Coastal Primary Production in North America: A Synthesis of Current Knowledge and Its Application to Carbon Cycle and Ecosystem Dynamics

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OCB
Ocean Carbon & Biogeochemistry

A CORE ELEMENT OF THE U.S. GLOBAL CHANGE RESEARCH PROGRAM
North American Carbon Program
CONTINENTAL CARBON BUDGETS, DYNAMICS, PROCESSES, AND MANAGEMENT

Acknowledgements

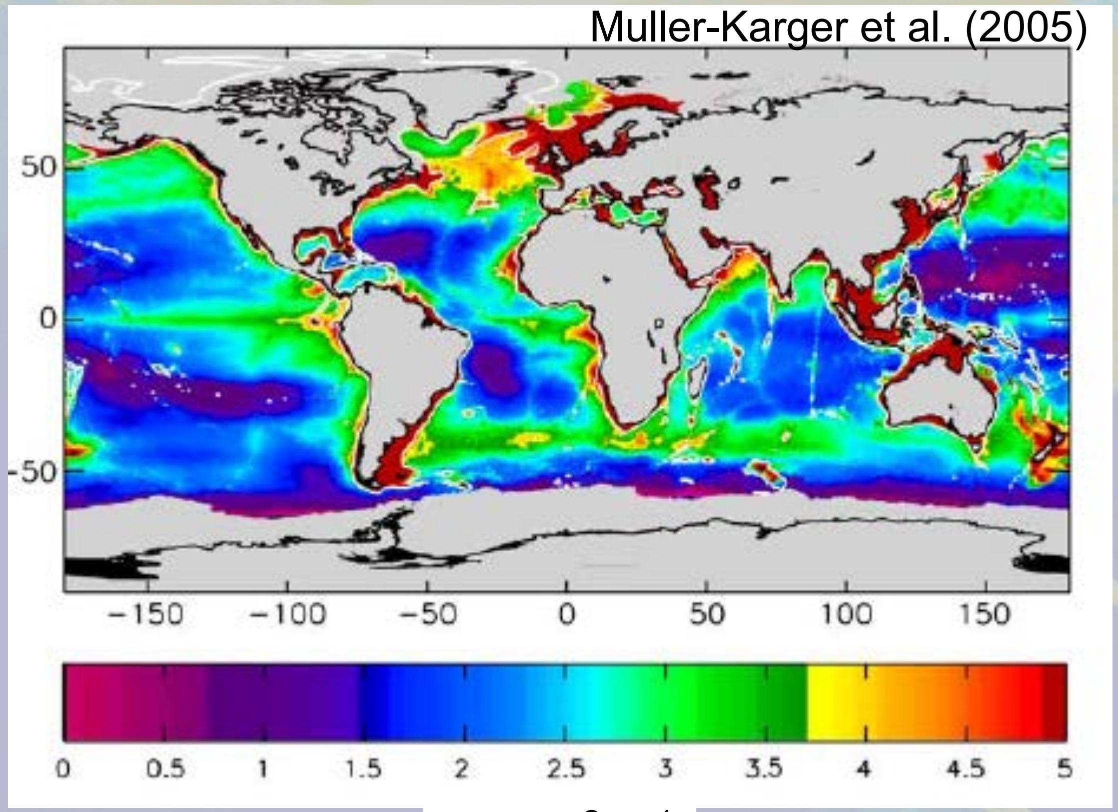
- Support provided for this effort from NASA, NSF, and NOAA

Overview

- Introduction
  - *Global significance of coastal primary production*
  - *Challenges in defining and estimating*
  - *Importance of PP for understanding coastal and global ocean carbon cycling*
- Objectives
- Brief Overview of North American Coastal Carbon PP Synthesis Activities
- Application of PP for Characterization of Coastal Carbon Cycles and Ecosystem Processes
- Recommendations for Future Work

Introduction – Global Significance of Coastal PP

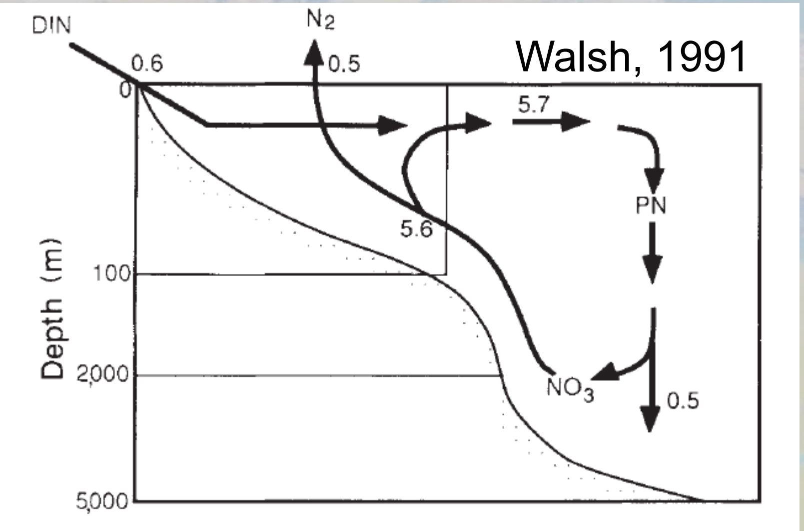
- Disproportionately high contribution to global primary production by coastal margins
  - *Ryther, 1969; Walsh et al., 1981; Longhurst et al., 1995; Antoine et al., 1996; Muller-Karger et al., 2005; Dunne et al., 2007*
  - *as much as 10 - 30% of global PP*



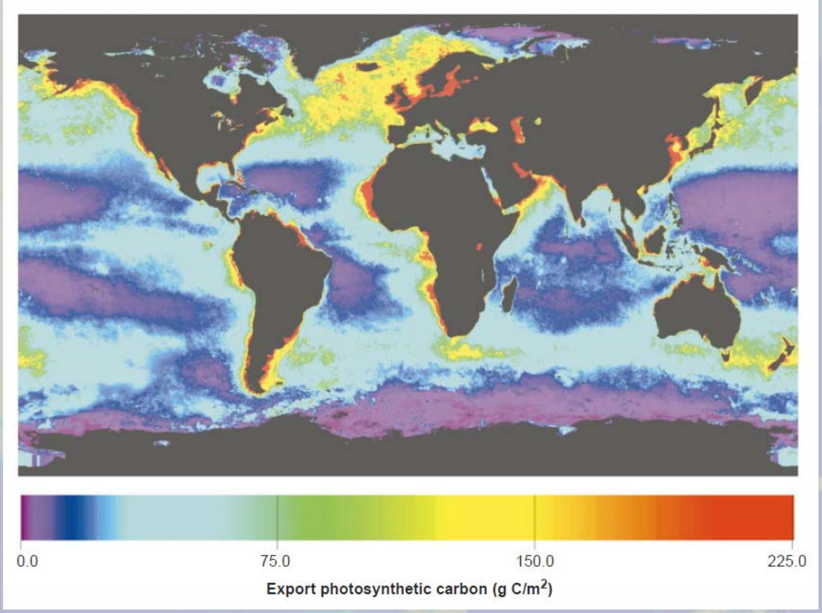
gC m^{-2} y^{-1}

Introduction – Global Significance of Coastal PP

- High productivity, much of it supported by “new” nitrogen sources, may contribute to high export of carbon from continental margins (e.g., Walsh, 1991)
- Export production by continental margins estimated at 20-44% of global carbon export based on estimated 20% of ocean PP occurring on margins (Jahnke, 2010)
- Coastal zones account for 80% of oceanic carbon burial and 50% of oceanic $CaCO_3$ deposition (Gattuso, 1998 in Borges, 2011)
- Increasing human impacts on coastal environments likely to alter carbon cycles in these systems (Borges and Gypens, 2010; Bauer et al., 2013)



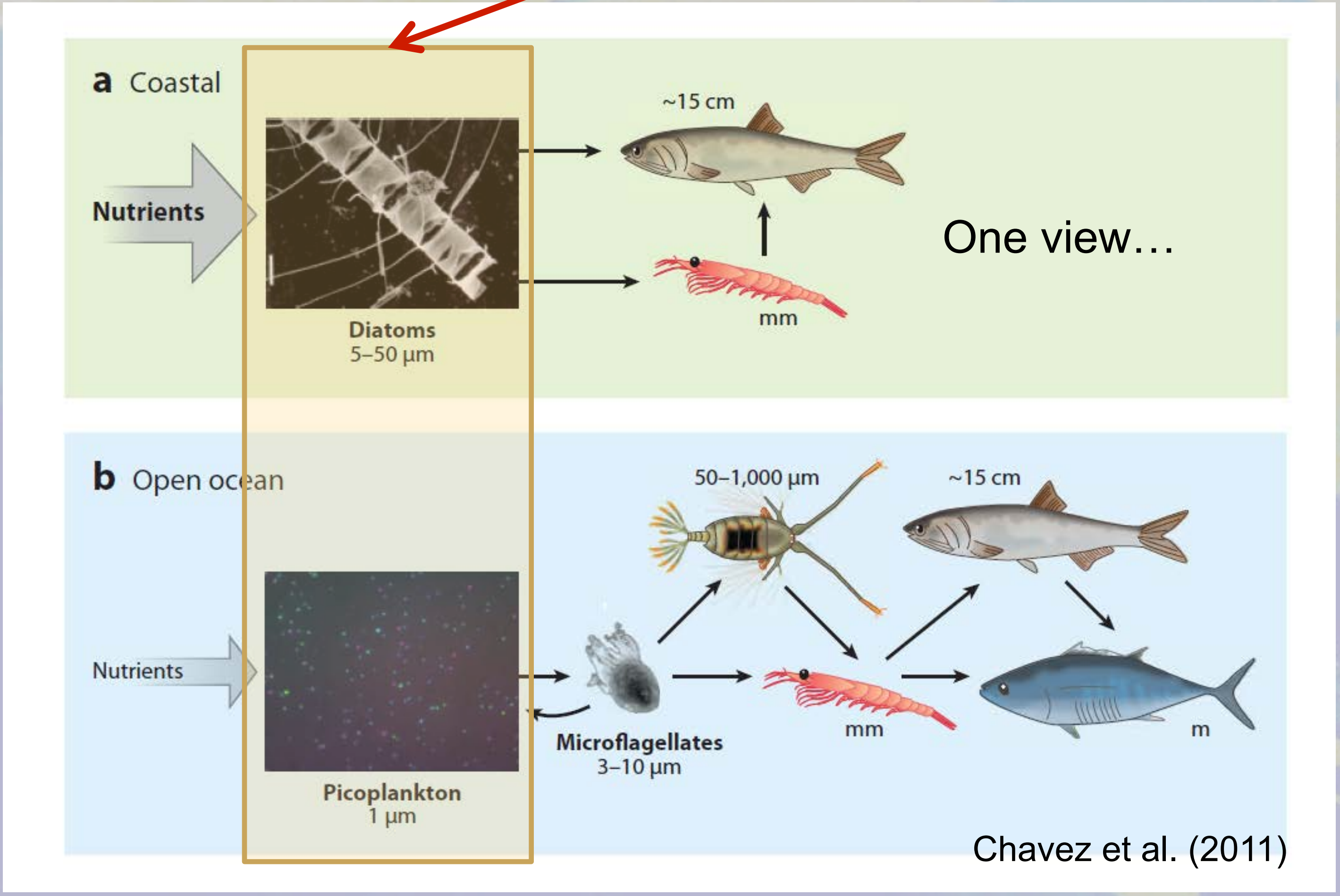
Walsh, 1991



Falkowski, 1998

Introduction – Defining and Estimating PP

- What is primary production?



Introduction – Defining and Estimating PP

- **Gross Primary Production (GPP)** – total autotrophic conversion of inorganic to organic carbon
- **Ecosystem Respiration (R or ER)** – total oxidation of organic C to inorganic (autotrophic + heterotrophic)
- ER = Autotrophic Respiration (AR) + Heterotrophic Respiration (HR)
- **Net Ecosystem Production (NEP)** = GPP – ER
  - *Net Community Production, Net Ecosystem Metabolism*
- **Net Primary Production (NPP)** = GPP – AR
- **Net Ecosystem Carbon Balance (NECB)** – Net accumulation or loss of carbon (Chapin et al., 2006)

See also Staehr et al. (2012)

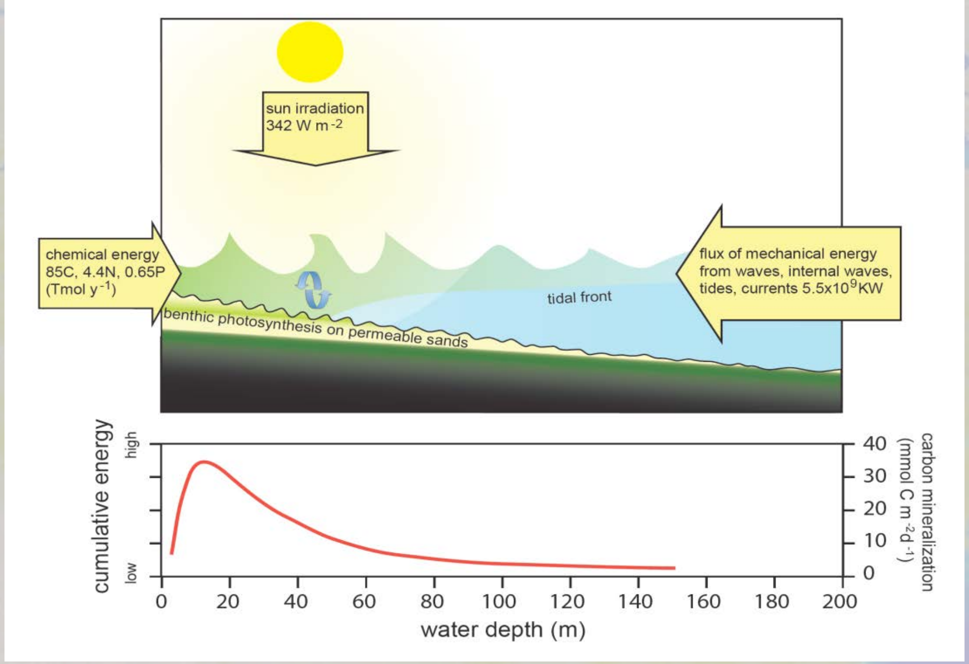
Introduction – Defining and Estimating PP

- Biomass vs. rate measurements (e.g., Marra, 2002)
- Bottle incubation approaches (Staehr et al., 2012; Chavez, 2011; Peterson, 1980, etc.)
  - *^{14}C method most widely referenced (~NPP, large uncertainties)*
  - *Oxygen light-dark bottle method*
  - *Other isotopic approaches (^{18}O, ^{13}C)*
  - *In situ vs. deck incubations*

- Open water methods (Munro et al., 2013; Staehr et al., 2012; Needoba et al., 2012; Quay et al., 2010; etc.)
- Ecosystem budgets (mass balance)
- Bio-optical approaches (P-E models, FRR, e.g., Bidigare et al., 1987; Morel, 1991; Kolber and Falkowski, 1993; Uitz et al., 2008)
- Satellite-derived approaches (e.g., Platt et al., 1991; Behrenfeld and Falkowski, 1997; Carr et al., 2006; Friedrichs et al. 2009; Saba et al., 2011; numerous others)
- Biogeochemical modeling approaches
- Challenge of scaling
  - *Enclosure studies vs. system wide budgets differ due to exchanges*
  - *Whole system and bottle/enclosure comparisons are often in disagreement*
  - *Accounting for spatially localized or transient phenomena*
- Accounting for DOC production in estimation of PP

Introduction – Defining and Estimating PP

- Dynamic and heterogeneous nature of coastal systems pose challenges (strong vertical and horizontal gradients in light and nutrients – high variability in rate estimates
- Benthic versus water column

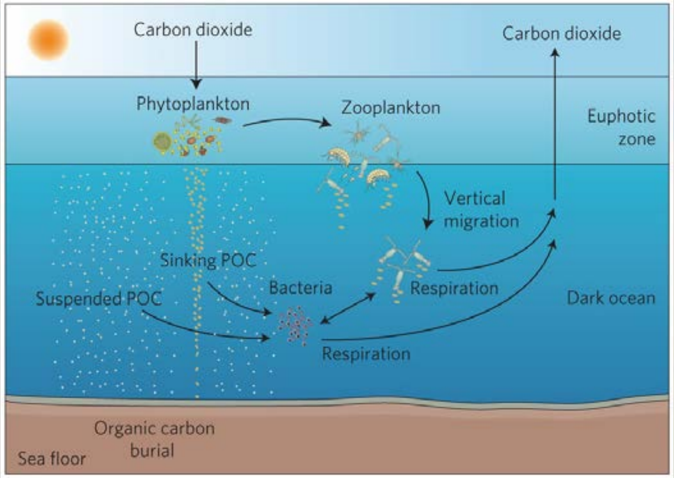


Huettel et al. (2014)

- Importance of estuarine/wetlands to overall coastal productivity
  - *Estimated contribution by mangroves, salt marsh, seagrasses, mangroves exceeds pelagic ocean production (Cloern et al., 2014; Duarte et al., 2005)*
  - *Net heterotrophy in marginal seas argued to be balanced by net autotrophy in marginal seas (Chen and Borges, 2009, Cai, 2011; Staehr et al., 2012)*

Introduction – Importance of PP for Understanding Aquatic Carbon Cycles

- PP remains a critically important quantity in characterizing ecosystem function and its relationship to environmental variability, elemental cycling, and community structure



Herndl and Reinthaler (2013)

- A key consideration for this synthesis is how can PP be used to better understand variations in coastal carbon cycles, particularly as it relates to:
  - *fluxes of carbon (air-sea exchange, vertical export, burial, lateral transport, etc.)*
  - *trophodynamics (productivity of higher trophic levels)*
  - *net ecosystem production (balance of heterotrophic respiration versus net autotrophic production)*
  - *strength of biological pump*

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Coastal Interim Synthesis Activity Objective

- Stimulate the synthesis and publication of recent observational and modeling results on carbon cycle fluxes and processes along the North American continental margin
- Specifically address important exchanges and transformation of the various carbon forms and nutrients as they are transported from terrestrial ecosystems through river systems to coastal oceans or the Great Lakes

Coastal Carbon Synthesis Primary Production Objectives (this talk)

- Provide a high-level overview of the current state of knowledge of primary production in coastal margins, and identify gaps in knowledge and understanding
- Consider how information about PP can be useful in improving our understanding of coastal carbon cycling
- Provide recommendations for future work related to characterization of PP in coastal margins

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Coastal Carbon Cycling in North America – General Patterns

- **Slope vs. Shelf Dominated Systems (Jahnke, 2009)**
  - Shelf dominated
    - Greater role of benthic processes in shelf dominated
    - Longer shelf residence times
  - Slope dominated
    - Increased amount of export to slope and offshore
    - Short shelf residence times
    - Less contribution from benthic processes

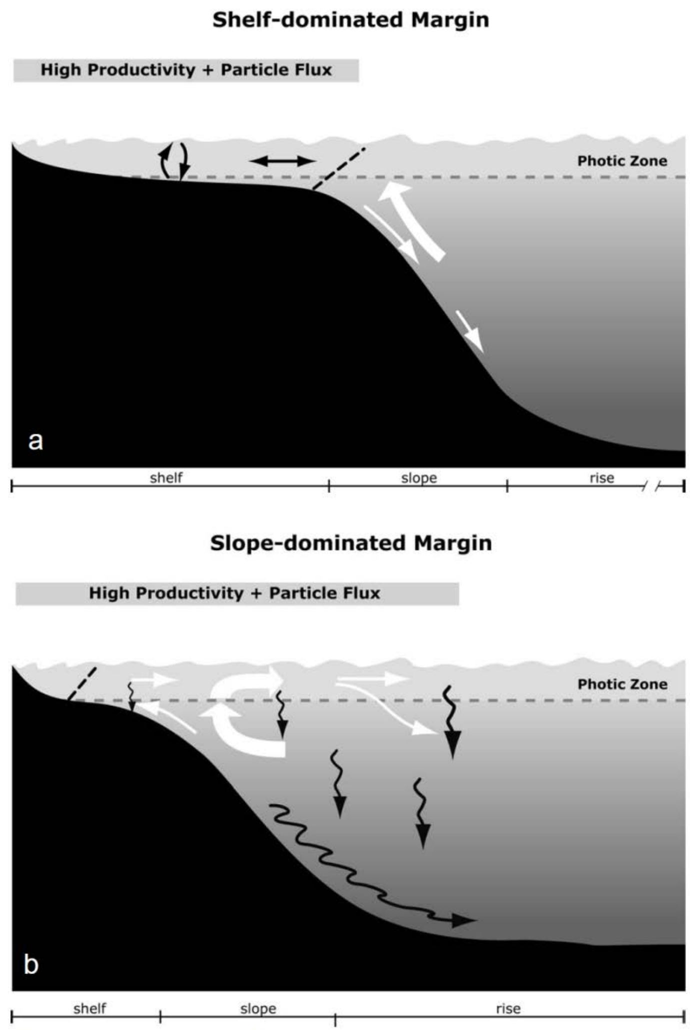
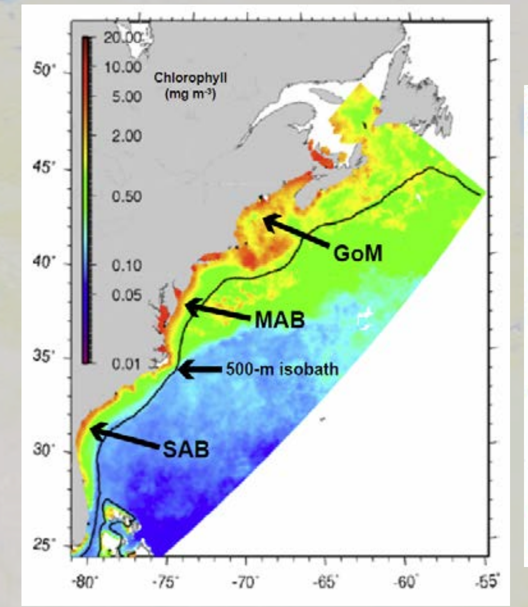
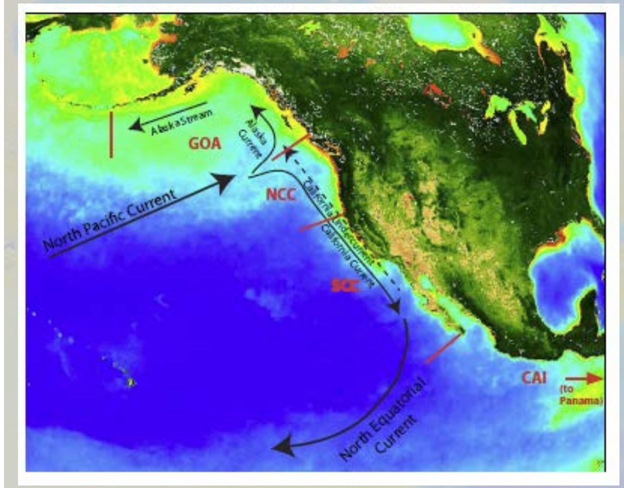


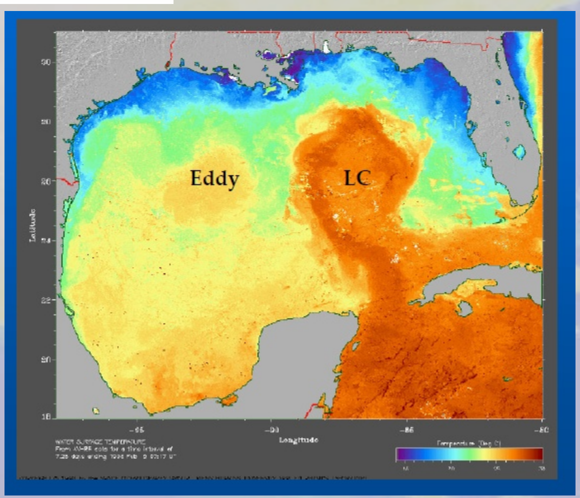
Figure 2. Generalized representation of major distinctions between a) a shelf-dominated and b) a slope-dominated margin.

Coastal Carbon Cycling in North America – General Patterns

- **East Coast**
  - Shelf driven
  - Western Boundary Current interactions
- **West Coast**
  - Slope driven
  - Eastern Boundary Current interactions
  - Upwelling
- **Gulf of Mexico**
  - Largely shelf driven
  - Loop Current interactions
  - Mississippi River

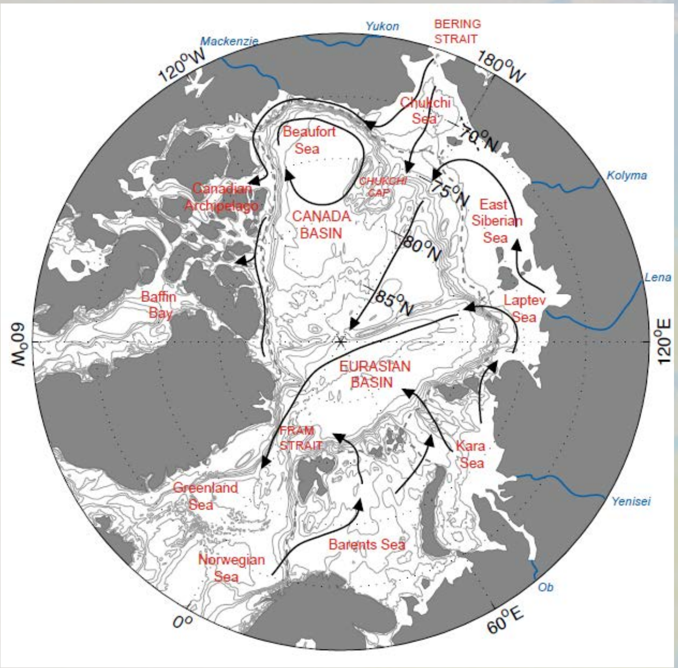






Coastal Carbon Cycling in North America – General Patterns

- **Arctic**
  - Wind influences
  - Ice effects
  - Complex coastal morphology

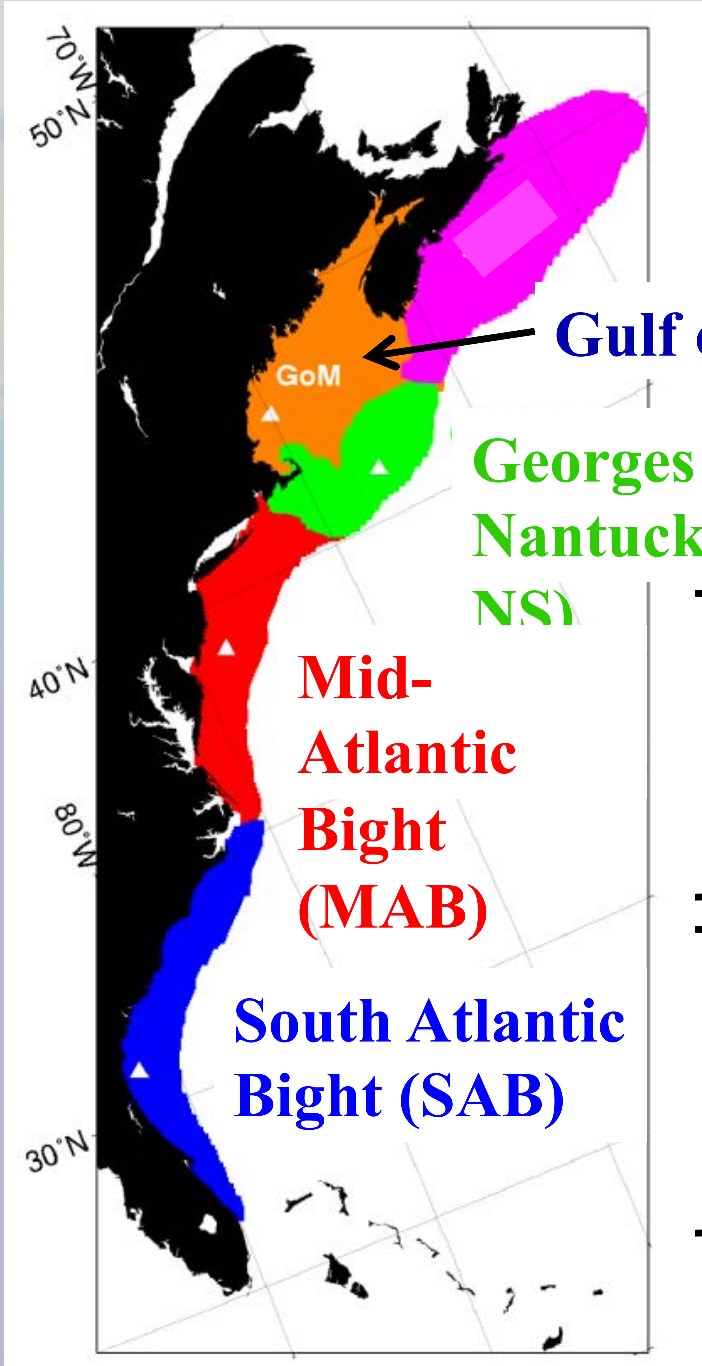


- **Great Lakes**
  - Contrasting lake conditions
  - Varying levels of human impact
  - Role of invasive species

Coastal Carbon Cycling in North America – Summary of Estimates

- **East Coast**
  - 94-120 Tg C y^{-1}
  - Friedrichs et al.
- **West Coast**
  - Highly variable?
  - Regionally dependent
  - TBD
- **Gulf of Mexico**
  - 282 Tg C y^{-1} (water column)
  - 182 Tg C y^{-1} (benthic)
  - Lohrenz, Huettel, others
- **Arctic**
  - 513 Tg C y^{-1} - Arrigo et al. (2008)
  - 466 – 993 Tg C y^{-1} Hill et al. (2013)
- **Great Lakes**
  - 3.4 – 9.5 Tg C y^{-1}
  - Total 30 Tg C y^{-1}
  - McKinley (2011)

East coast primary production literature synthesis: 120 ± 30 Tg C yr^{-1}



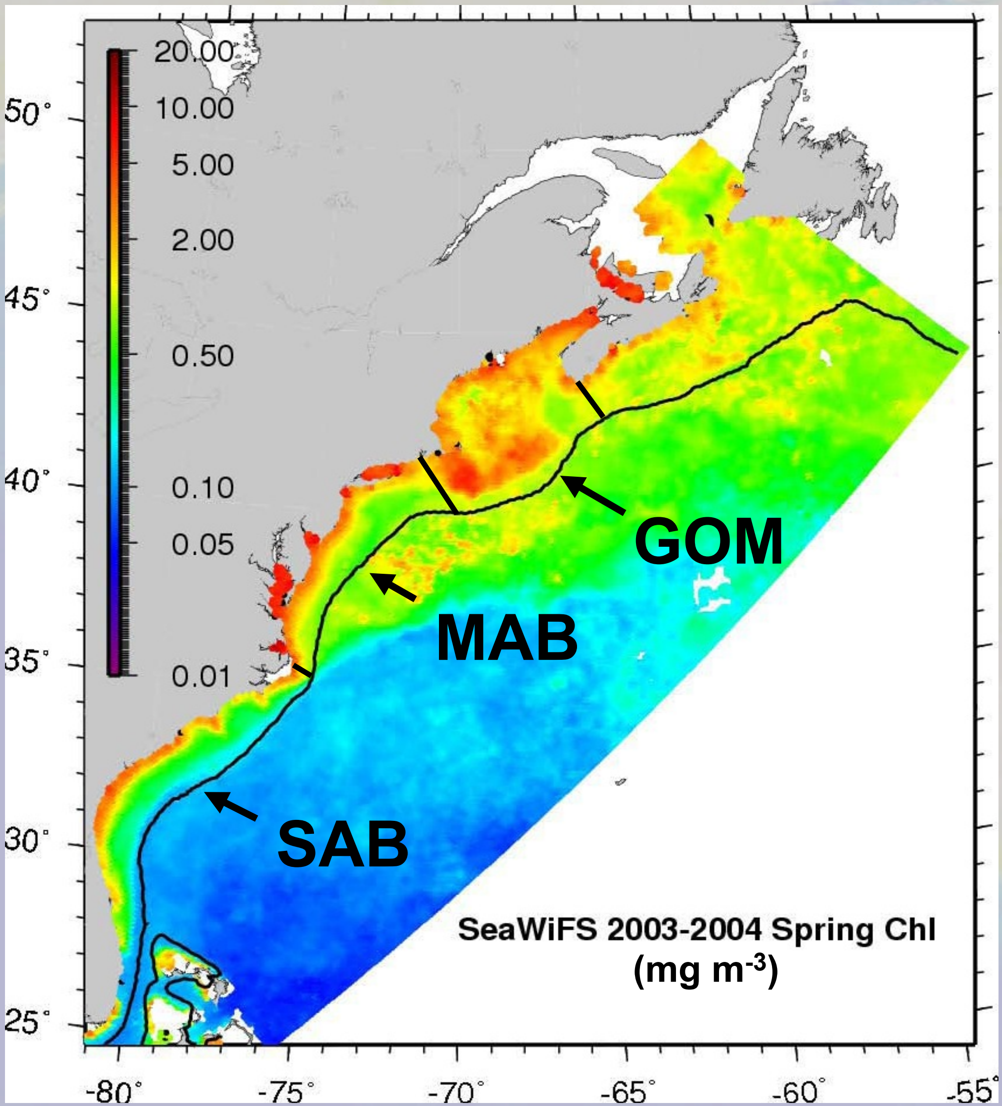
47 ± 20

34 ± 10

35 ± 10

- Currently a literature synthesis, including results from some satellite algorithms
- Respiration poorly constrained

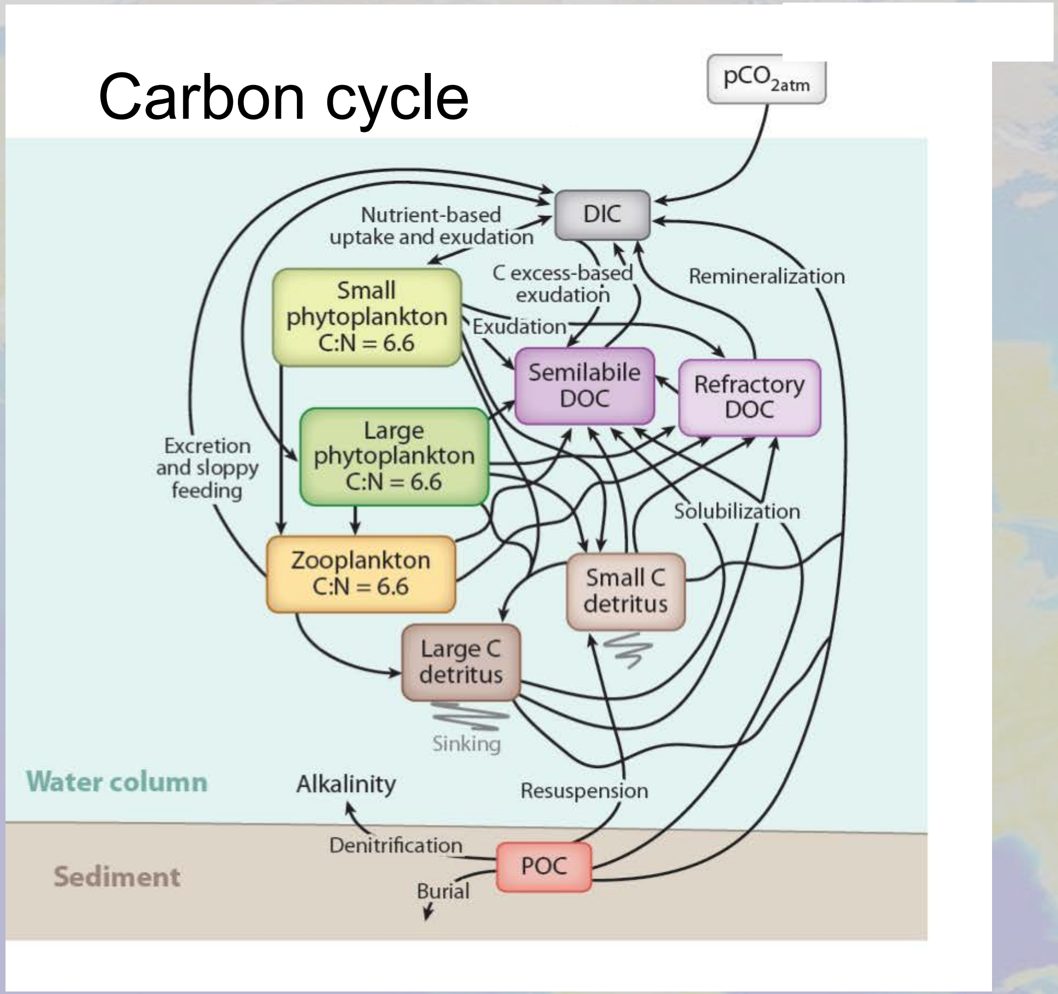
USECoS: Carbon-Biogeochemical Circulation Model for the US Eastern Continental Shelf



USECoS Model Properties:

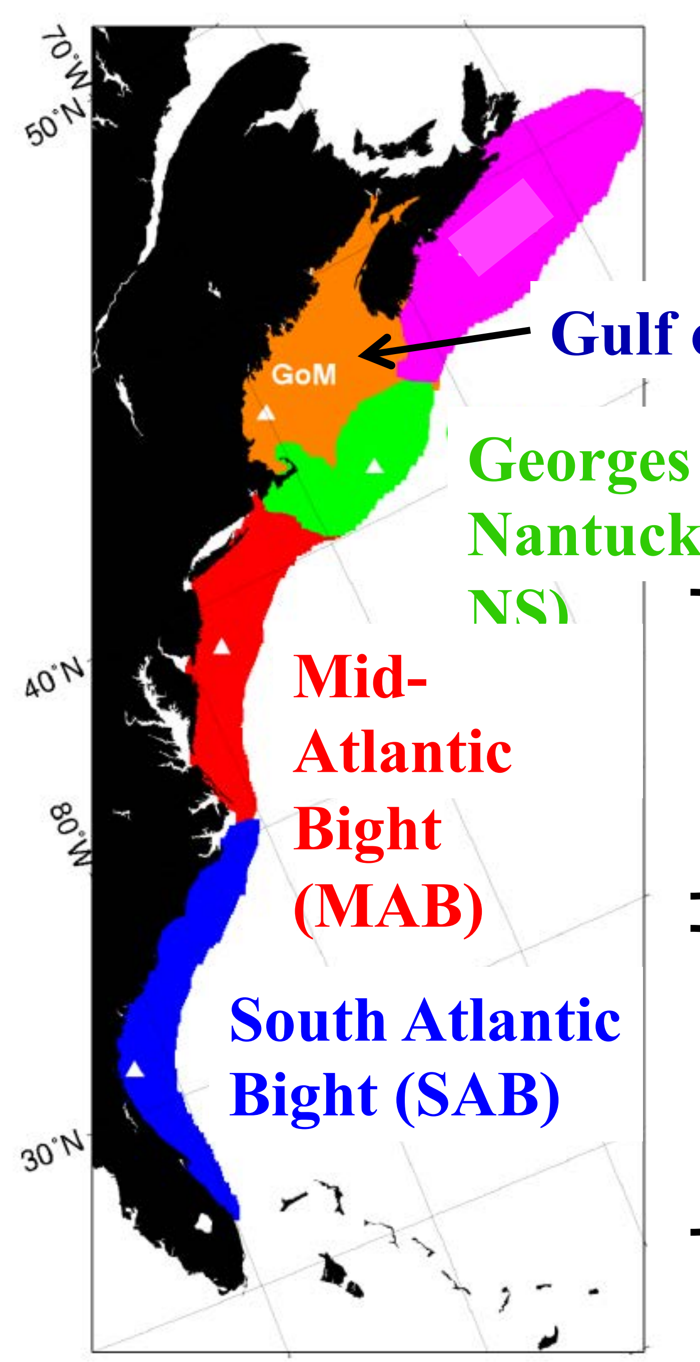
- ROMS (sigma coord.)
- 10 km horizontal resolution
- 30 vertical levels
- nested in N. Atlantic HYCOM simulation
- atm forcing = NCEP NARR 3 hourly fields
- Init NO3 = NODC climatology
- Init DIC, Alk = Lee et al. (2000) & Millero et al. (1998)
- Gas exchange = Wanninkhof (1992)

USECoS Model (Hofmann et al., 2011)



Burial (Druon et al., 2010)
DOC dynamics (Druon et al., 2010)
multiple plankton components (Xiao & Friedrichs, 2014)

East coast primary production USECoS Model: $94 \pm 9^{*}$ Tg C yr^{-1}



GoM + GB + NS: 44 ± 7

MAB: 24 ± 2

SAB: 26 ± 2

- PP is in good agreement with literature estimates
- NCP is **~14 TgC yr^{-1}** for US Eastern shelf

*Two standard errors, based on monthly estimates for 4 years

Primary Production in North American Coastal Regimes

– *Gulf of Mexico*

Table 6.1. Annual regional water column primary production based on median estimates for the different regions.

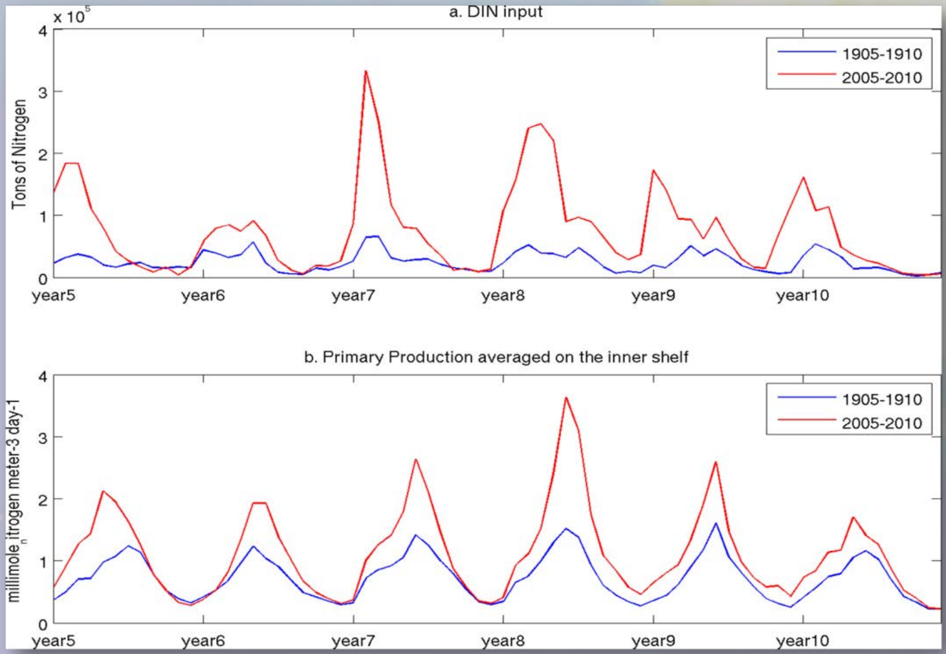
Region	**Daily PP** $gC\ m^{-2}\ d^{-1}$	**Annual PP** $gC\ m^{-2}\ y^{-1}$	**Area** km^2	**Regional PP** $Gt\ C\ y^{-1}$
Open	0.28	102.2	9.89E+05	0.101
TX	0.33	120.45	8.68E+04	0.010
N Central	1.1	401.5	1.47E+05	0.059
WFS	1.3	474.5	1.47E+05	0.070
MX	0.23	83.95	1.83E+05	0.015
			Total	0.256

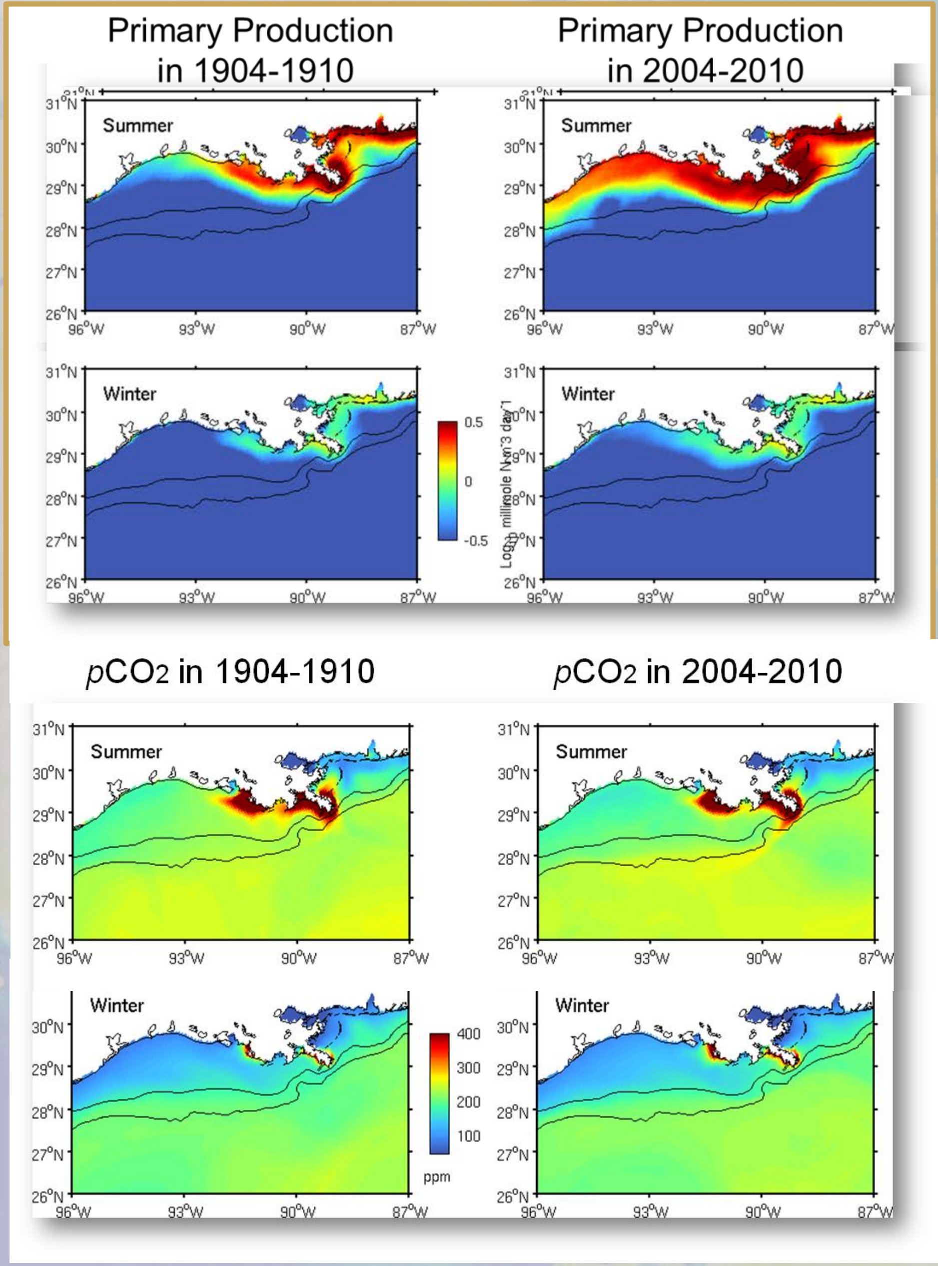
– *Satellite derived estimates (Wiggert and Denton) were 50-200% higher*

– *Huettel estimated BPP (0.182 Gt C y^{-1})!!*

Coupled Model Simulations: 1904-1910 vs. 2004-2010

- Increase in DIN export from MARB from 1904-1910 compared to 2004-2010
- Significant increase (18%) in ocean primary production

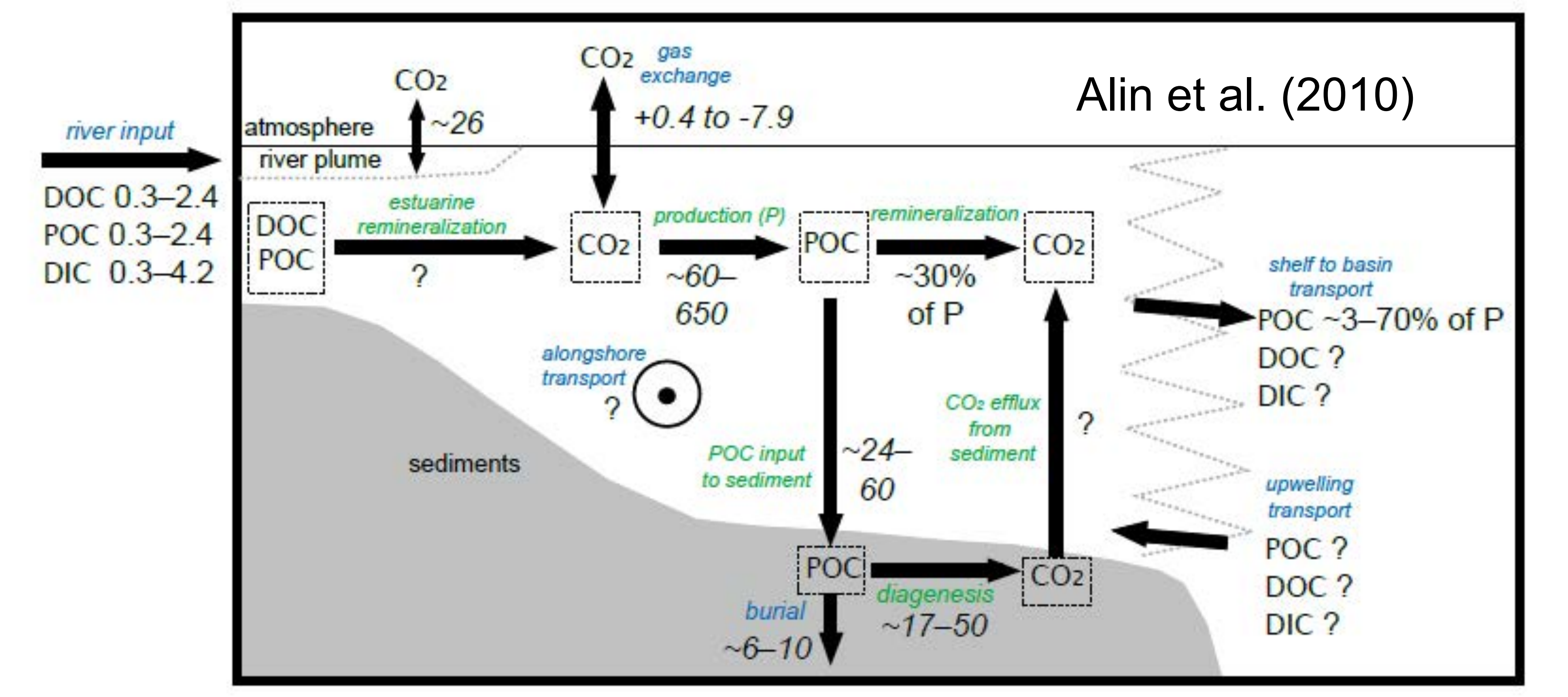




He, Xue, and Tian

Primary Production in North American Coastal Regimes

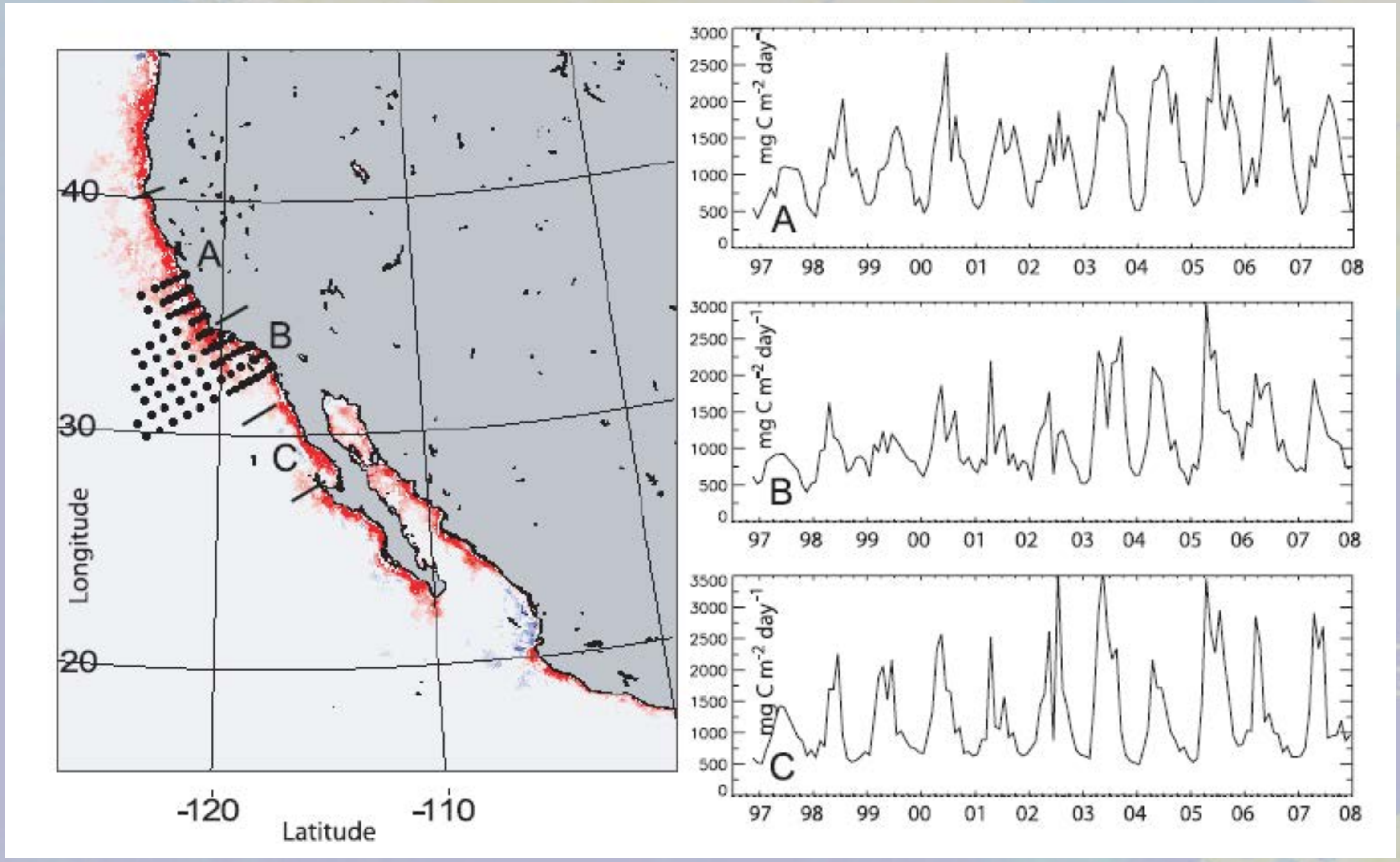
– *West Coast – large discrepancies in rates and differences among regions*



Primary Production in North American Coastal Regimes

– *West Coast*

Kahru et al. (2009)



Primary Production in North American Coastal Regimes

- Great Lakes

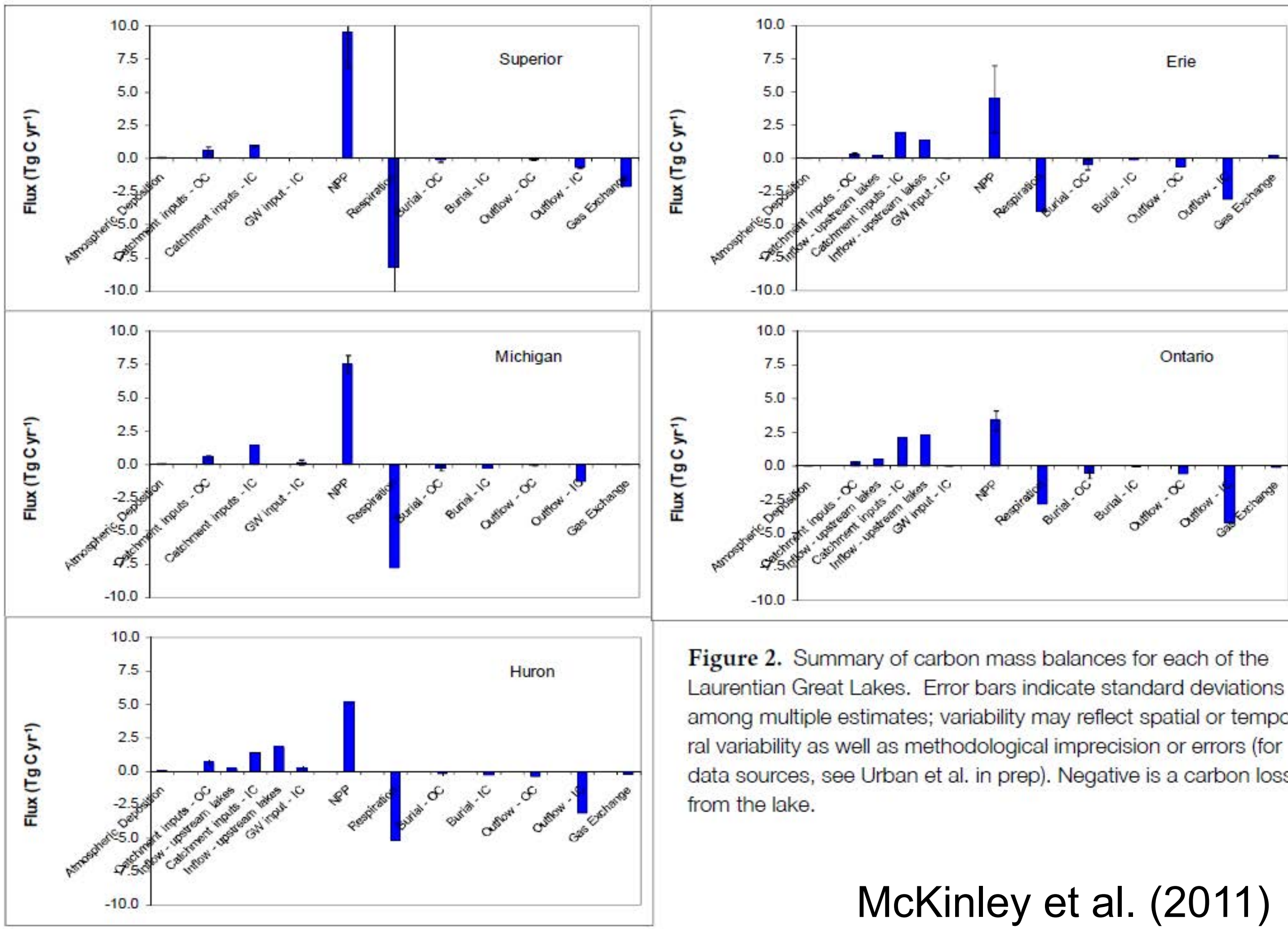


Figure 2. Summary of carbon mass balances for each of the Laurentian Great Lakes. Error bars indicate standard deviations among multiple estimates; variability may reflect spatial or temporal variability as well as methodological imprecision or errors (for data sources, see Urban et al. in prep). Negative is a carbon loss from the lake.

McKinley et al. (2011)

Primary production in Lake Superior

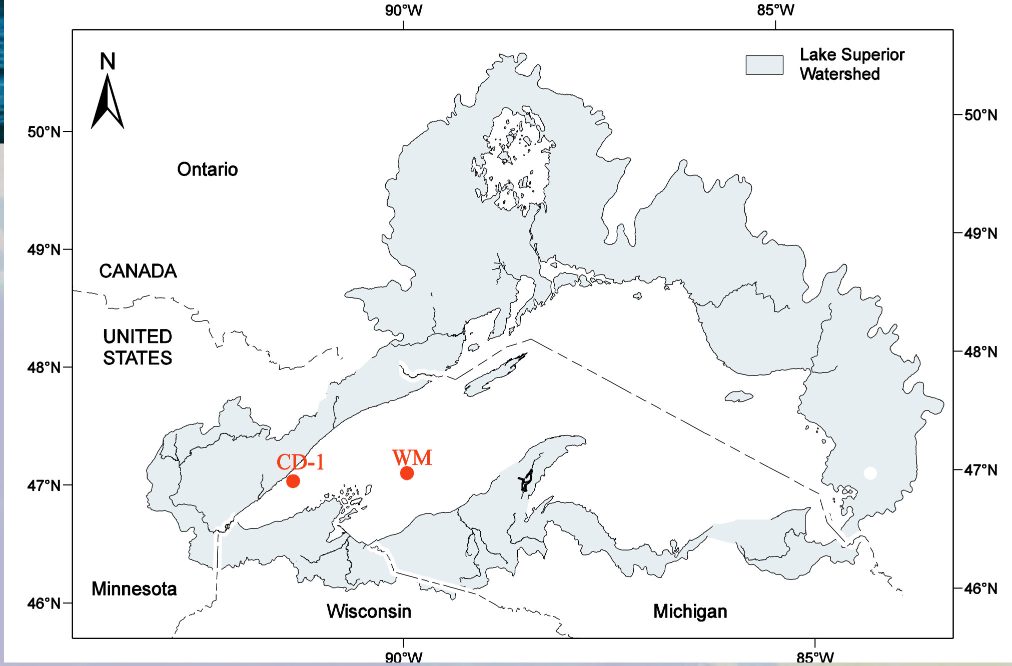
Robert W. Sterner

Large Lakes Observatory, U. Minnesota Duluth

Few previous studies of PP in oligotrophic Laurentian Great Lakes.

Organic C budget was wildly out of balance.

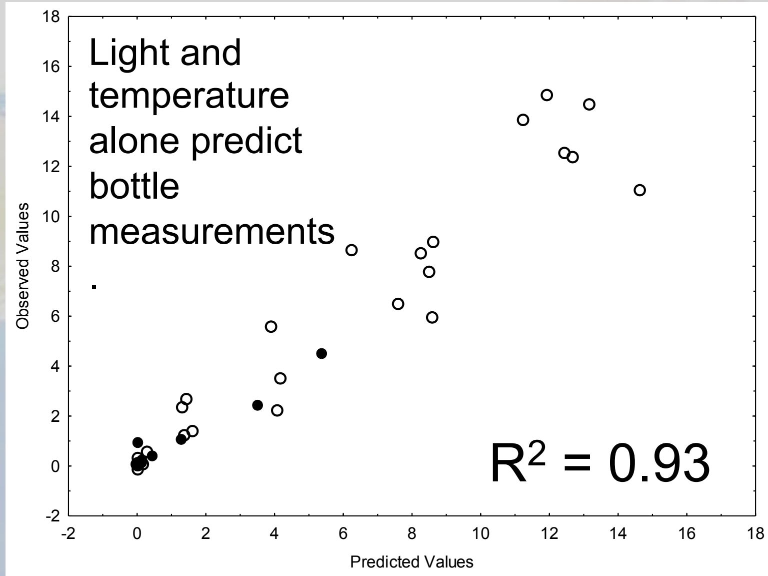
Adopted JGOFS 14C in situ protocol to generate comparative data



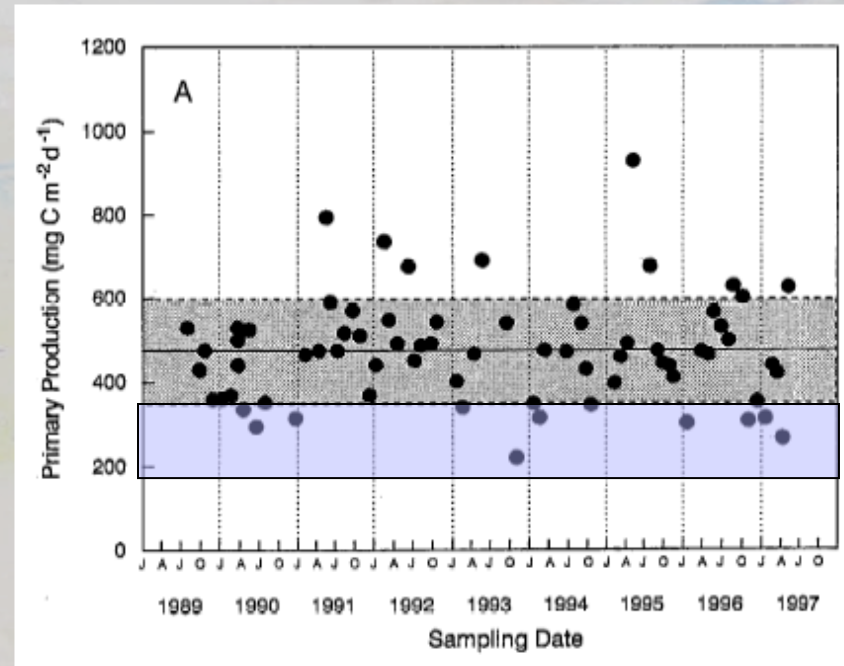
Sea Grant Minnesota

NSF

Scaling up to whole lake

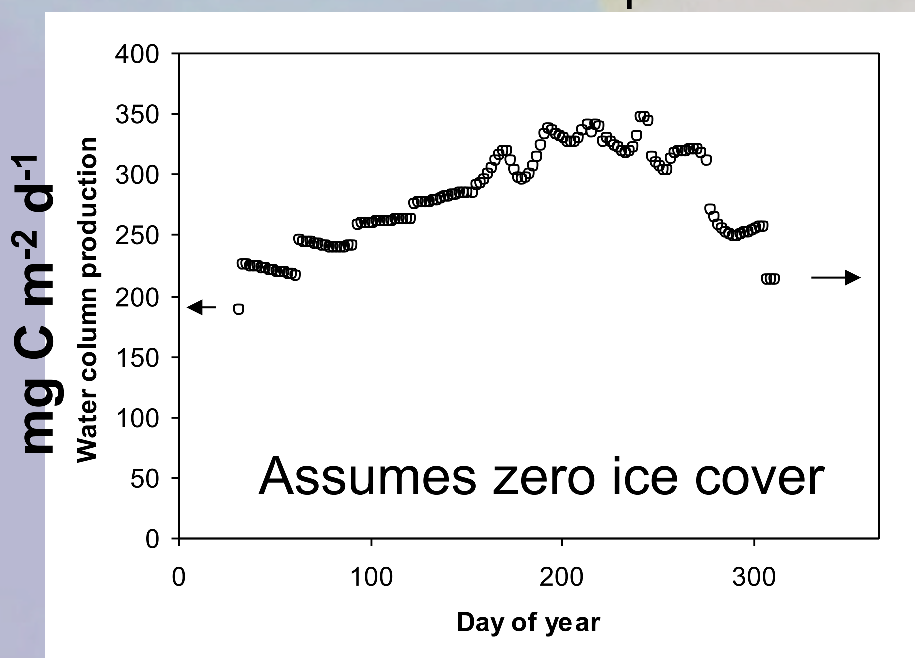


Comparison to HOTS



Water column PP in L. Superior (range in blue) is lower than observed in N. Pacific gyre.

Modeled annual production



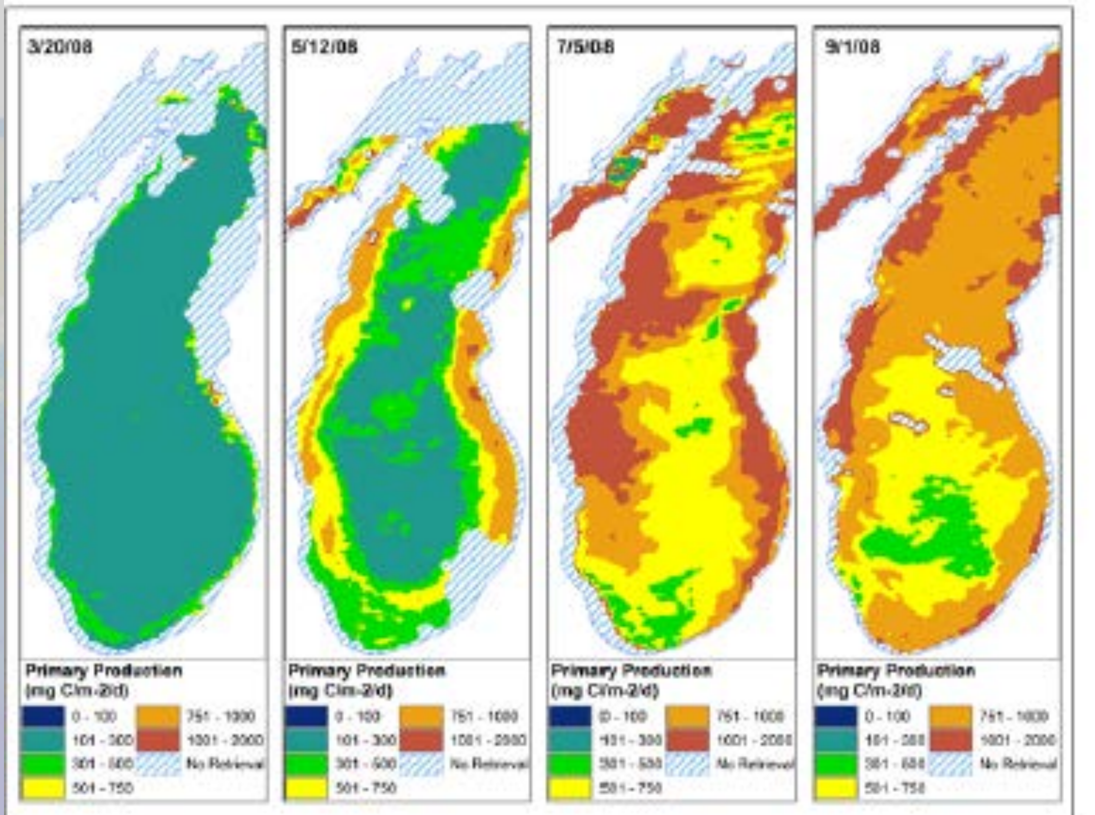
Additional measurements have been performed in 2009-2011 with ongoing measurements in 2014-15. “Big Chill” (polar vortex) – high ice year in winter 2013-4. Will this depress whole lake PP?

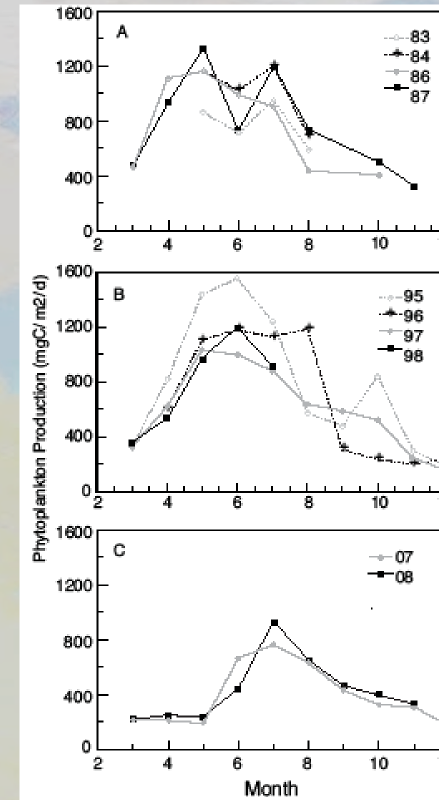
Sterner

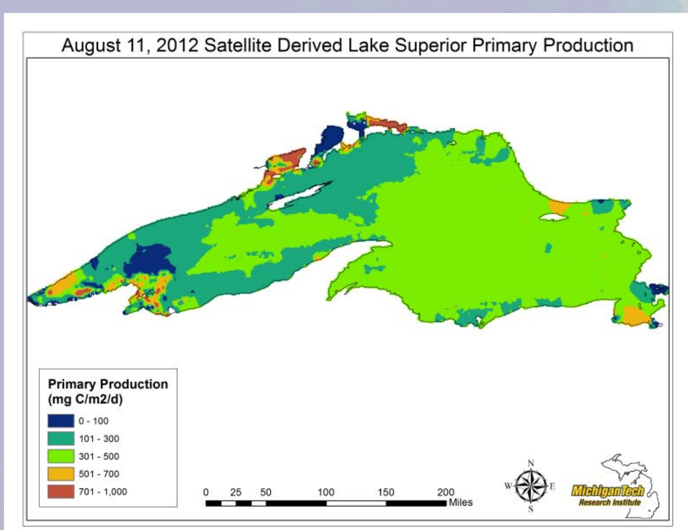
REMOTELY SENSED PRODUCTION

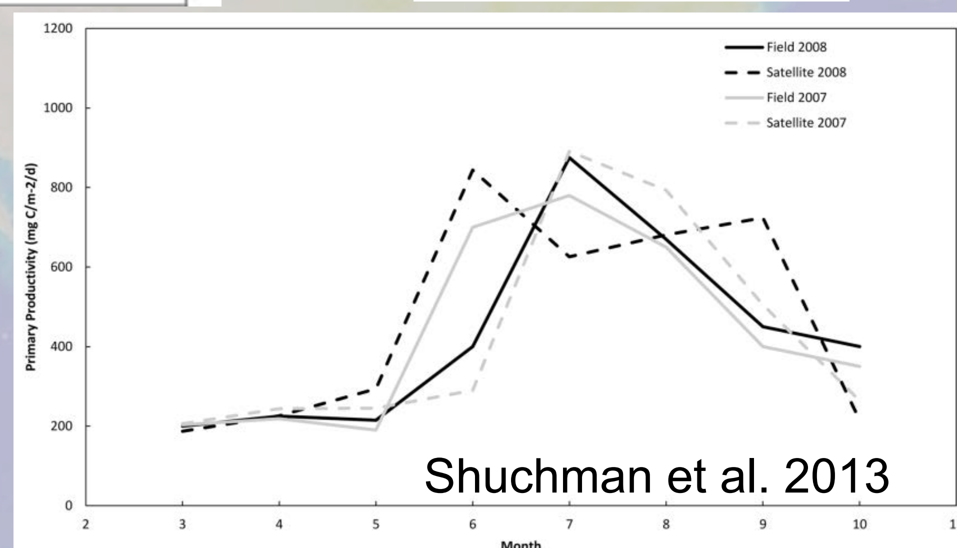
WIM-GLPPM (I_o, K_d, Chl, P-E)

Field Measurements



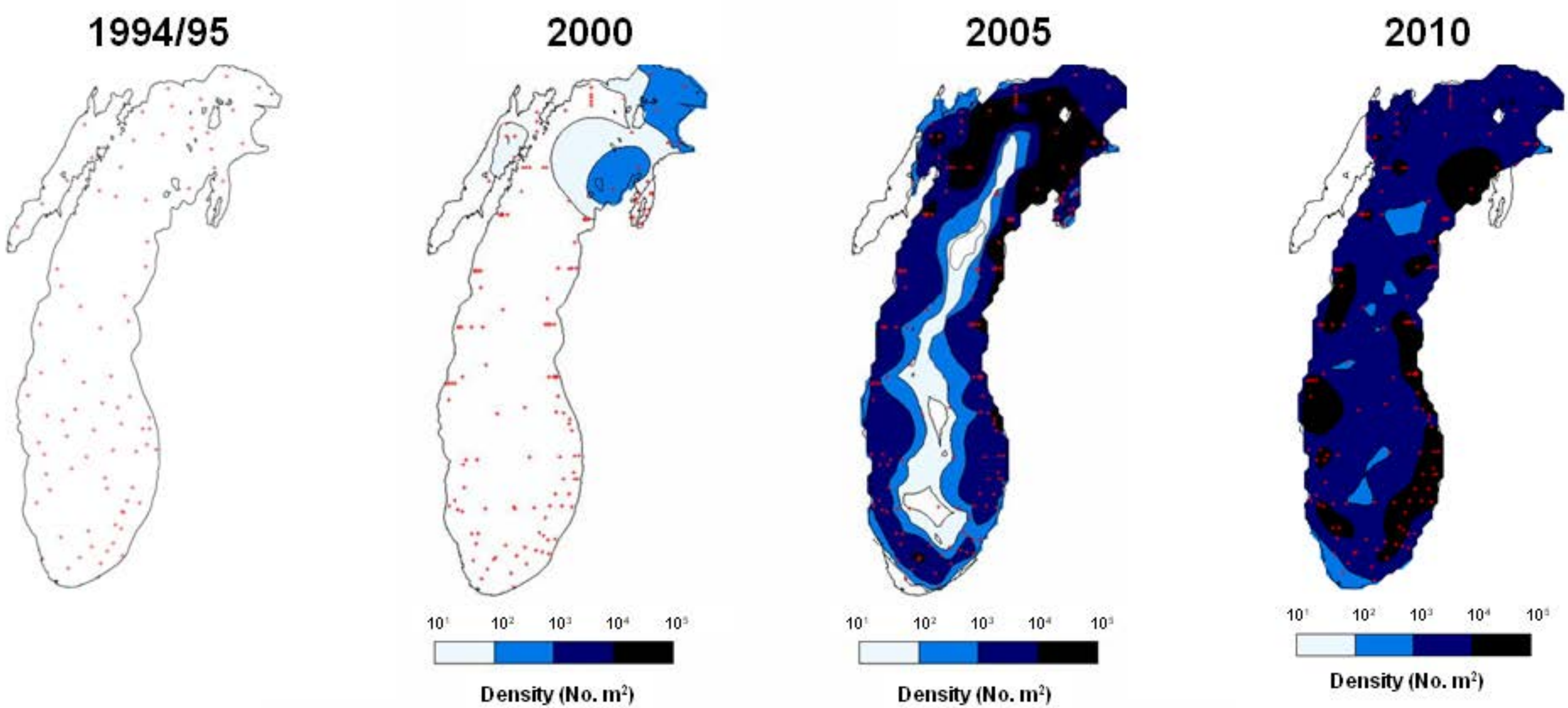






Shuchman et al. 2013

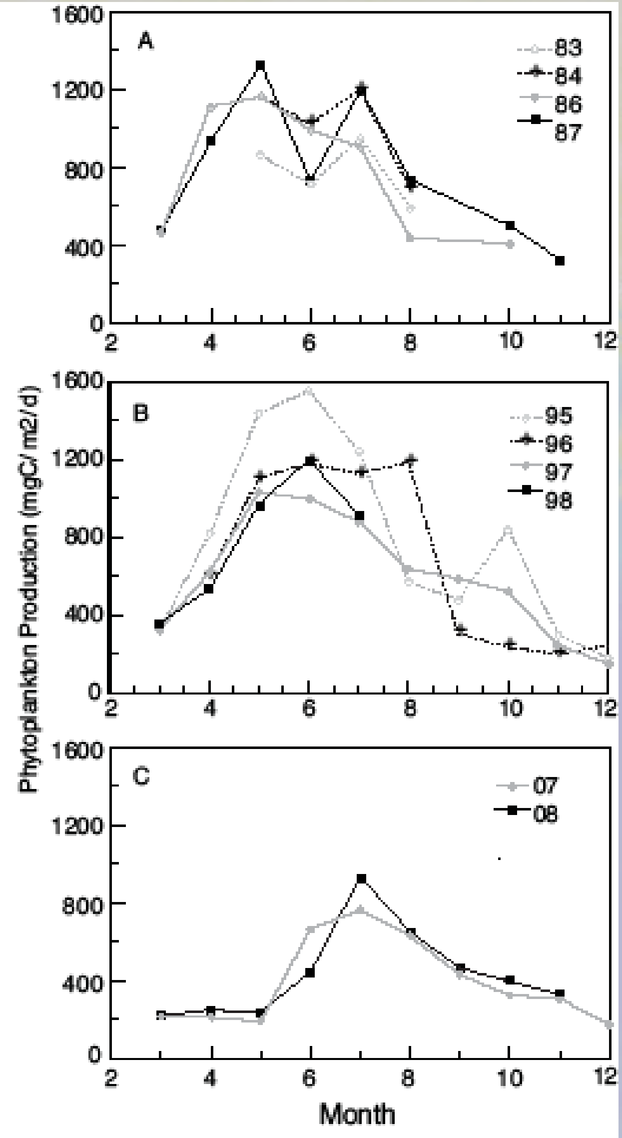
Quagga Mussel

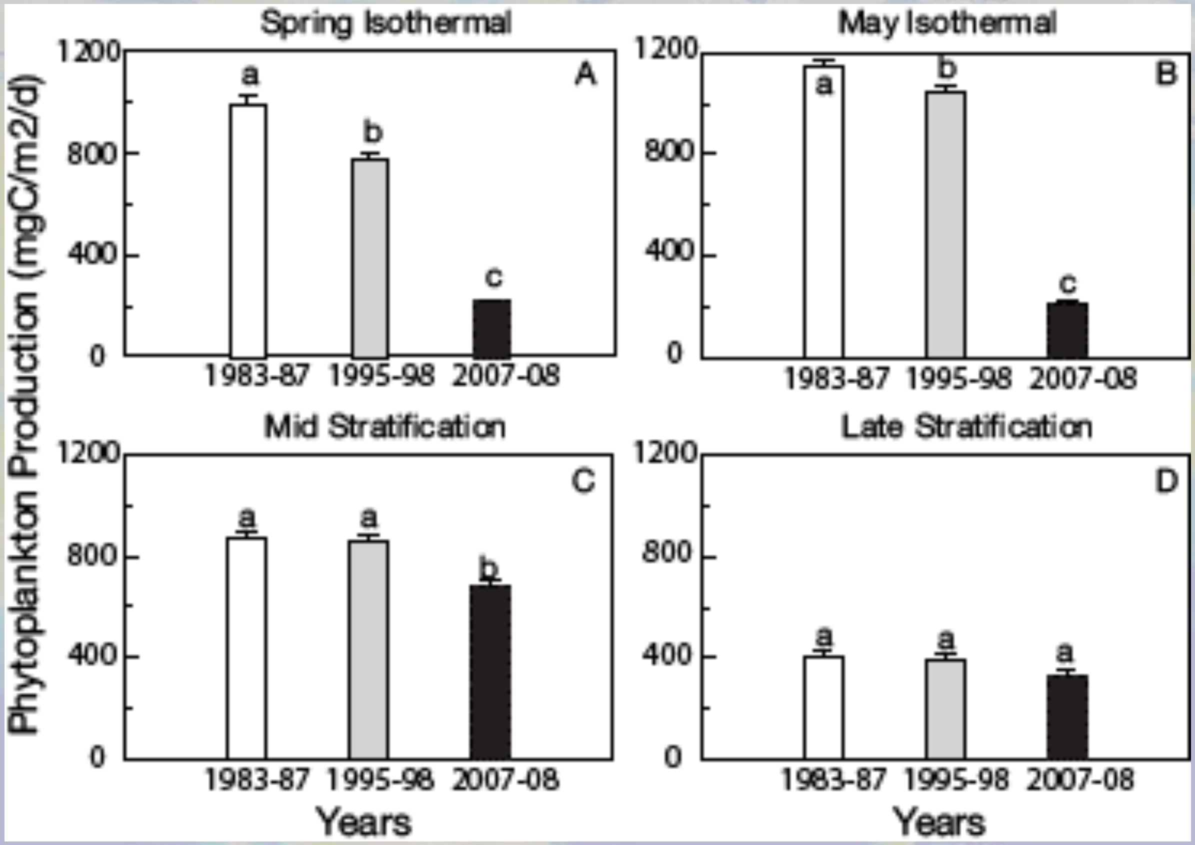


>900 Trillion Dreissenids
in Lake Michigan (99% Quaggas)

Nalepa

Offshore Pelagic Primary Productivity Trends (mgC/m2/d)
SE Lake Michigan (100-110 m stations)





Tremendous decrease in spring 2007/10 (60-70%)

Annual decrease > 30%

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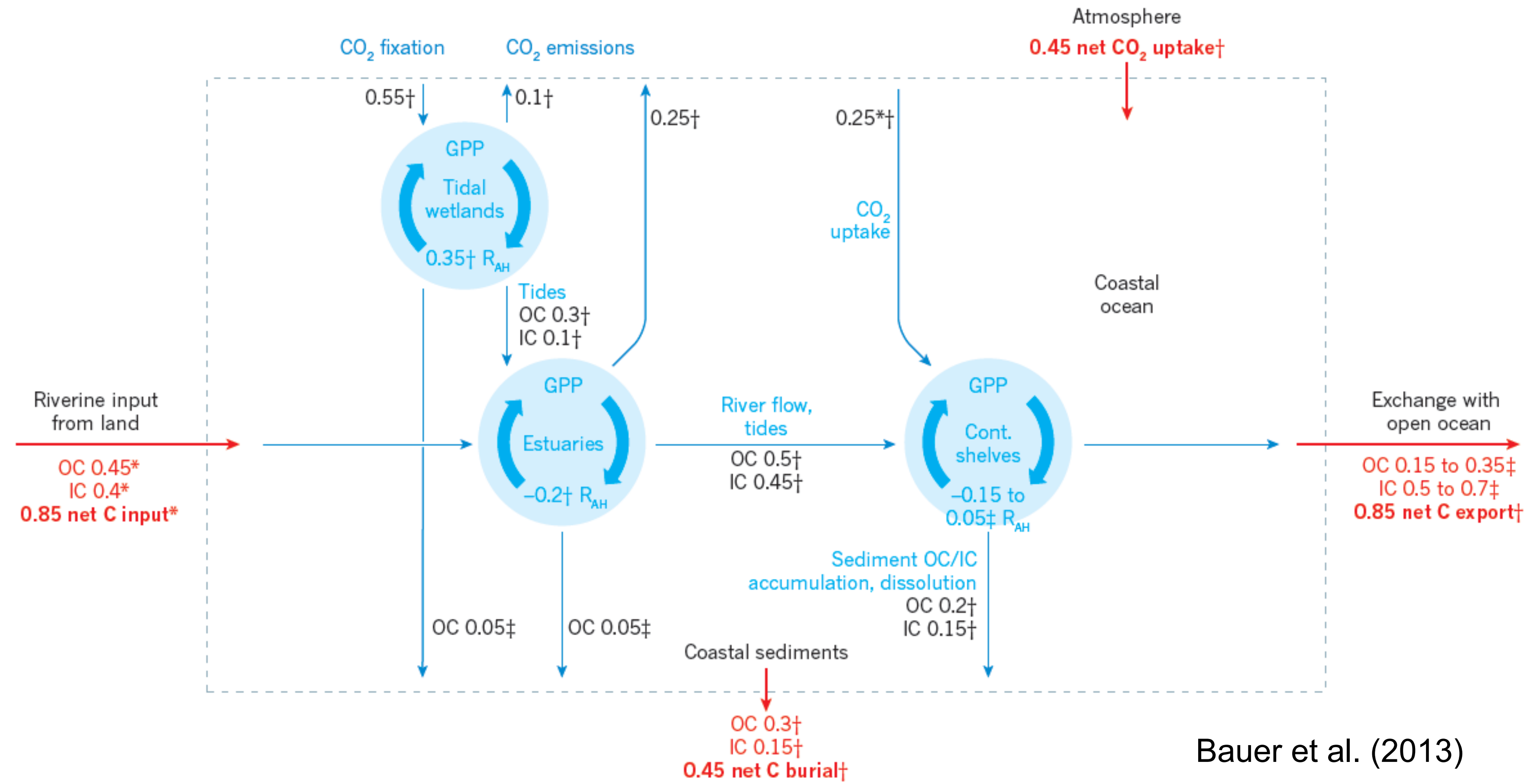
Application of PP for Characterization of Coastal Carbon Cycling

- Relationships to other processes
  - *Air-sea CO_2 flux (e.g., Cai et al., 2010;)*
  - *Eutrophication (Rabalais et al., 2009; Howarth et al., 2011)*
  - *Phytoplankton community composition and food web structure*
  - *Secondary production, fisheries (Pauly and Christensen, 1995; Gattuso et al., 1998; Friedland et al., 2012, etc.)*
  - *Carbon export (Eppley and Peterson, 1979)*
  - *DOM production and consumption and the Redfield ratio, especially as it affects C export and export efficiency (Hopkinson et al., 2005; Bianchi, 2011)*
- Model validation
- Cross-system comparisons

Application of PP for Characterization of Coastal Carbon Cycling

- Primary production is a central term in current scenarios of changing coastal carbon cycles -



Bauer et al. (2013)

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Recommendations for future studies

- Examination of long term changes in coastal PP in relationship to climate and anthropogenic drivers
- More extensive cross system analysis – comparisons and identification of dominant processes, standardization of approaches
- Exploring utility of primary production in integrated ecosystem management approaches – improved management of living marine resources
- Identification of regime shifts (e.g., shifts between benthic vs. water column related to eutrophication)
- Linkages between phytoplankton community structure and PP
- Relative importance of inorganic vs. organic nutrient inputs
    - *competition for inorganic nutrients between bacteria and phytoplankton*
    - *effects of nutrient limitation on phytoplankton size and community composition*
    - *food web length vs. production of higher trophic levels*
- Importance of stoichiometry (nutrient, uptake, organic matter composition)
- Importance of scaling – capturing smaller spatial scale patterns for inland waters, estuaries, wetlands and event scale transport phenomena (intrusions, upwelling, shelf exchange processes)
- Ocean acidification and PP and community structure relationships