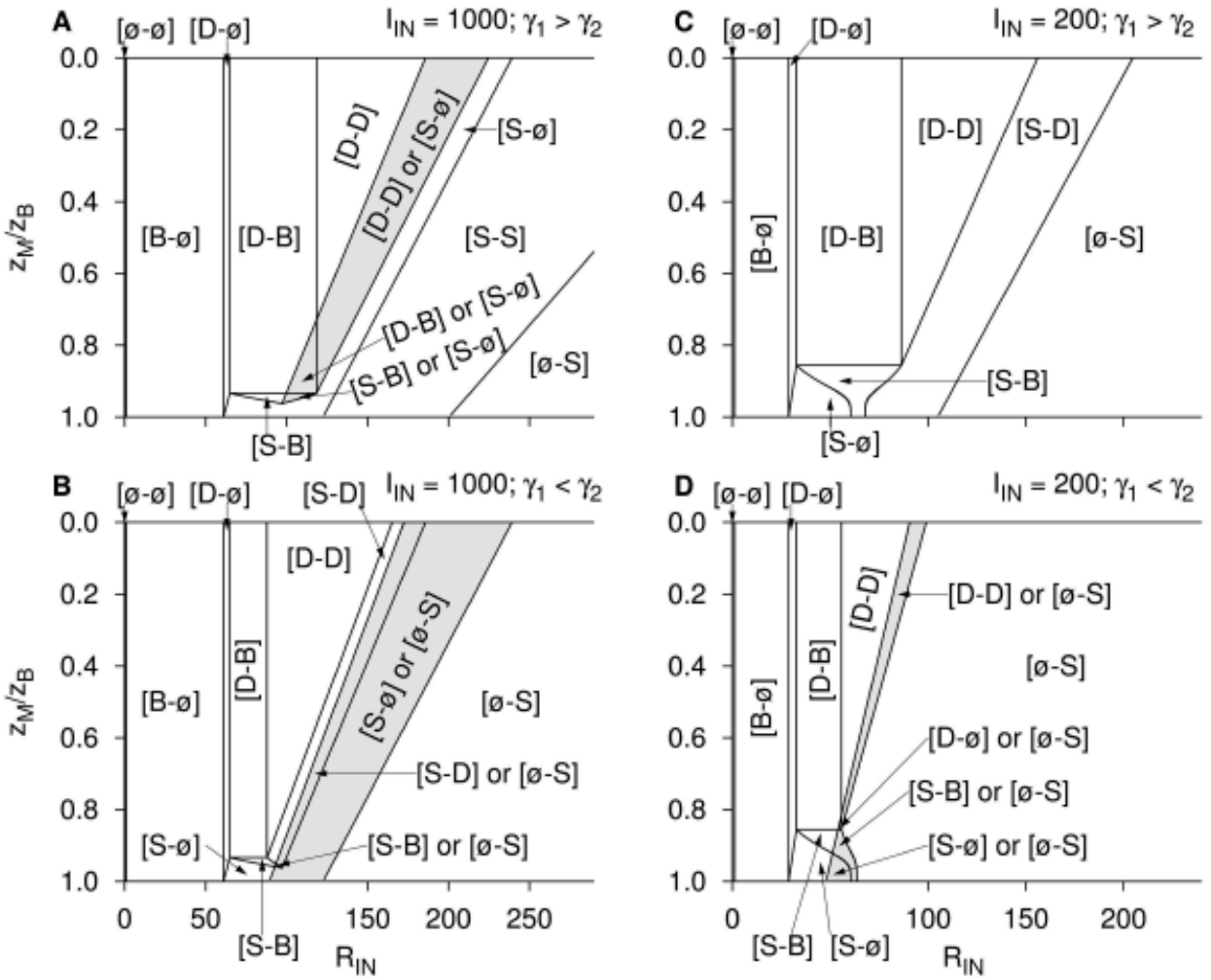
(Yoshiyama et al. 2009 Am Nat)

Two competitors, stratified



(Yoshiyama et al. 2009 Am Nat)

Two competitors, stratified



(Yoshiyama et al. 2009 Am Nat)

Acknowledgments

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  - Kohei Yoshiyama
  - Jarad Mellard
  - Dennis Ruppe
  - Yonatan Natan
- Funding sources
  - NSF DEB-0610531, DEB-0845825
  - James S McDonnell Foundation