

Modeling the Impacts of Water Quality on SAV and other Living Resources in the Tidal Chesapeake Bay

Richard C. Zimmerman, Victoria J. Hill

Bio-Optical Research Group

Department of Ocean, Earth & Atmospheric Sciences

Old Dominion University

Norfolk VA

Charles L. Gallegos

Smithsonian Environmental Research Center

Edgewater, MD



Motivation for this work:

Basic:

- Link hydrologic optics with physiology to develop fundamental understanding of climate impacts on aquatic photosynthesis

Applied:

- Improve our ability to model & manage the impacts of water quality on shallow water resources in the Chesapeake Bay
 - Existing Bay Model works well in the main stem of the Bay but fails to predict WQ and SAV distributions in shallow water, esp tributaries

SAV and Climate Change:

- High light requirements (10 - 20% surface E)
- Vulnerable to poor water quality
- Sensitive to high summer temperatures



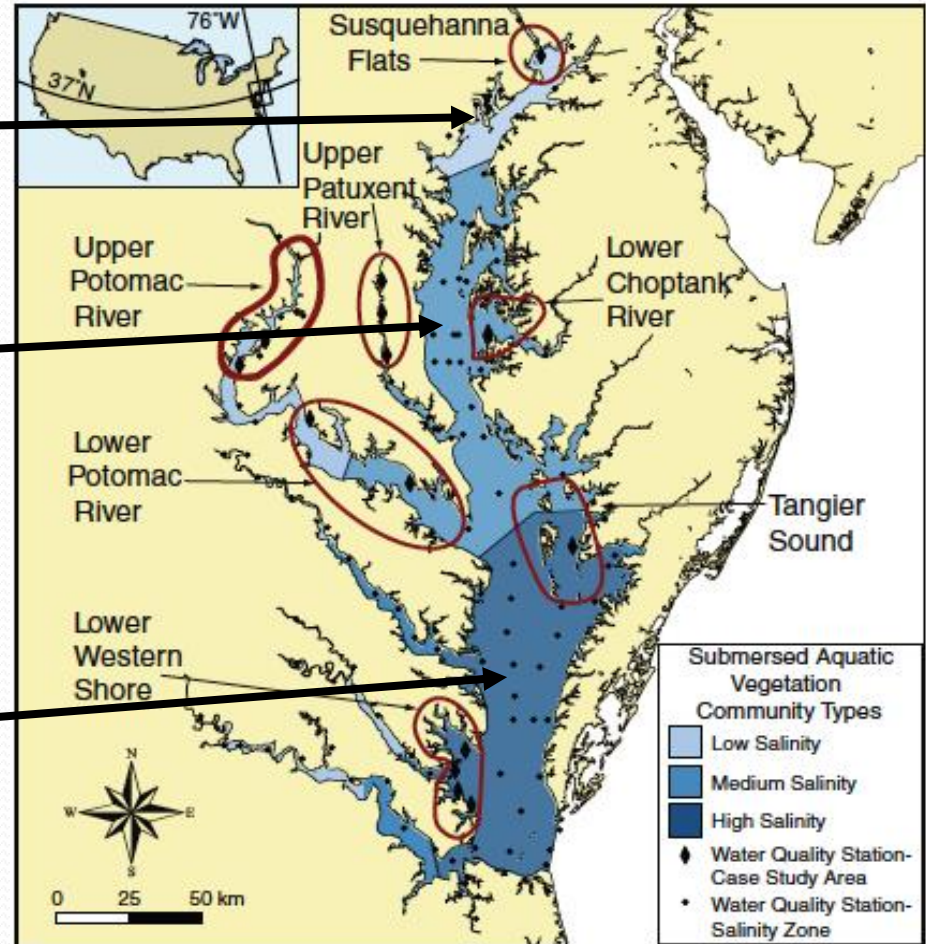
SAV loss threatens provision of major ecosystem services in shallow coastal environments

- Habitat structure and sediment stability
 - Loss of "blue carbon" deposits
- Productivity shift from benthos to plankton
- Shifts in sediment biogeochemistry
 - Reduced flux of C_{org} and O_2 to sediments



Salinity controls SAV community structure

- 3 Broad Salinity regimes
- Oligohaline
 - Salinity <5 (PSS)
 - Fresh water habitat
- Mesohaline
 - 5 to 15 (PSS)
 - Highly variable
 - Most affected by dry/wet rainfall patterns
- Polyhaline
 - Salinity >15 (PSS)
 - Southern Bay
 - Mostly marine habitat



Map by R. J. Orth, VIMS

So, what does climate change have in store for SAV?

- Climate warming will increase summer stress
 - Chesapeake Bay eelgrass
 - Moore & Jarvis. 2008. *J. Coast. Res* **55**:135-247
 - Mediterranean *Posidonia*
 - Marbà, N. and C. Duarte. 2010. *Global Change Biology* **16**:2366-2375.
- Heat stress events will become more frequent
 - European eelgrass
 - Franssen, S. and others 2012. Transcriptomic resilience to global warming in the seagrass *Zostera marina*, a marine foundation species. *Proc. Nat. Acad. Sci.* **108**: 19276-19281.
 - Winters, G., P. Nelle, B. Fricke, G. Rauch, and T. Reusch. 2011. Effects of a simulated heat wave on photophysiology and gene expression of high- and low-latitude populations of *Zostera marina*. *Mar. Ecol. Prog. Ser.* **435**: 83-95.
- Water quality continues to deteriorate

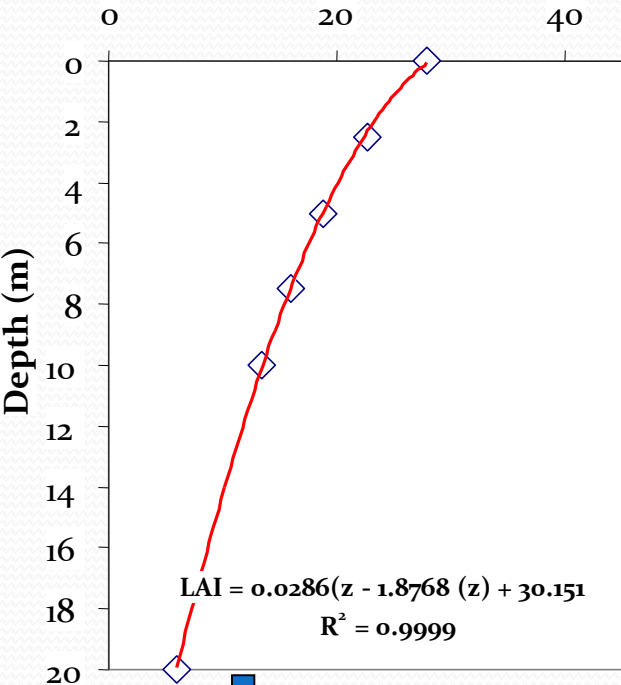
And what about Ocean Acidification?

- CO_2 availability modifies eelgrass response to temperature:
 - Increased photosynthesis and positive C balance
 - Survival & reproduction
 - Shoot Size
 - Growth
 - Below-ground biomass
- Long term experiments on whole plants support short-term responses of individual leaves
- Can we combine physiology with bio-optical modeling to predict SAV response across the aquatic landscape?

Predicting SAV Distributions:

Leaf Area Index as
Function of Depth

lai ($m^2 m^{-2}$)



Photosynthesis: Light & CO₂ Model

CO₂ dependence of P_m

$$P_m = 82 \cdot e^{(-0.53 \cdot pH)}$$

Absorbance:

$$A(\lambda) = 1 - R - \exp[a(\lambda) - a(750)]$$

Quantum Efficiency:

$$\alpha(\lambda) = \phi_{max} A(\lambda)$$

Instantaneous Photosynthesis

$$P(h, \lambda) = \int_h B(h) \cdot P_m \cdot \left[1 - \exp\left(-\frac{\alpha(\lambda) E(h, \lambda)}{P_m}\right) \right]$$

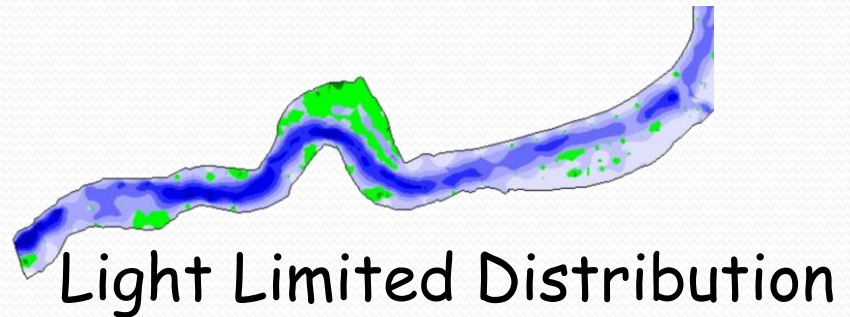
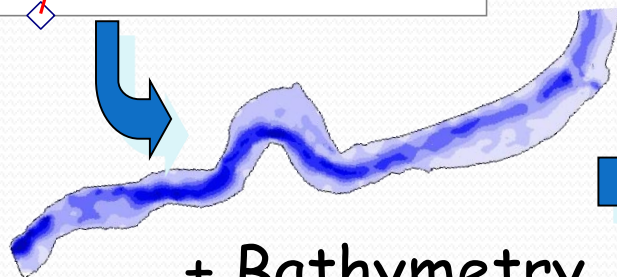
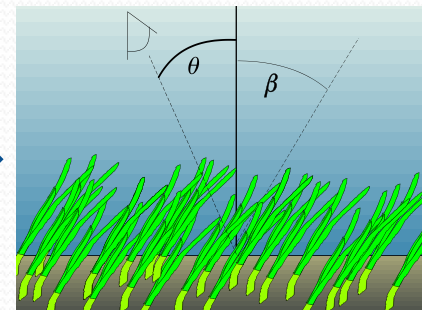
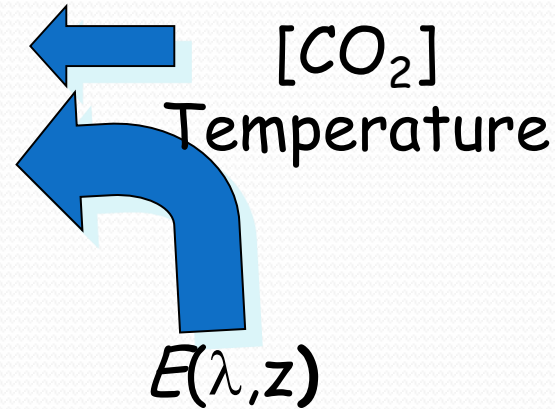
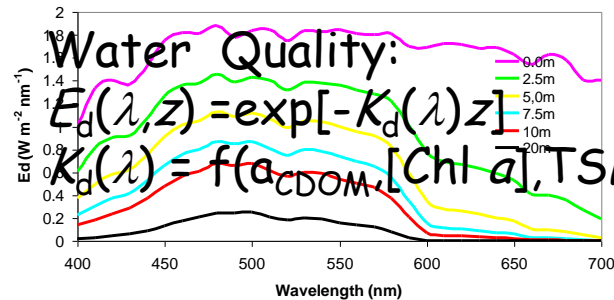
Daily Production Integral:

$$\iint_{t,h} P(\lambda) = \int_h B(h) \cdot D \cdot P_m \cdot \left[1 - \exp\left(-\frac{0.67 \alpha(\lambda) E(h, \lambda)}{P_m}\right) \right]$$

Determine maximum sustainable density at P:R=1

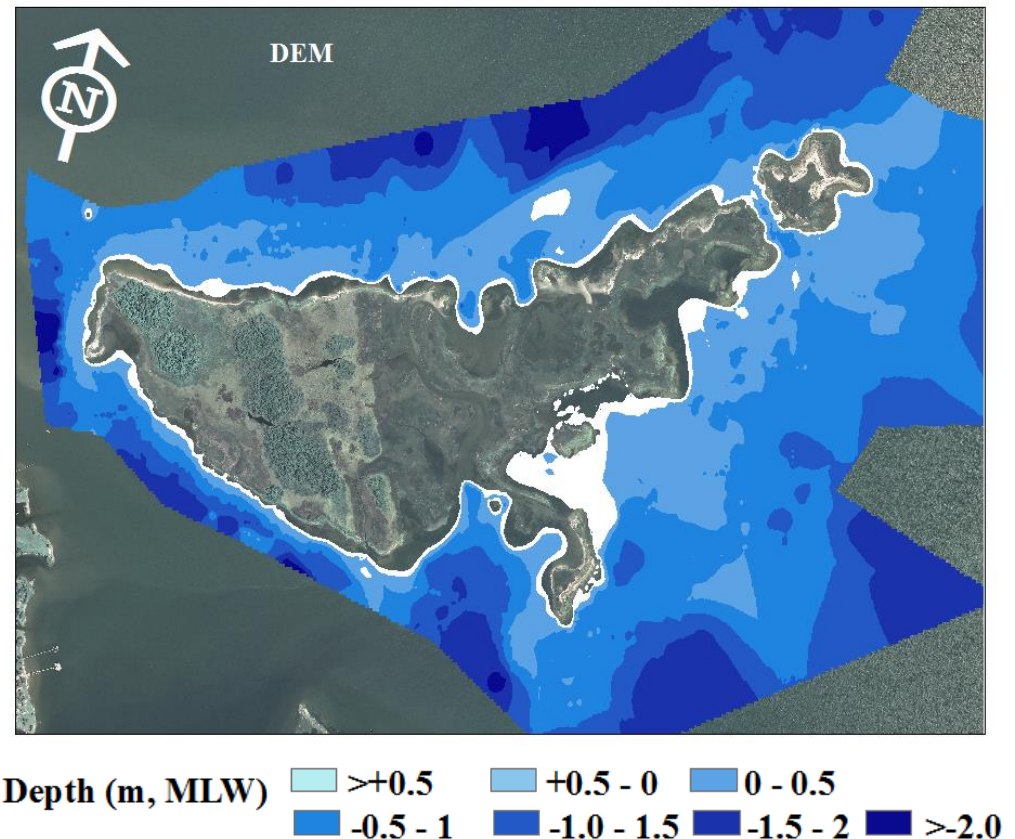
Result: Density and Leaf Area Index Estimate

Underwater Light Field



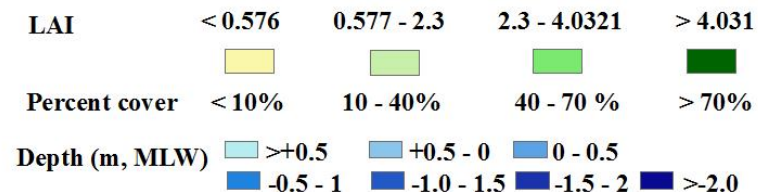
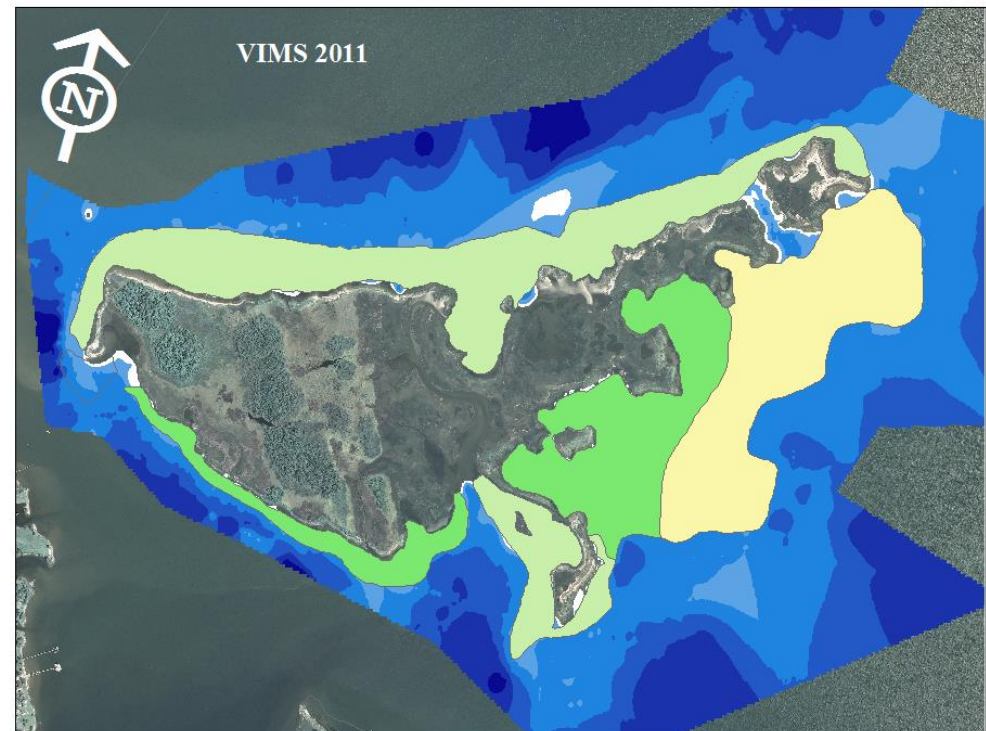
Goodwin Islands NERR

- SAV Vulnerable to thermal stress
- Time series of
 - Water quality measures to drive light availability
 - SAV abundances to compare model predictions
- Detailed bathymetry



Predicting climate effects on eelgrass distribution

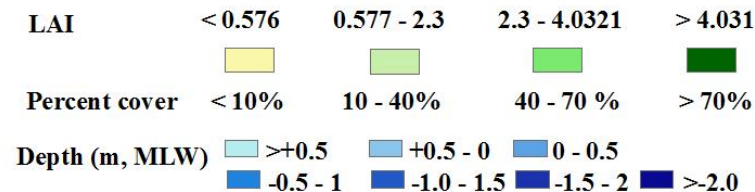
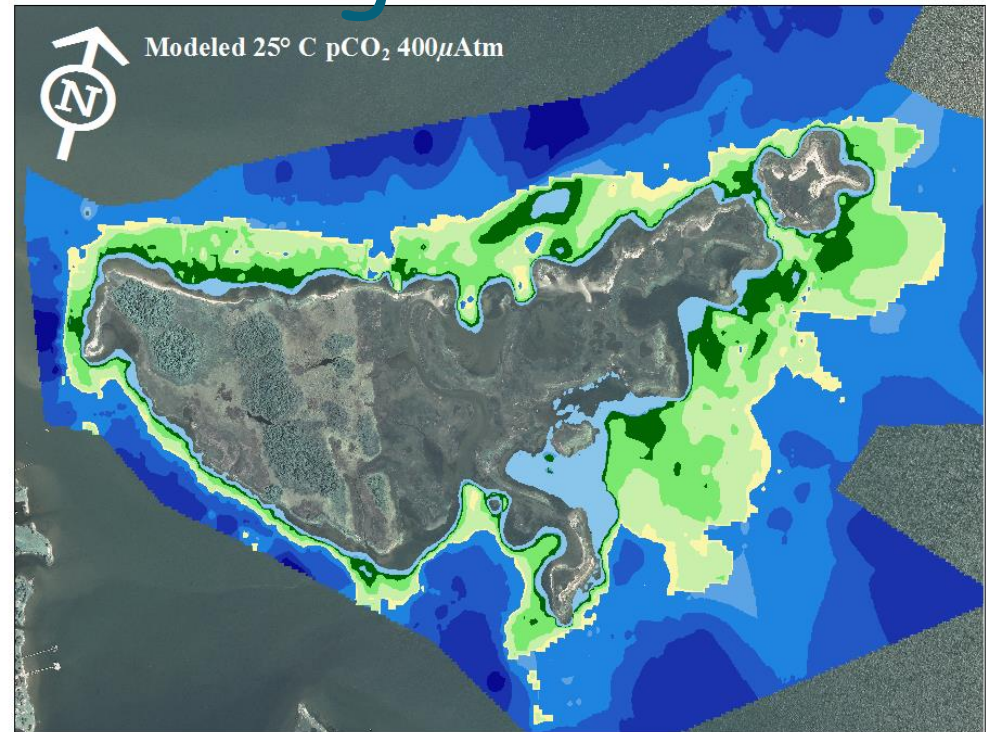
- Density decreases with depth
- Distribution limited to depths <1.5 m
- Consistent with VIMS 2011 SAV map



Zimmerman, R., V. Hill, and C. Gallegos. 2015. Predicting effects of ocean warming, acidification and water quality on Chesapeake region eelgrass. *Limnol. Oceanogr.* **60**:1781-1804.

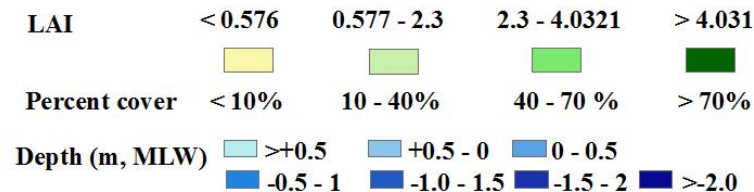
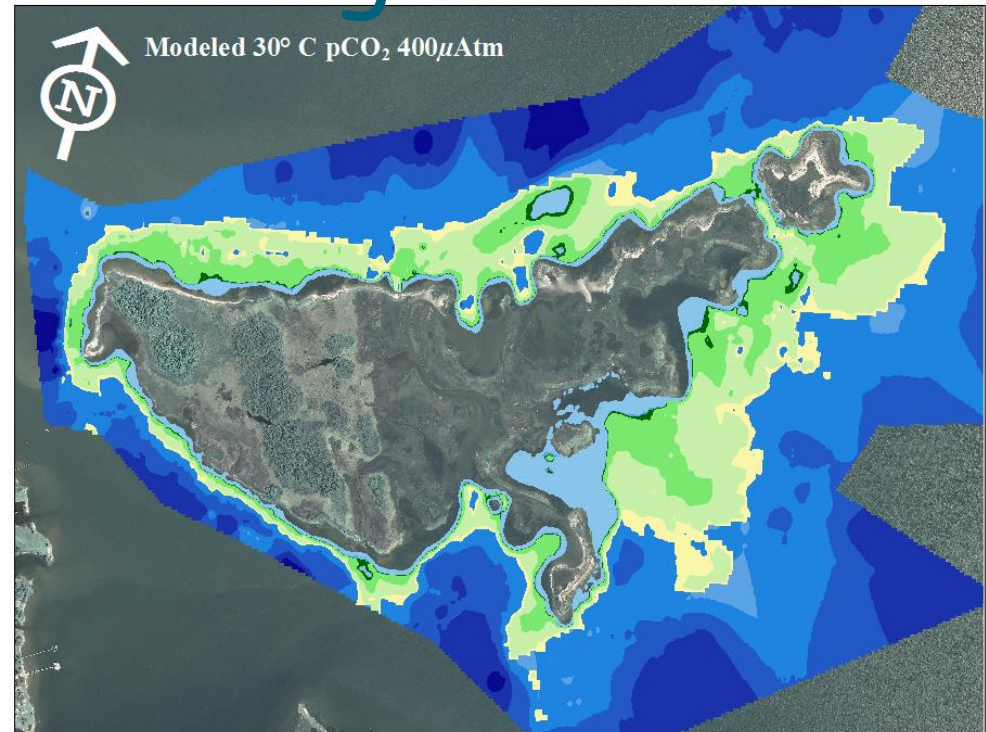
How will temperature and CO_2 interact to affect eelgrass distribution?

- Cool summer temperature
- Present-day CO_2 (pH 8)
- What happens if we increase temperature?



How will temperature and CO₂ interact to affect eelgrass distribution?

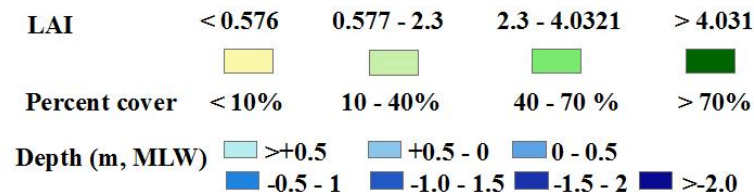
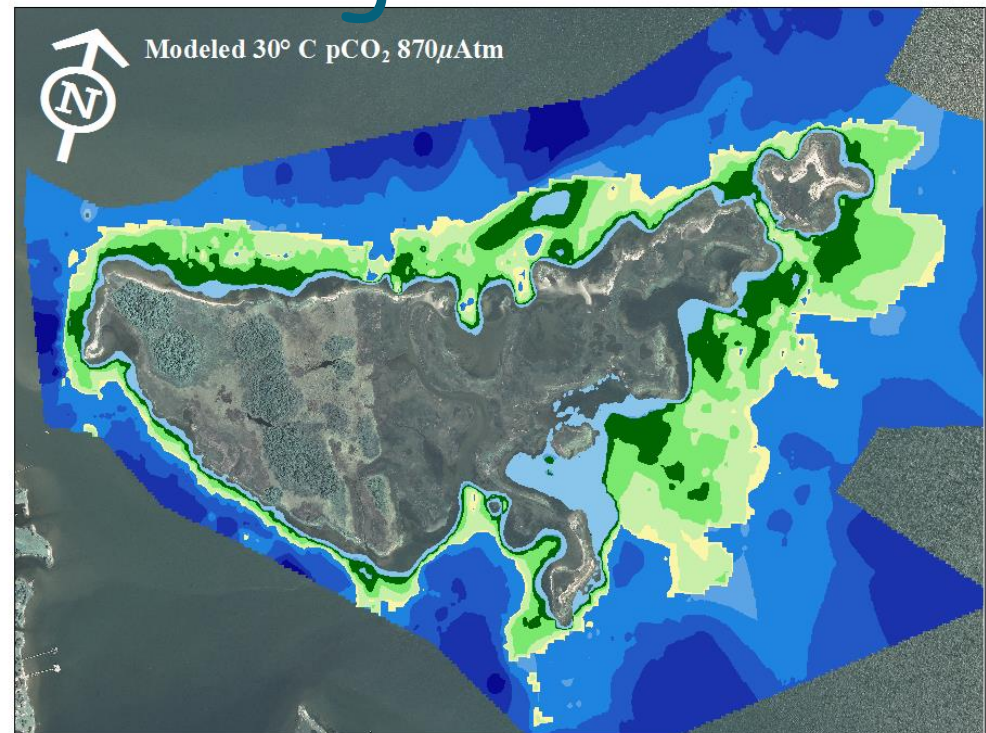
- Warming alone causes eelgrass die-back



Zimmerman, R., V. Hill, and C. Gallegos. 2015. Predicting effects of ocean warming, acidification and water quality on Chesapeake region eelgrass. *Limnol. Oceanogr.* **60**:1781-1804.

How will temperature and CO_2 interact to affect eelgrass distribution?

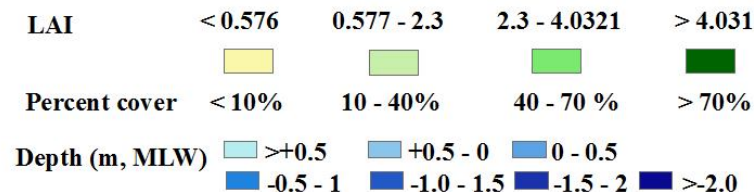
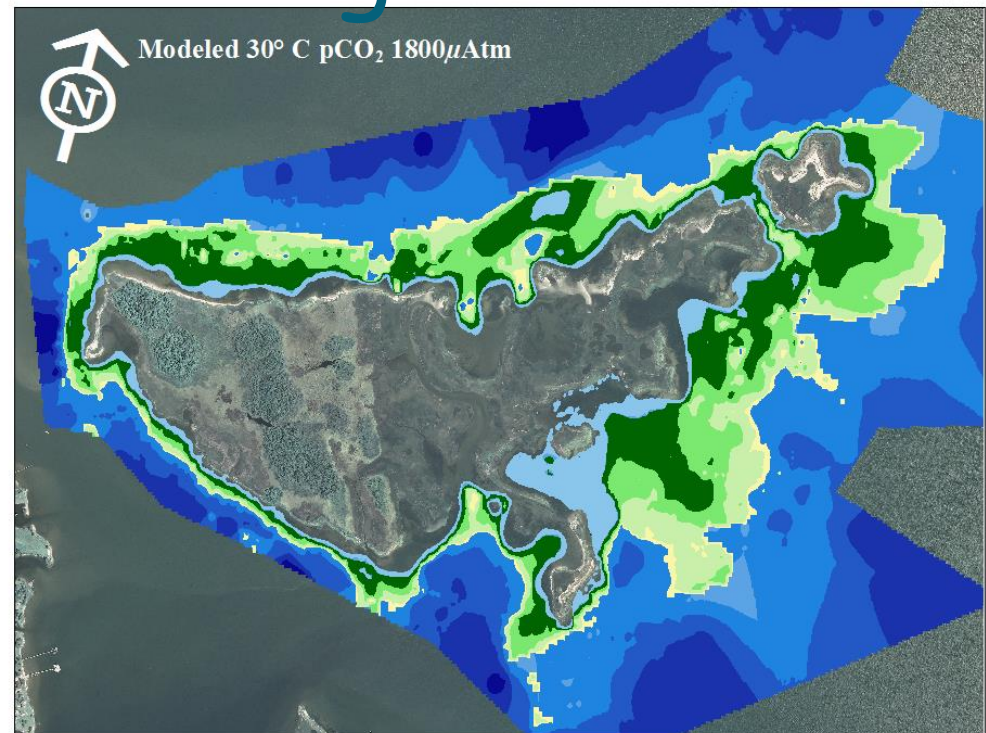
- Warming combined with CO_2 doubling (pH 7.8) causes re-growth of eelgrass



Zimmerman, R., V. Hill, and C. Gallegos. 2015. Predicting effects of ocean warming, acidification and water quality on Chesapeake region eelgrass. *Limnol. Oceanogr.* **60**:1781 - 1804.

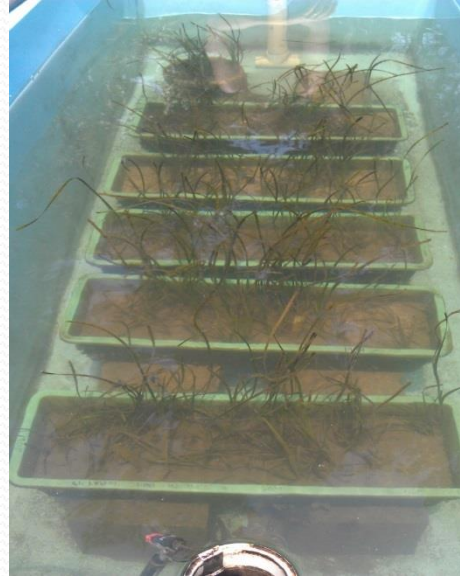
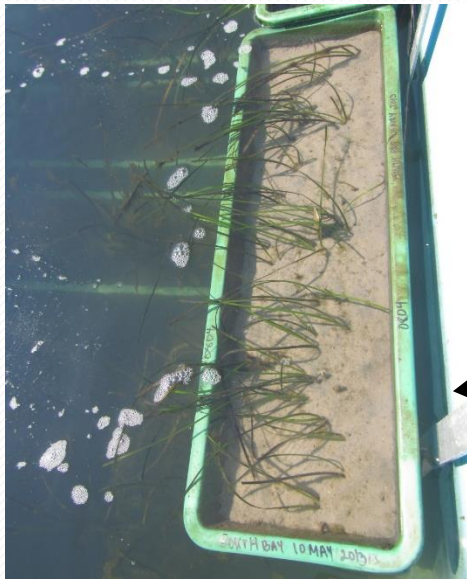
How will temperature and CO₂ interact to affect eelgrass distribution?

- Warm summer temperature
- CO₂ quadrupling (pH 7.5) further increases shallow water density
- Minimal effects on depth distribution



Experimental Results Support Model Predictions re: Temperature and CO₂

77 days T>25° C
No CO₂ addition

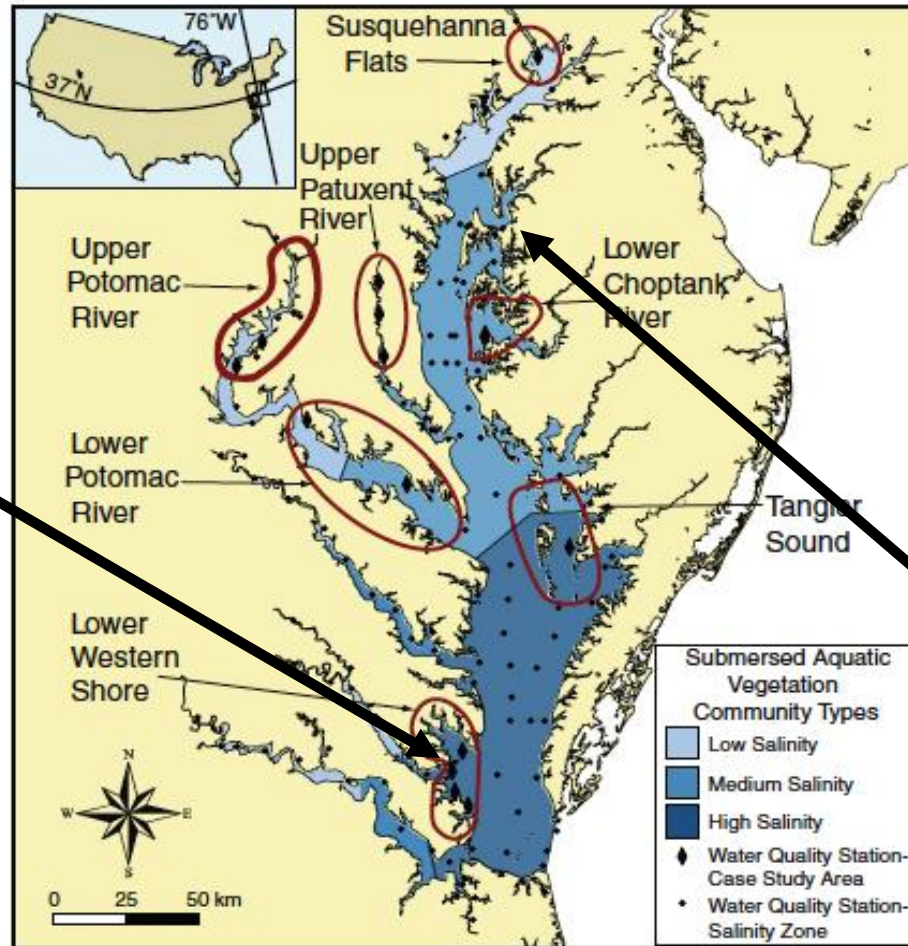


77 days T>25° C
With CO₂



So,

- The model predicts eelgrass in the polyhaline region of the Bay...



- Will it work for SAV in fresher parts of the Bay?
- Chester River

Map by R. J. Orth, VIMS

Applying *GrassLight* to the Chester River

- Mesohaline near the mouth
- Oligohaline to fresh in the upper reaches
- Highly turbid
 - $TSM \gg 30 \text{ mg L}^{-1}$
- Eutrophic
 - $Chl\ a \gg 20 \text{ mg m}^{-3}$

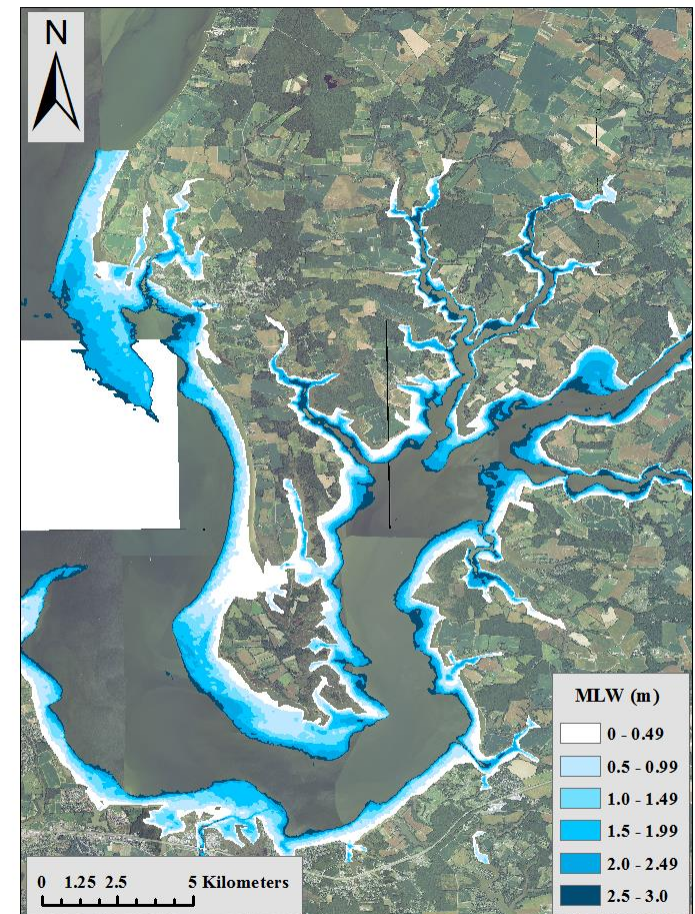
Chester River Potential SAV Habitat



Applying *GrassLight* to the Chester River

- Mesohaline tributary
- Highly turbid
 - TSM $\gg 30 \text{ mg L}^{-1}$
- Eutrophic
 - Chl *a* $\gg 20 \text{ mg m}^{-3}$
- Gridded 30 m bathymetry
- Potential SAV habitat (< 3 m depth) fringing the shore

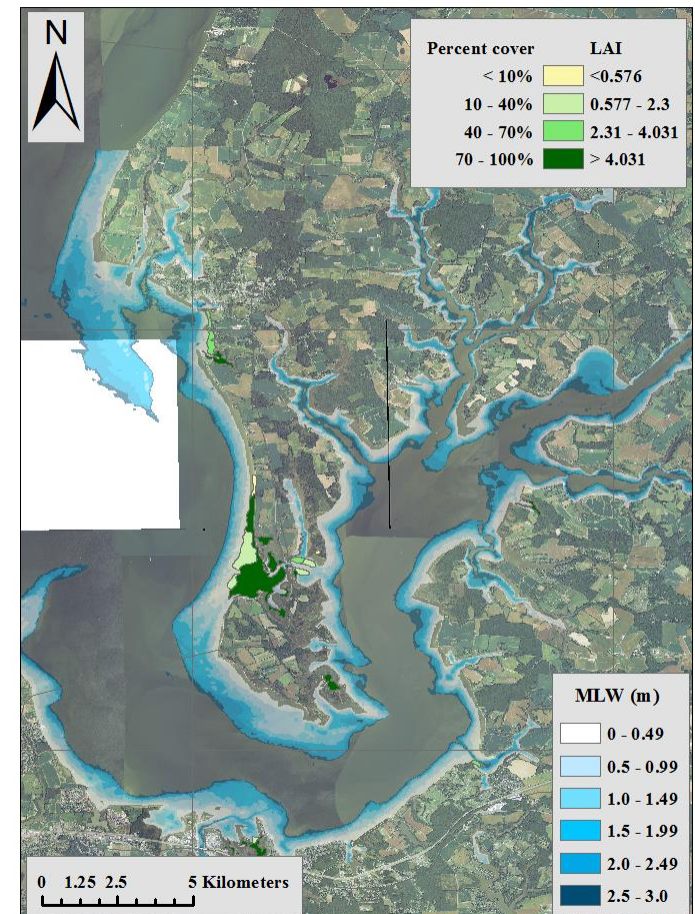
Chester River DEM



Applying *GrassLight* to the Chester River

- SAV distribution
 - Most persistent in shallows around Eastern Neck Island and Chester shoreline
 - Species composition depends on salinity
 - Abundance depends on water quality
 - Temporally variable

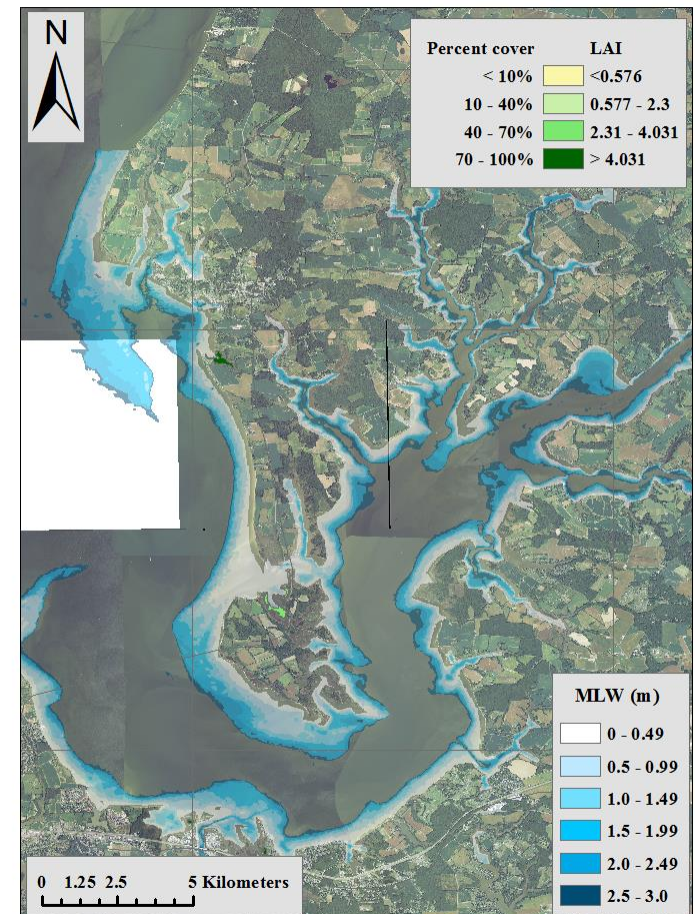
Chester River VIMS SAV distribution 2011



Applying *GrassLight* to the Chester River

- SAV distribution
 - Most persistent in shallows around Eastern Neck Island and Chester shoreline
 - Species composition depends on salinity
 - Abundance depends on water quality
 - Temporally variable

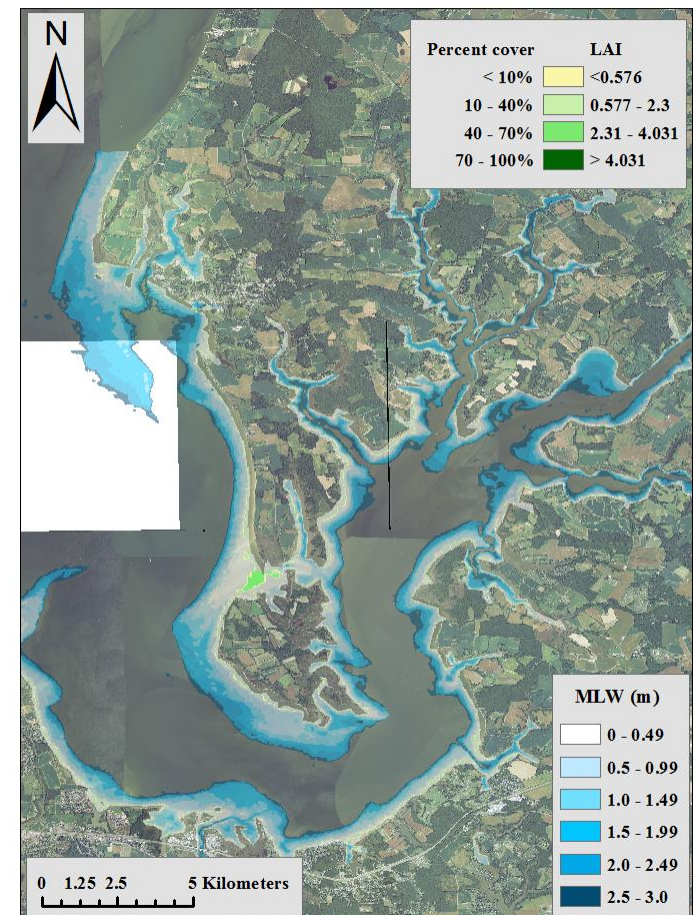
Chester River VIMS SAV distribution 2013



Applying *GrassLight* to the Chester River

- *GrassLight* prediction of SAV density based on average WQ data is consistent with VIMS field observations
- $TSM = 30 \text{ mg L}^{-1}$
- $Chl\ a = 20 \text{ mg m}^{-3}$
- $Z_{E(22\%)} = 0.2 \text{ m}$
- $Z_{E(13\%)} = 0.3 \text{ m}$
- $Z_{E(1\%)} = 0.8 \text{ m}$

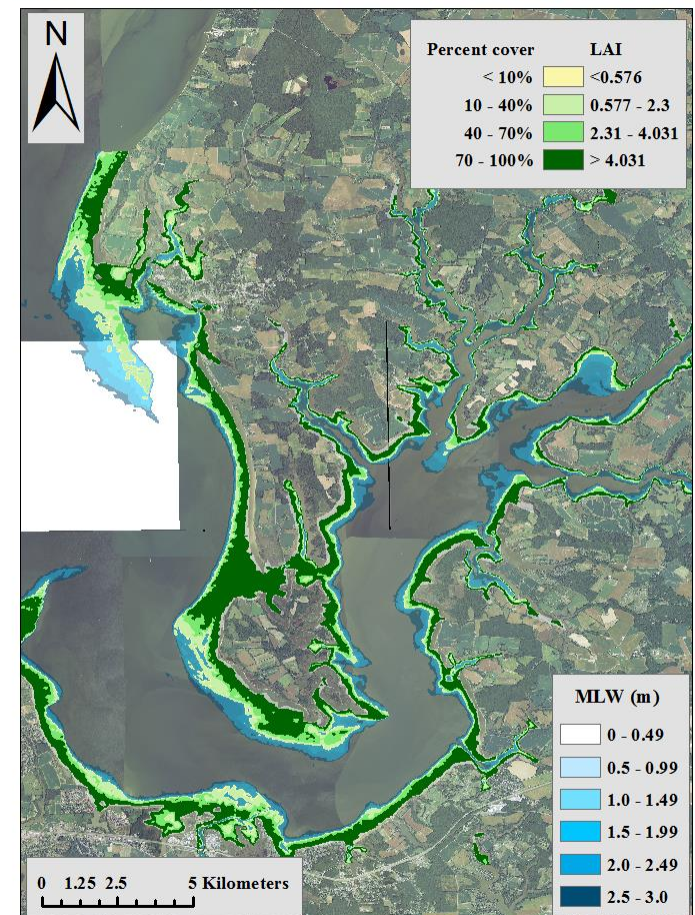
Chester River potential SAV distribution Corsica WQ



Applying *GrassLight* to the Chester River

- Improving water quality to average for Sandy Point
 - $TSM = 10 \text{ mg L}^{-1}$
 - $Chl a = 10 \text{ mg m}^{-3}$
 - $z_{E(22\%)} = 0.7 \text{ m}$
 - $z_{E(13\%)} = 0.9 \text{ m}$
- SAV distribution expands
- Still below "historic" distribution limit of 3 m
- Euphotic depth $z_{E(1\%)} = 2 \text{ m}$
- So, what about the phytoplankton?

Chester River potential SAV distribution Sandy Pt WQ



Modeling the plankton component

- Bio-optical components already built into *GrassLight* for given levels of Chl *a*
- Metabolic component required to calculate
 - Gas exchange
 - Nutrient removal & regeneration
 - Algae growth, grazing and sinking
 - Subsequent impact on water transparency

Modeling the plankton component

- The 2-D (depth,time) model:
 - Easily integrated into *GrassLight* bio-optical structure
 - Calculates biologically mediated changes in
 - O₂, DIC & therefore pH
 - Dissolved nutrients
 - Ultimately driven by light availability
 - Includes a self-shading component from algal biomass
 - Responsive to nutrient concentrations
 - But does not require explicit definition of Michaelis-Menten coefficients
- It does NOT presently consider
 - Mixotrophic & motile algae (e.g. Dinoflagellates) that exhibit complex behaviors & trophic relations
 - Benthic & pelagic grazing
 - Advection

Modeling the photosynthesis

- $P_g^B(z)$ is controlled by light availability:

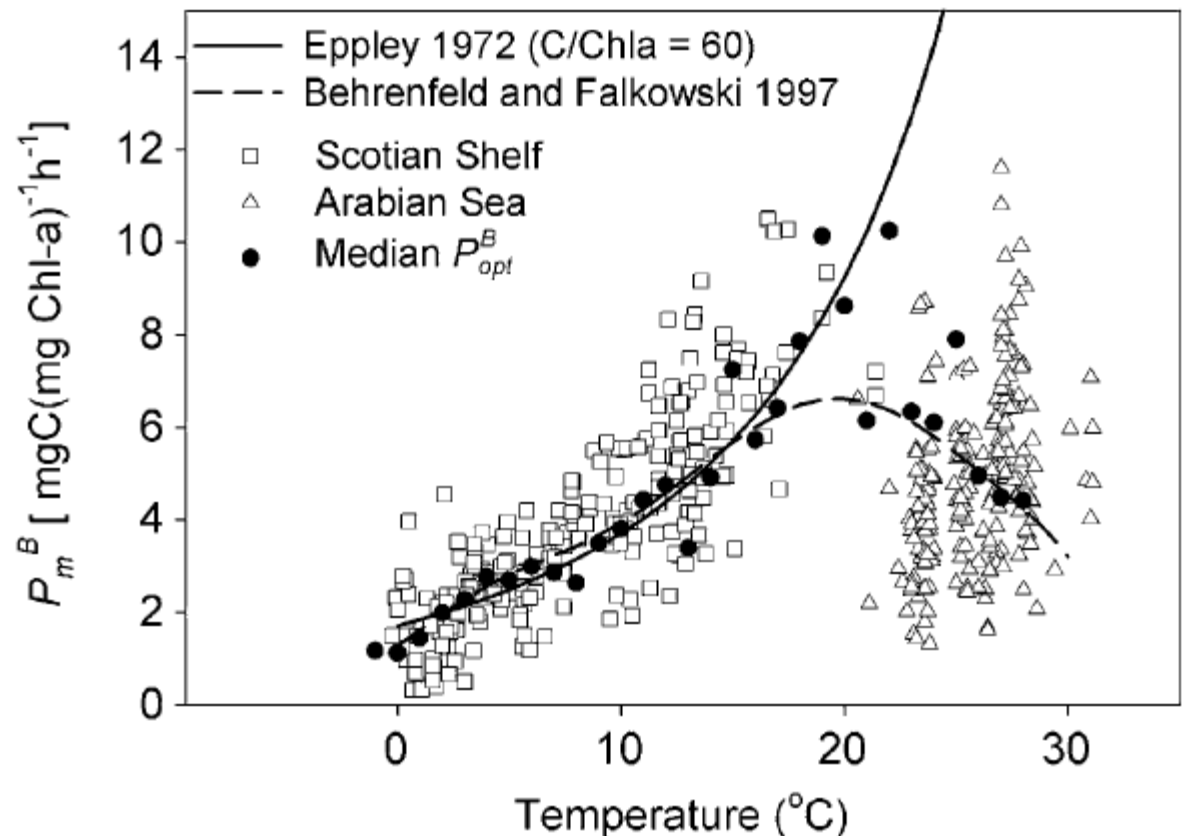
$$P_g^B = P_E^B \left(1 - e^{-\frac{\phi_p \cdot A_\phi^*(\lambda) \cdot [\text{Chl } a] \cdot E(\lambda, t, z)}{P_E^B}} \right)$$

- ϕ_p - quantum yield of photosynthesis (=1/8)
- $A_\phi^*(\lambda)$ - spectral phytoplankton absorptance
- [Chl *a*] - biomass, to scale absorptance
- $E(\lambda, t, z)$ - wavelength, time and depth-dependent irradiance

Modeling temperature effects

$$\log P_E^B \text{ or } \log R^B = T \left(\frac{\log Q_{10}}{10} \right) + C$$

- P_E^B and R are temperature dependent
- $Q_{10} = 3$ to 20°C
- P_E^B decreases linearly with T to 38°C



Bouman, H., T. Platt, S. Sathyendranath, and V. Stuart. 2005. Dependence of light-saturated photosynthesis on temperature and community structure. Deep Sea Research Part I: Oceanographic Research Papers 52: 1284-1299.

Modeling carbon balance and nutrient requirements

- Net productivity is defined by the balance between photosynthesis and respiration

$$P_{net}^V = B \left[P_g^B - R^B \right]$$

- Redfield Ratios define the amounts of dissolved inorganic nitrogen (N) and phosphorus (P) required to convert net photosynthesis into new biomass:

$$\frac{\partial N}{\partial t} = \frac{16}{106} P_{net}^V$$

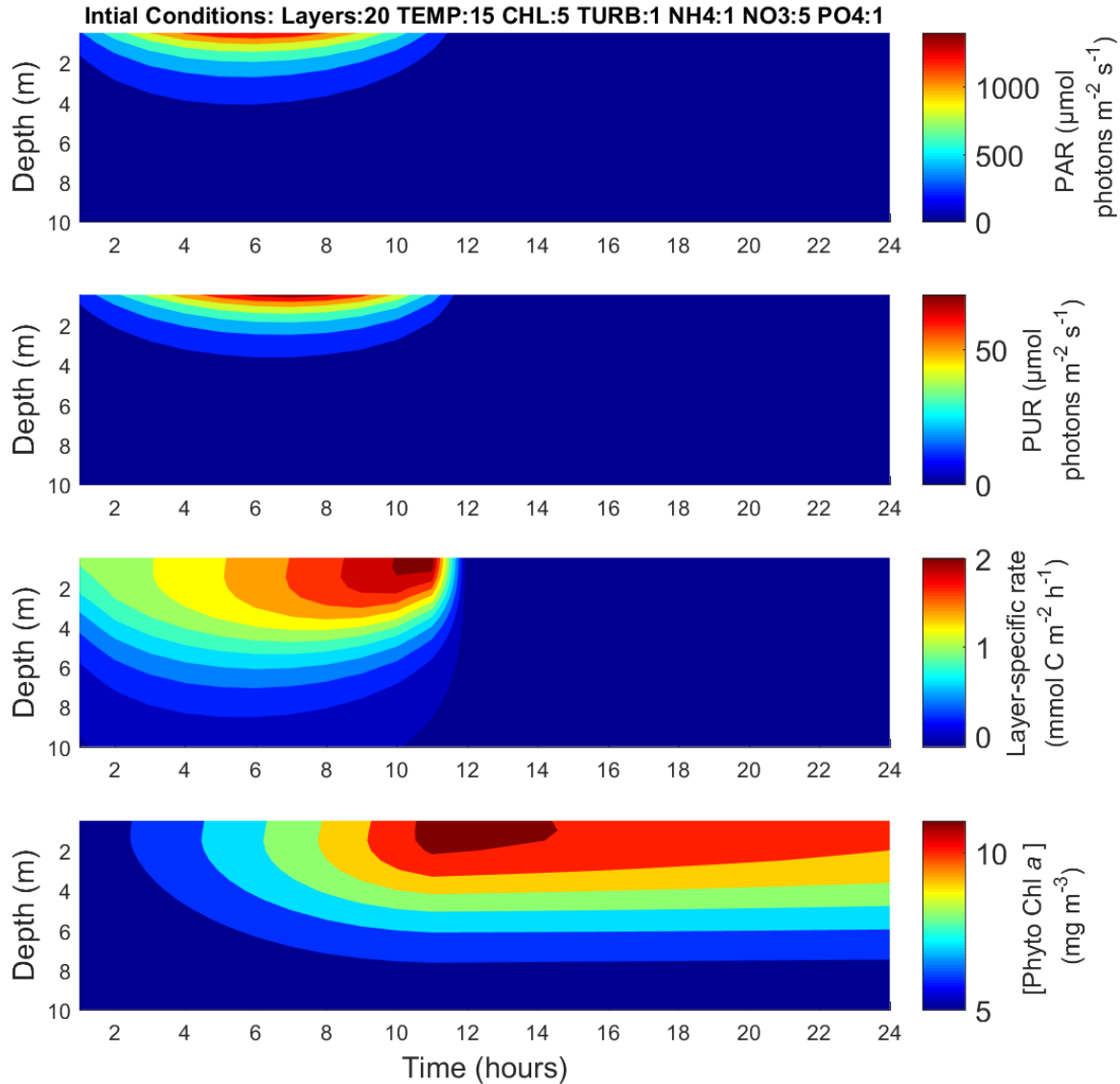
$$\frac{\partial P}{\partial t} = \frac{1}{106} P_{net}^V$$

Modeling nutrient limitation

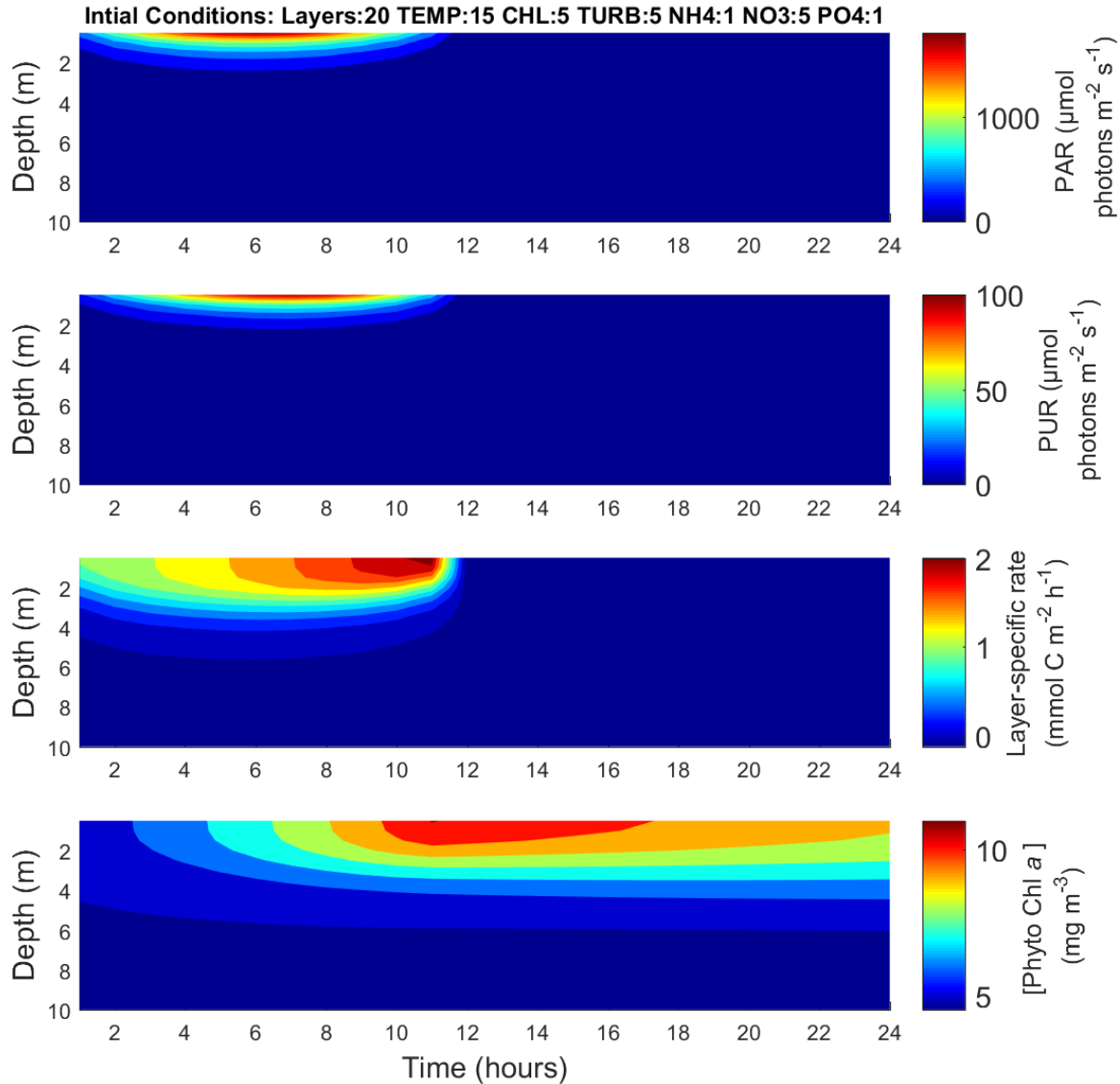
- if $\frac{\partial N}{[N]} \leq 1$ and $\frac{\partial P}{[P]} \leq 1$, phytoplankton growth is defined by P_{net}^V and the concentrations of dissolved inorganic N and P are reduced accordingly
- NH_4^+ taken up before NO_3^-
- If $\frac{\partial N}{[N]} > 1$ or $\frac{\partial P}{[P]} > 1$, phytoplankton growth is limited by the nutrient in shortest supply, all of which is taken up:

$$\frac{\partial \text{Phyto}}{\partial t} = P_{net}^V \cdot \text{lesser of } \frac{[N]}{\partial N}, \frac{[P]}{\partial P}$$

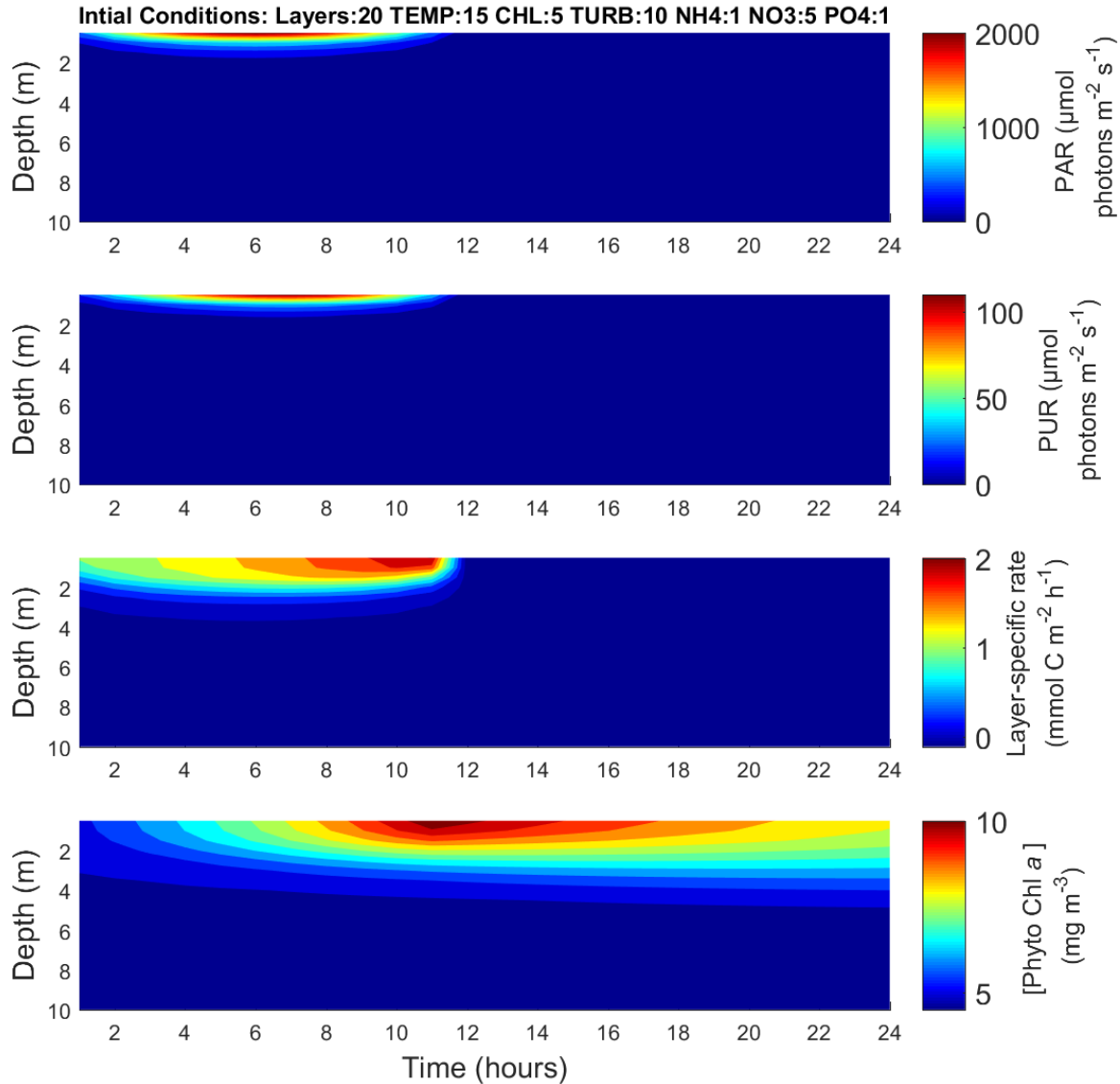
Effect of water transparency on phytoplankton productivity



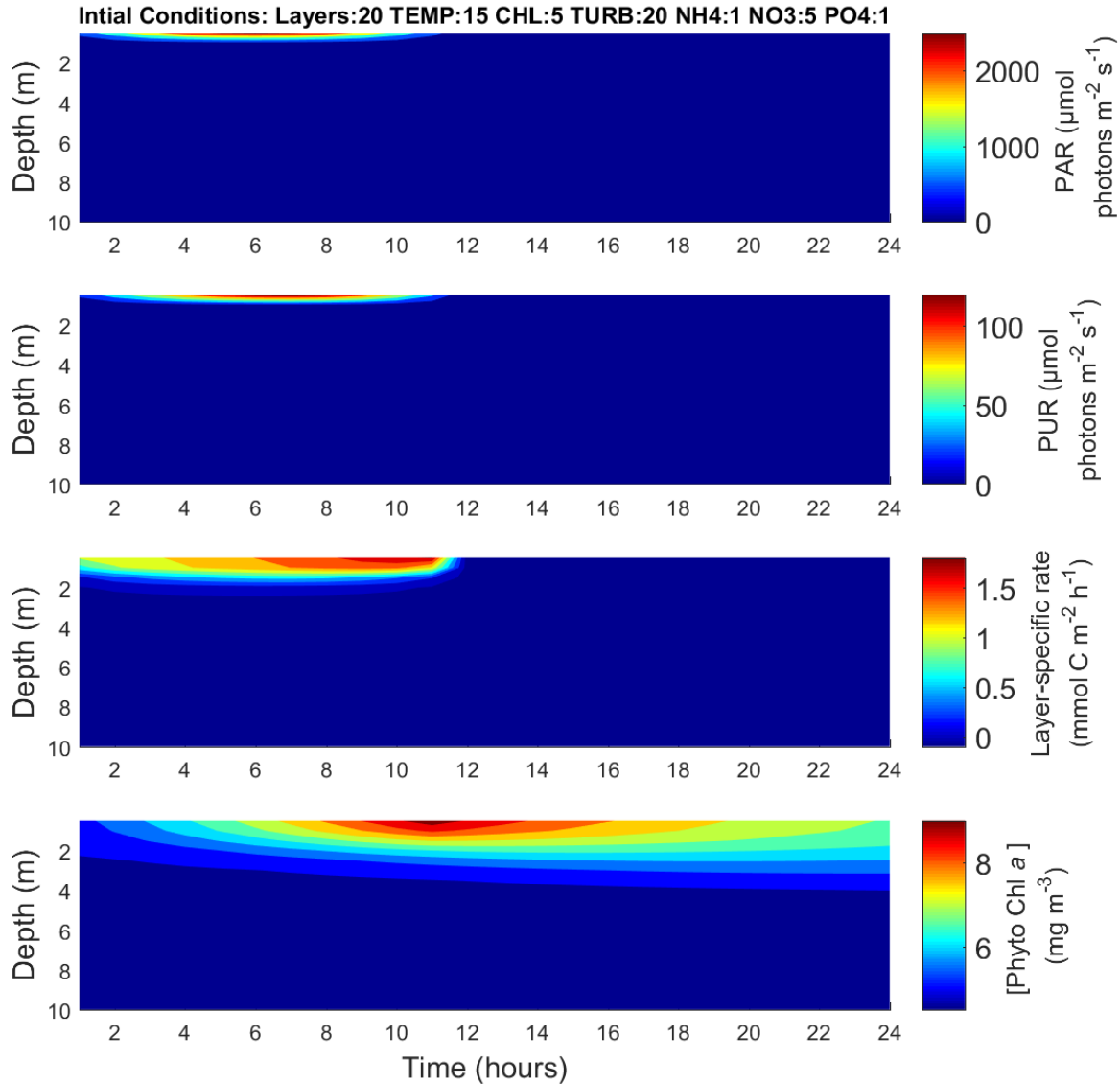
Effect of water transparency on phytoplankton productivity



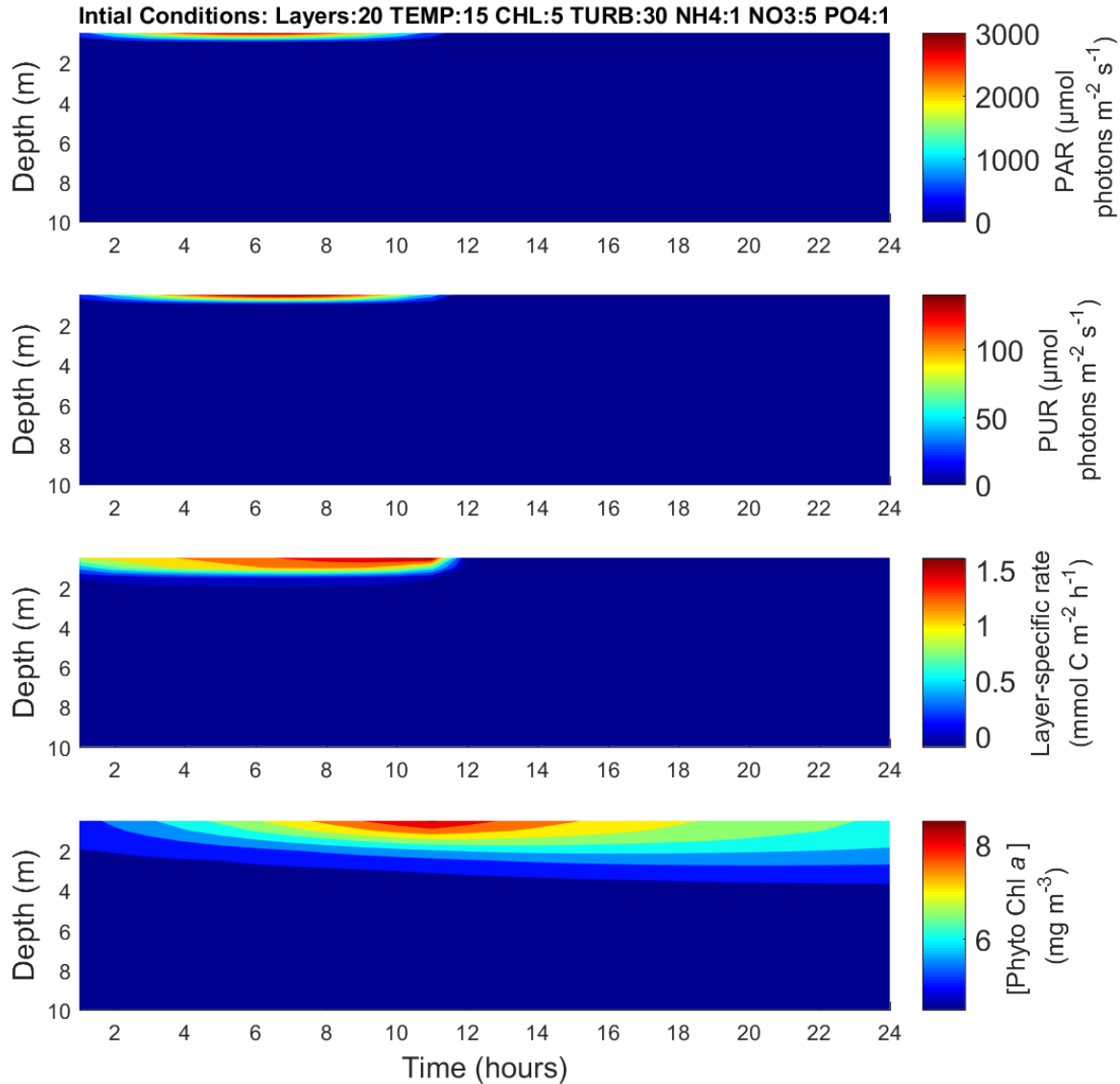
Effect of water transparency on phytoplankton productivity



Effect of water transparency on phytoplankton productivity



Effect of water transparency on phytoplankton productivity



Effect of water transparency on phytoplankton productivity

Chl a = 1 mg m⁻³

Net C uptake
(mmol C m⁻² d⁻¹)

Chl a = 5 mg m⁻³

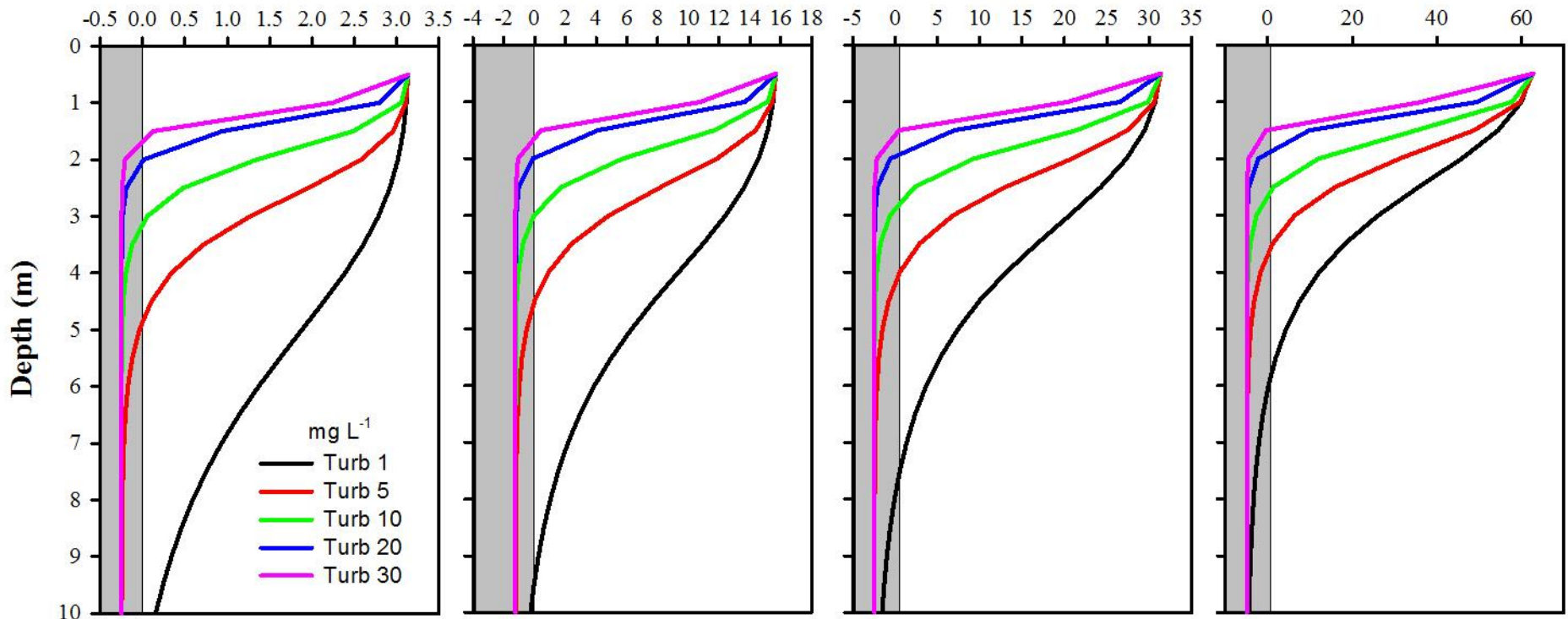
Net C uptake
(mmol C m⁻² d⁻¹)

Chl a = 10 mg m⁻³

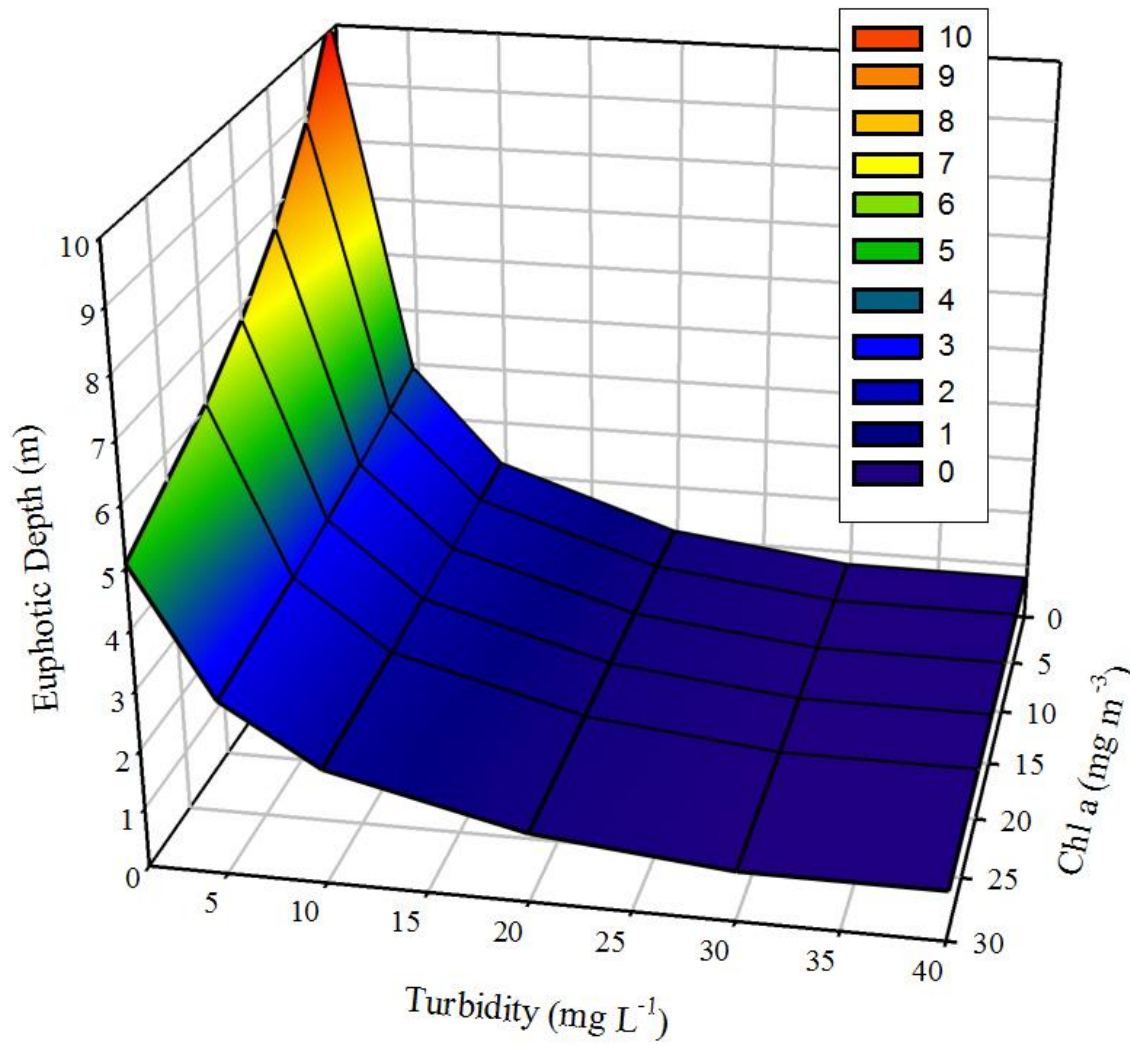
Net C uptake
(mmol C m⁻² d⁻¹)

Chl a = 20 mg m⁻³

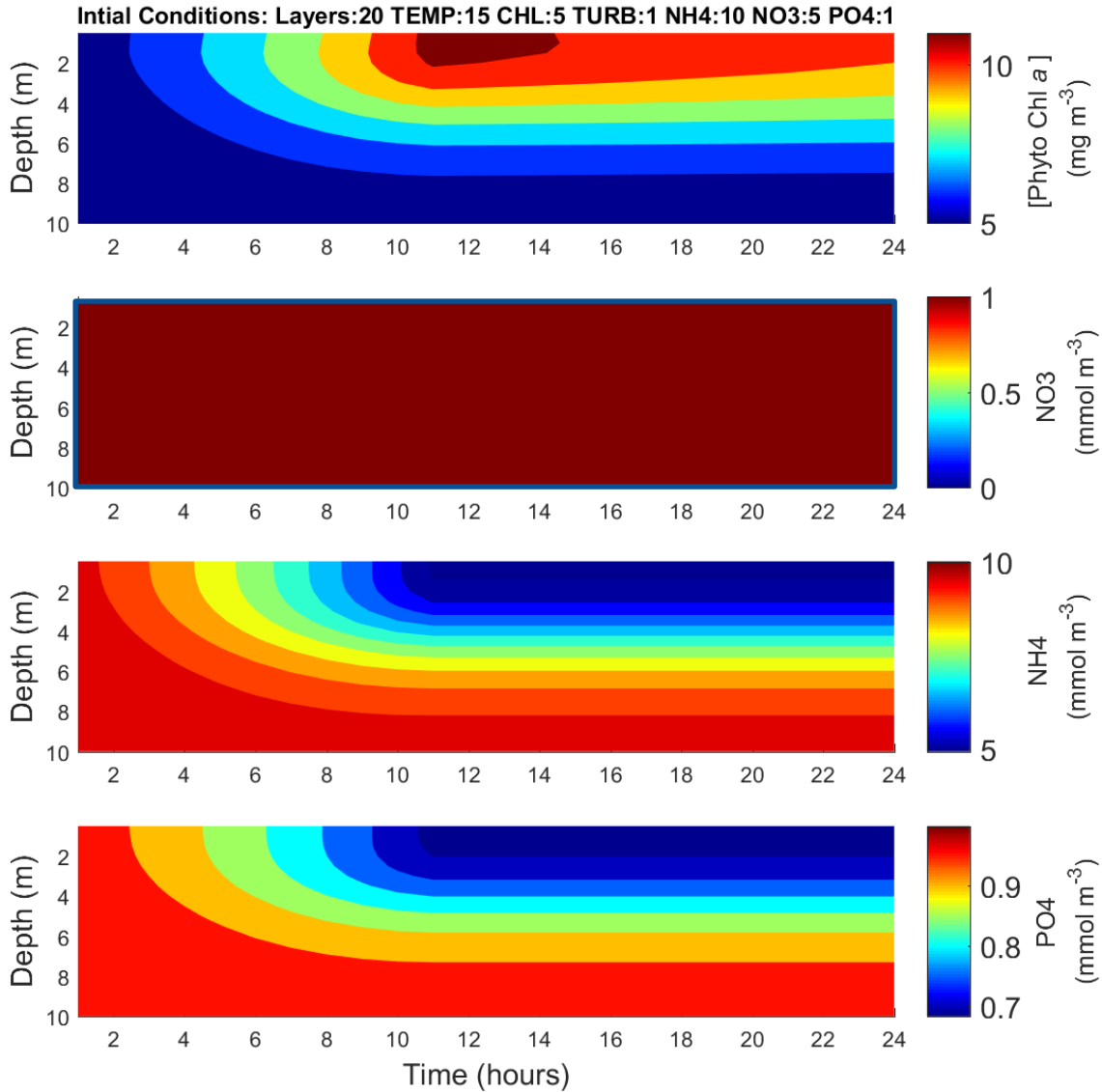
Net C uptake
(mmol C m⁻² d⁻¹)



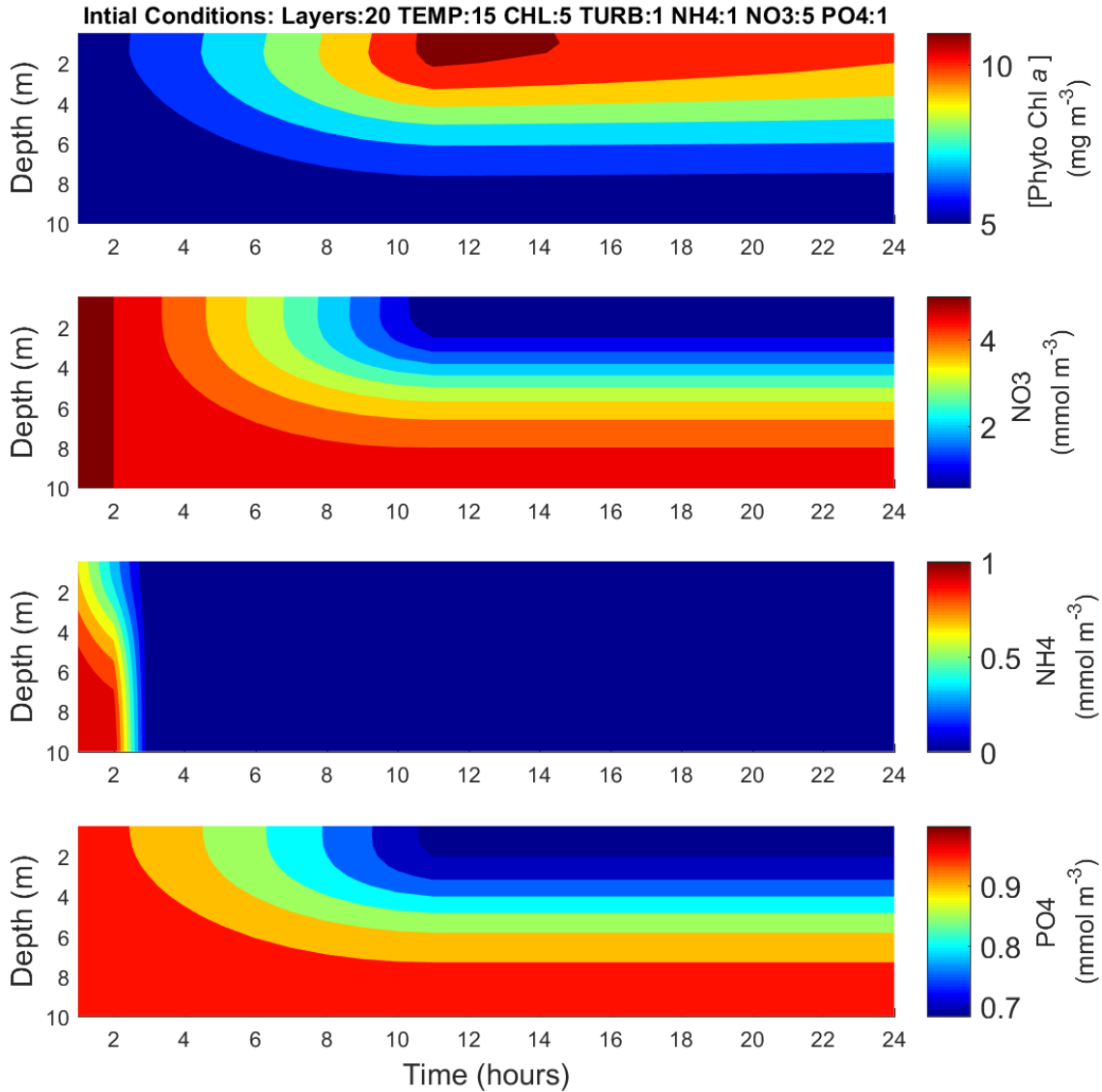
Turbidity has a greater effect on the euphotic depth than Chl *a*



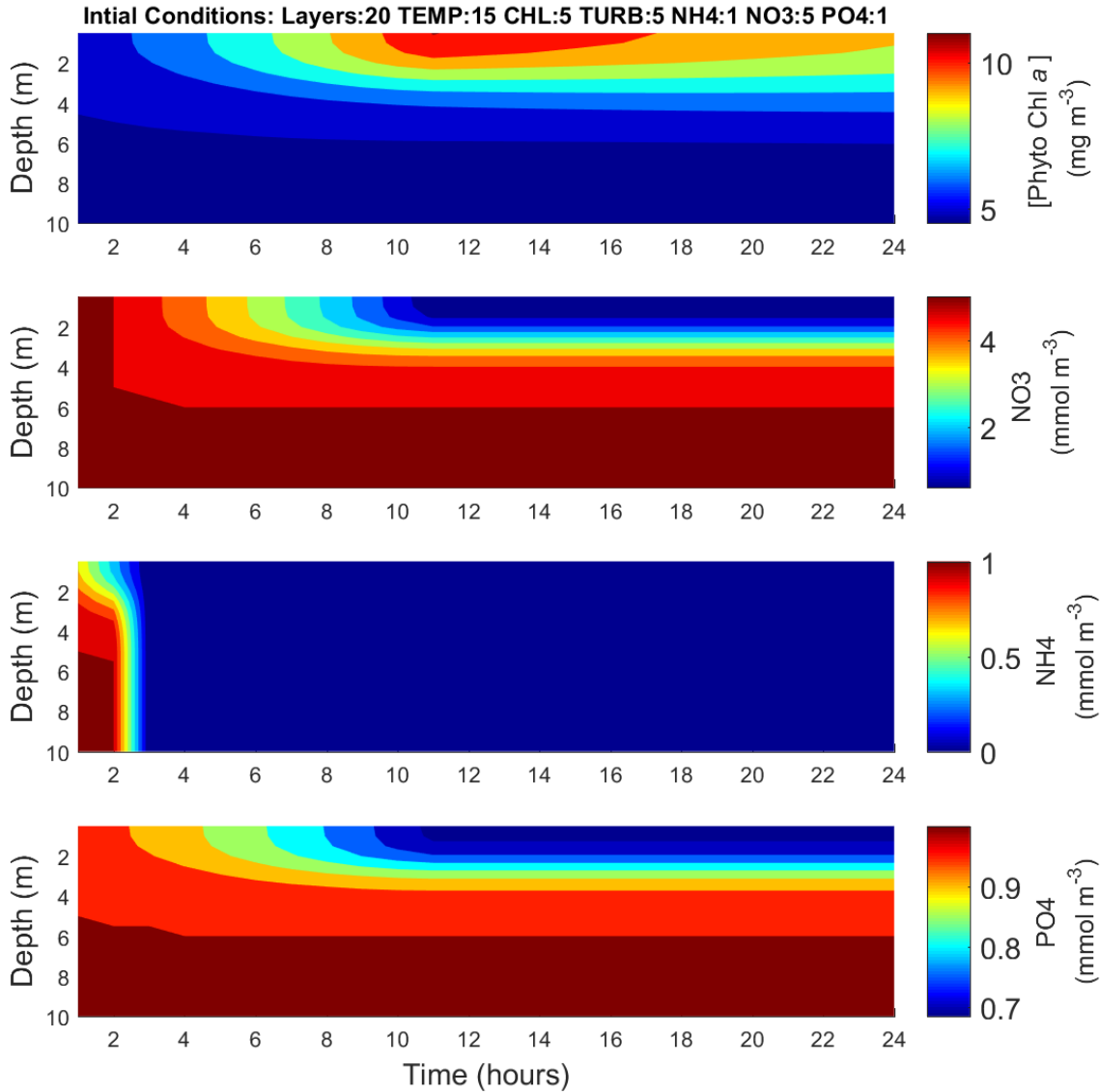
Effect of water transparency on nutrient use



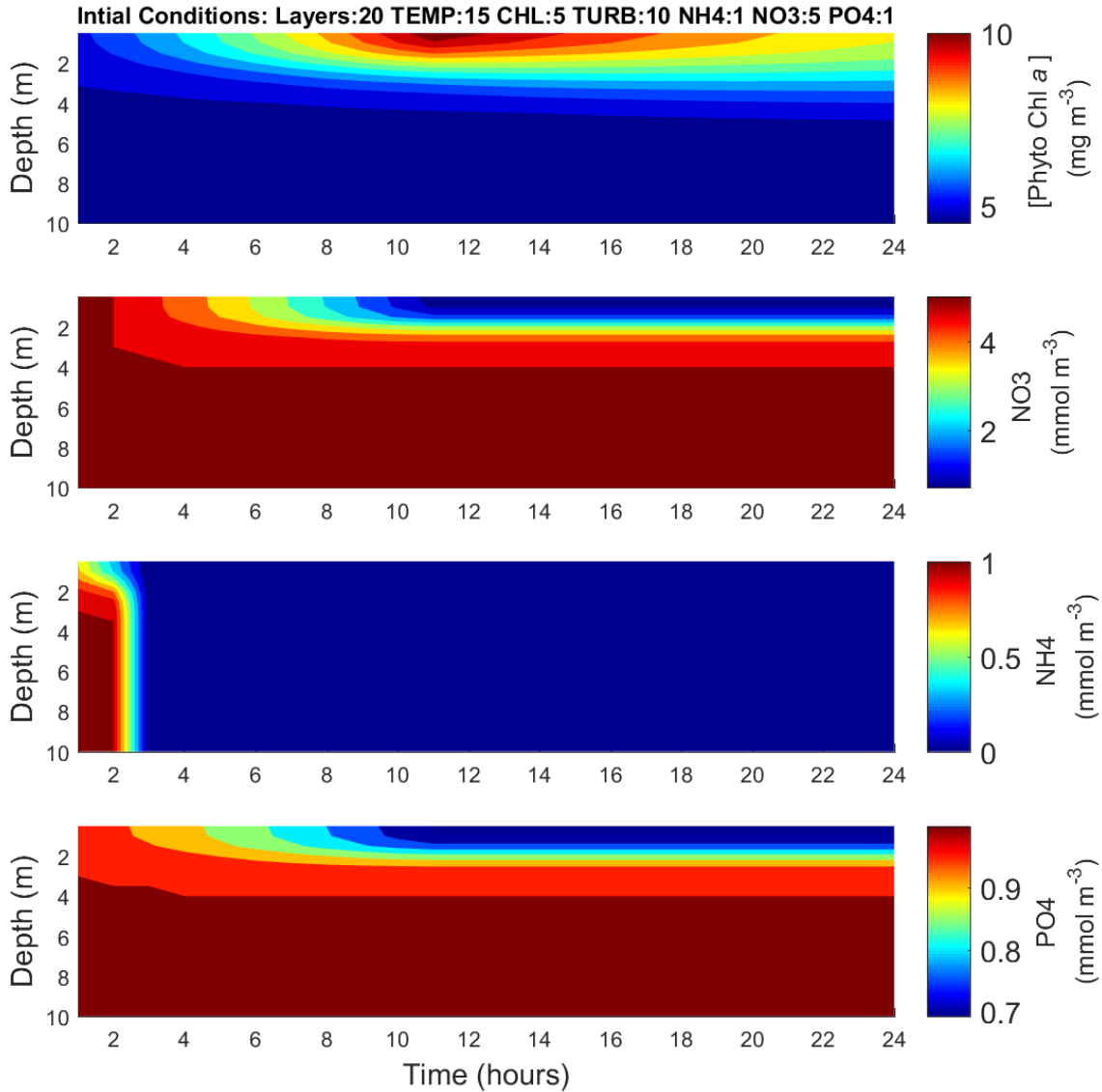
Effect of water transparency on nutrient use



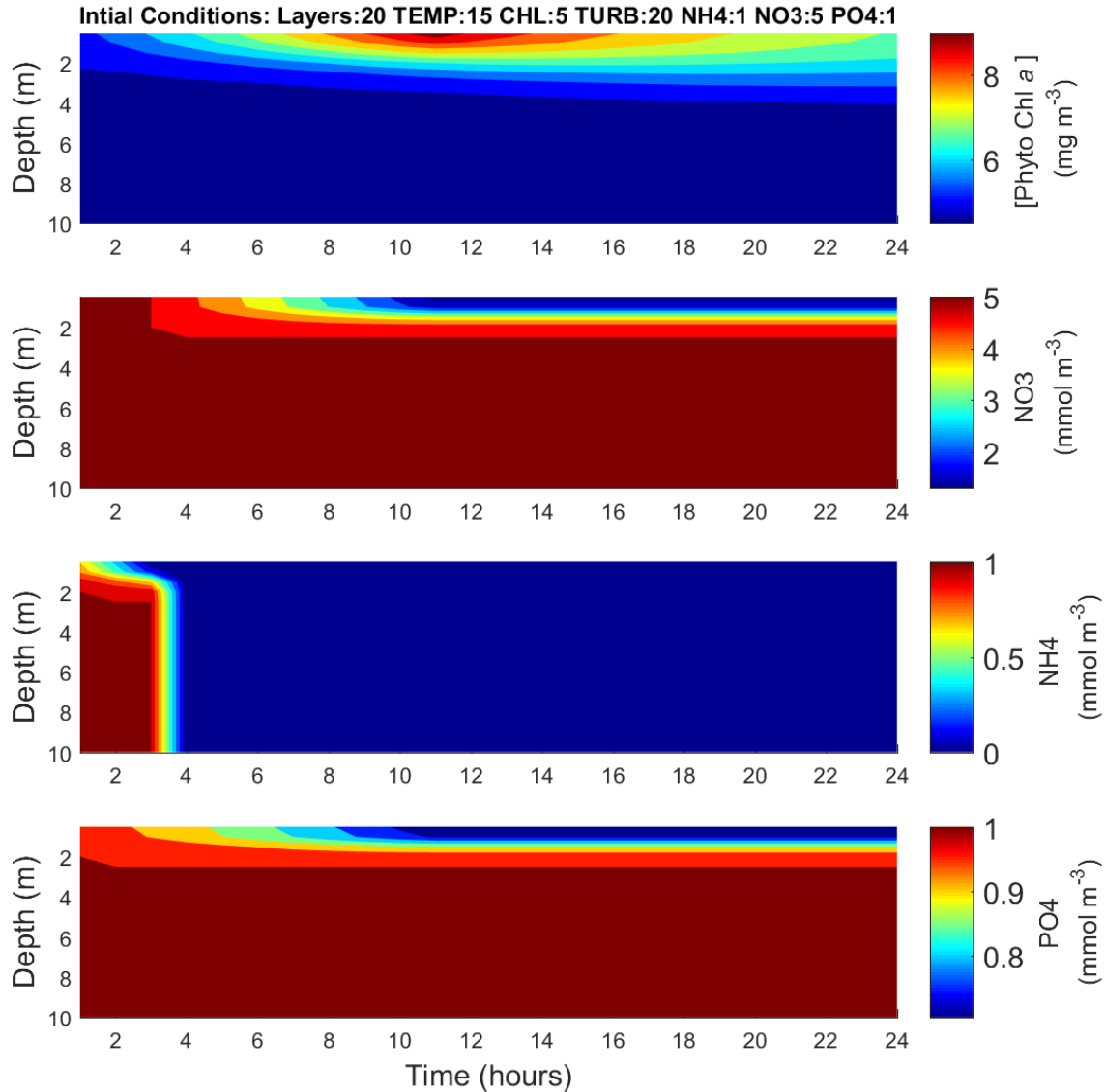
Effect of water transparency on nutrient use



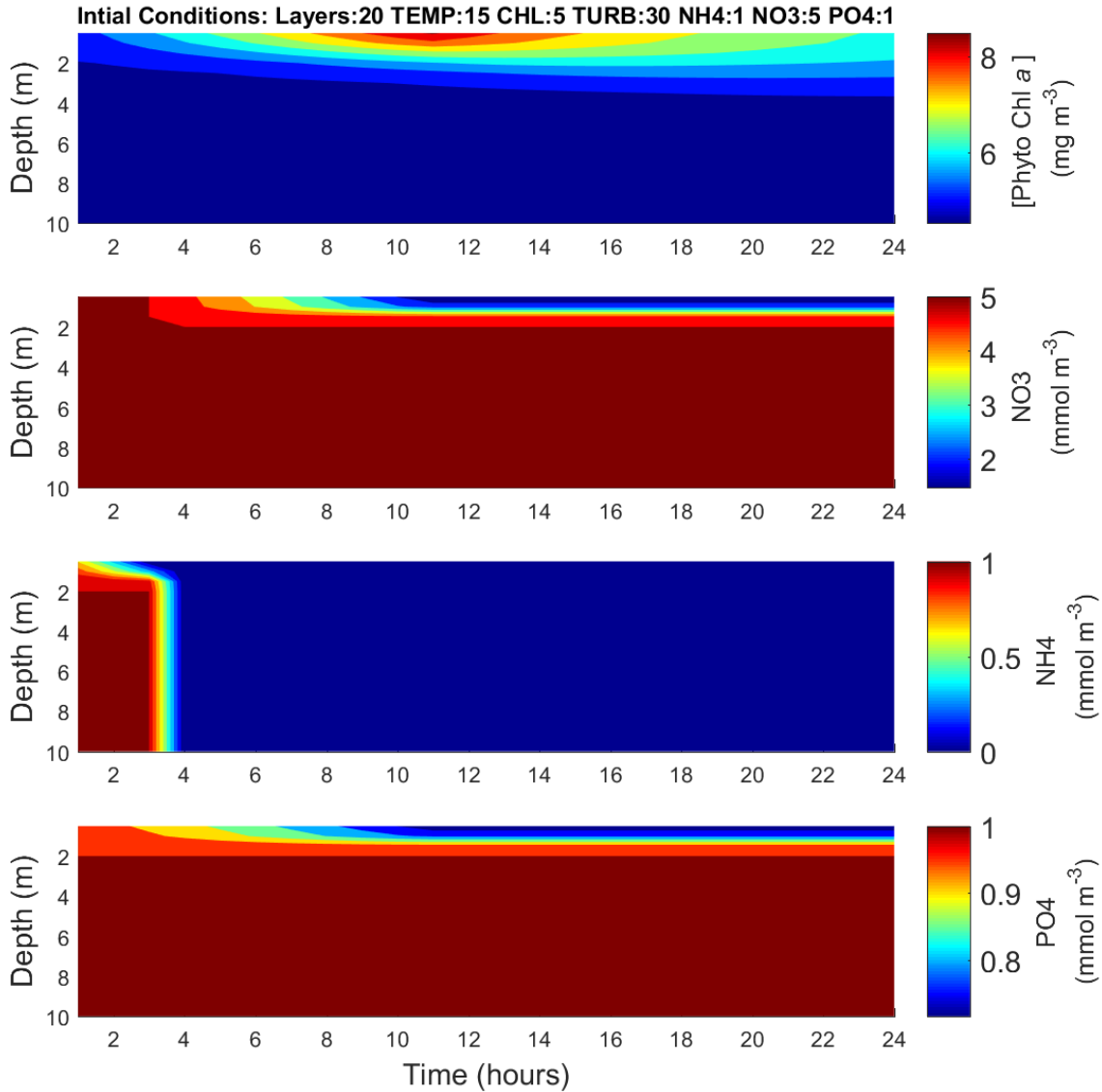
Effect of water transparency on nutrient use



Effect of water transparency on nutrient use



Effect of water transparency on nutrient use



Conclusions

- *GrassLight* accurately predicts
 - SAV distribution & density in polyhaline & mesohaline regions
 - Predicts some resilience to increasing temperature
 - Suggests potential for SAV expansion in response to improved water quality
- Phytoplankton module indicates
 - Tribs light limited from suspended particulates more than phytoplankton
 - Sediment and organic detritus
 - Light limitation prevents nutrient drawdown
 - Probably net heterotrophic
 - Vulnerable to hypoxia

