Impacts of Freshwater Discharge Patterns on the Carbon Cycle in Microtidal Estuaries

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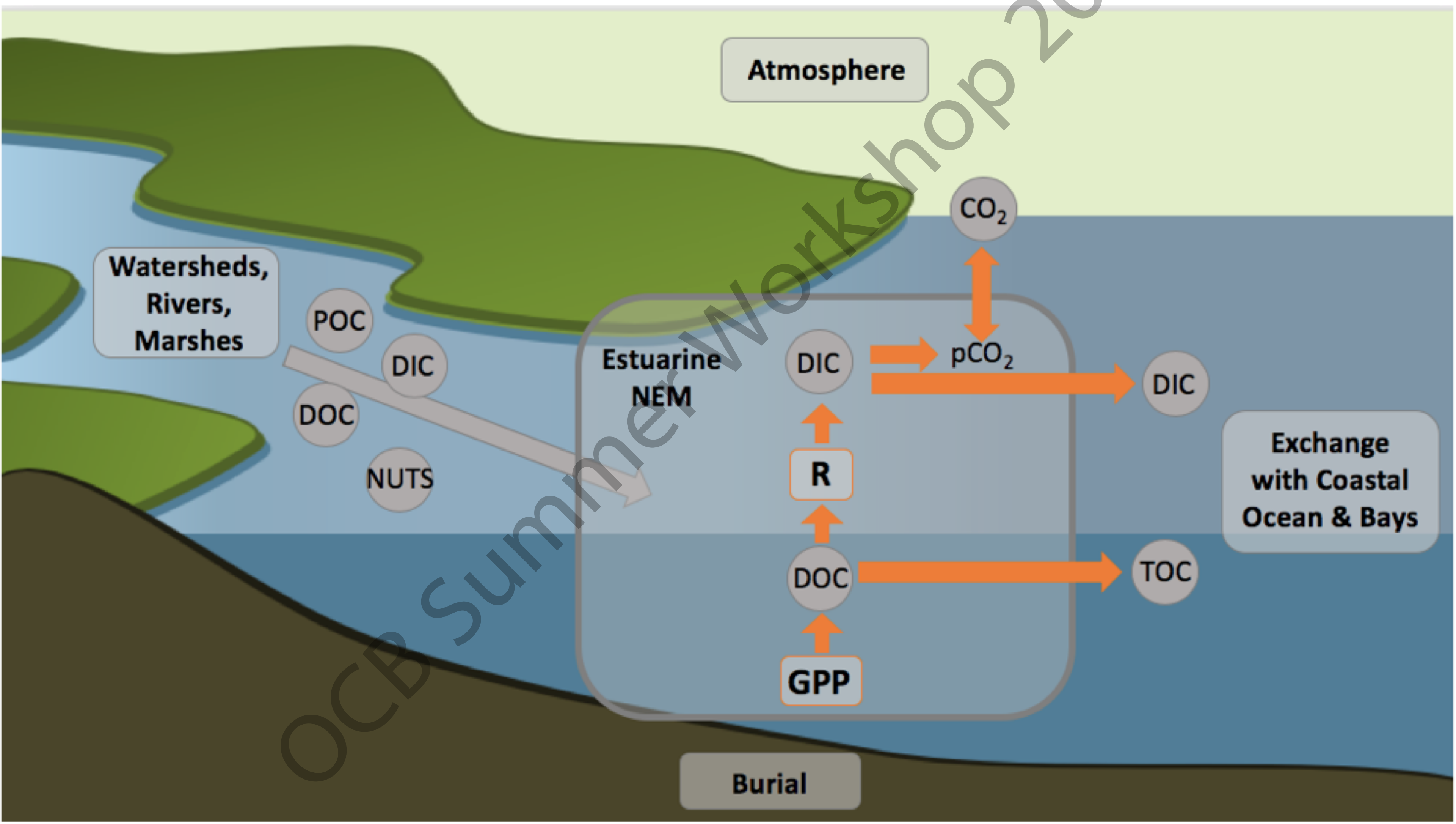
Net Ecosystem Metabolism, which is likely to play an important role in regulating FCO_2, is often not measured.



Potential drivers of CO_2 fluxes in estuaries

- Hydrology
  - FW discharge, FW age, residence time, mixing
- Temperature
- Allochthonous inputs of carbon and nutrients
  - From marshes - DIC vs. DOC
  - From industrial/urban sources – waste water treatment plants
  - Forested systems – humics
  - Groundwater and subterranean estuaries
- Autochthonous inputs of carbon and nutrients
  - Net autotrophic systems – uptake DIC/pCO2; produce TOC; burial
  - Net heterotrophic systems – mineralization of both autochthonous and allochthonous TOC
- Alkalinity production - sulfate and nitrate reduction

We focused on identifying mechanisms responsible for observed fluxes of CO_2 in two mid-Atlantic estuaries. We asked the following:

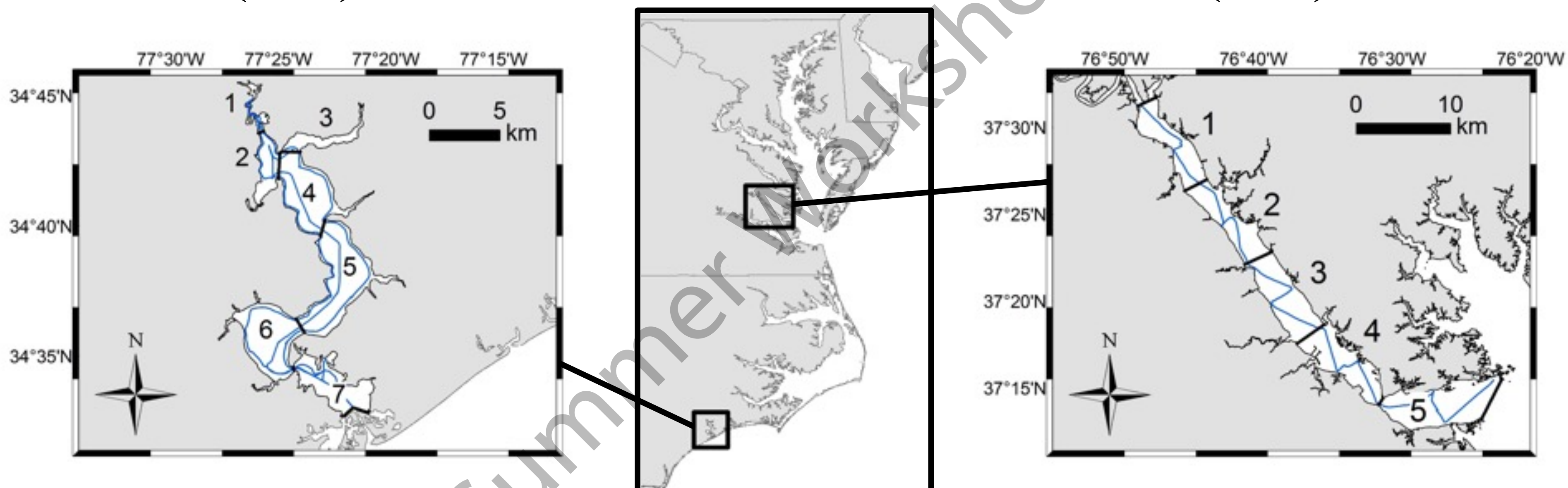
In the York River VA (YRE) and New River NC estuaries (NRE):

- How do air/sea CO_2 exchanges and net ecosystem metabolism vary temporally and spatially during years with different precipitation patterns?
- How does FW age influence net ecosystem metabolism and air/sea CO_2 exchanges?
- What are the direct vs. indirect regulators of CO_2 exchanges in the YRE?
- How do measured CO_2 fluxes in the YRE and NRE compare to other observed and modelled fluxes in estuaries along the Atlantic Coast of the US?

Study sites located in the mid-Atlantic region, USA

New River Estuary, NC (NRE)

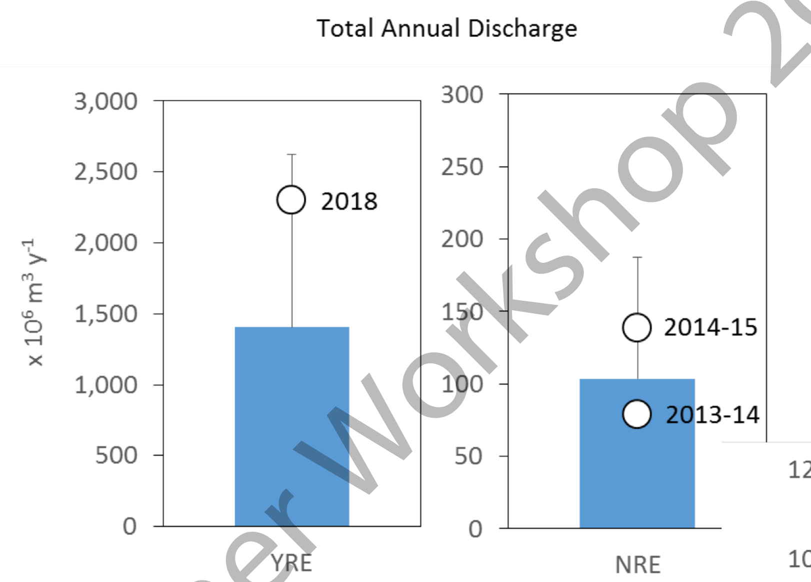
York River Estuary, VA (YRE)

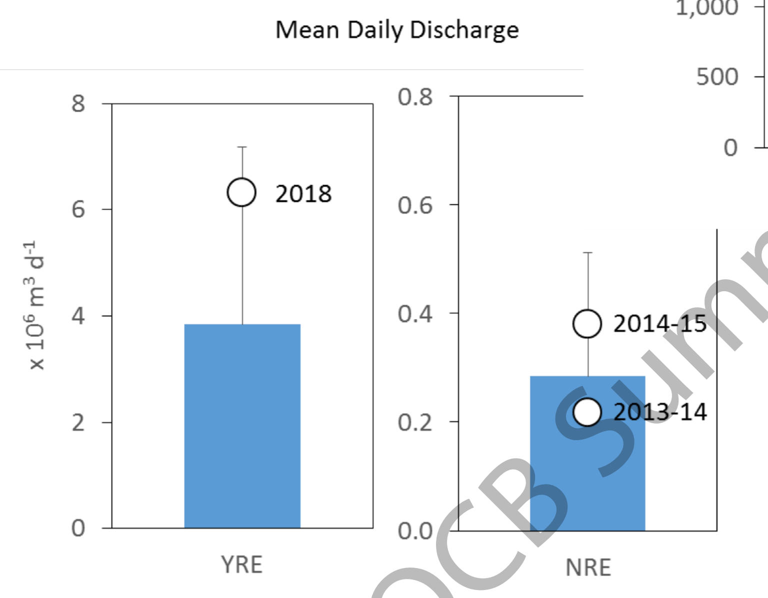


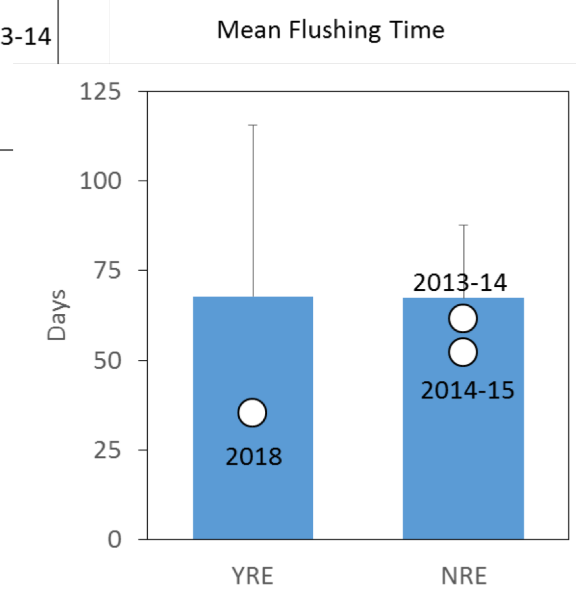
Comparison of the York and New River estuaries

	YRE	NRE
Watershed Area, x10^6 m^2	6,588	1,024
Estuary Area, x10^6 m^2	159	79
Watershed:Estuarine Area	41.5	13.0
Estuary Volume, x10^6 m^3	809	143
Mean Depth, m	5.1	1.8
% Area < 2 m	38%	56%
Mean Discharge, x10^6 m^3 d^{-1}	3.8	0.28
Discharge:Volume, d^{-1}	0.0048	0.0020
Mean Flushing Time, d	67.8	67.4
% Natural Vegetation	74.7%	69.3%
% Agriculture	17.4%	14.0%
% Developed	6.9%	15.5%

Patterns of mean annual FW discharge and flushing time differ for the YRE and NRE

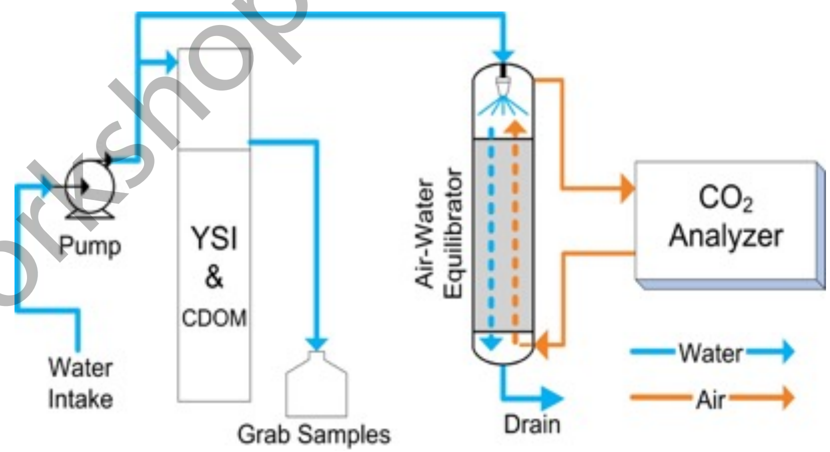






Net ecosystem metabolism was measured by the open water method

- Bimonthly dataflow cruises conducted at dawn, dusk, and dawn in the YRE (2018) and in the NRE (2013 – 14; 2014 – 2015).
- Water pumped to YSI 6600, CDOM sensor, and showerhead equilibrator.
- DO data distance weighted, averaged for each box, and interpolated over 24 h..
- Gas exchanges calculated (solubility coefficient, Weiss; Schmidt number, Wanninkhof, 1992; gas transfer parameterization, Jiang et al, 2008.
- Daily NEM calculated using average depth for each box and corrected for air/sea exchange.

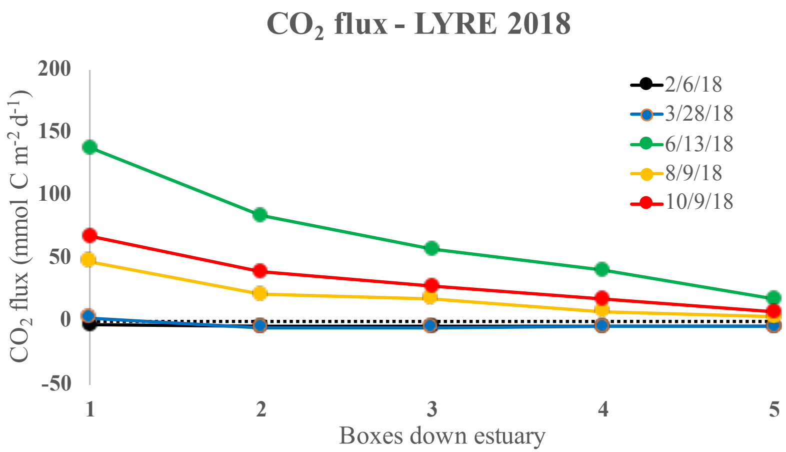


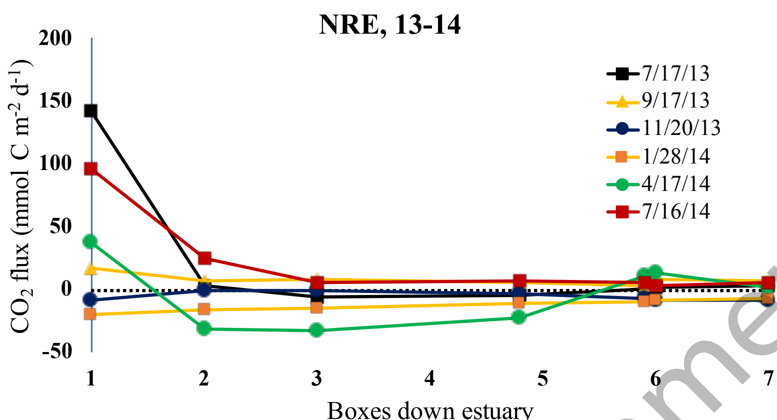
<u>YSI & CDOM</u>
- Chl *a*
- Turbidity
- pH
- DO
- Salinity
- Temp
- CDOM

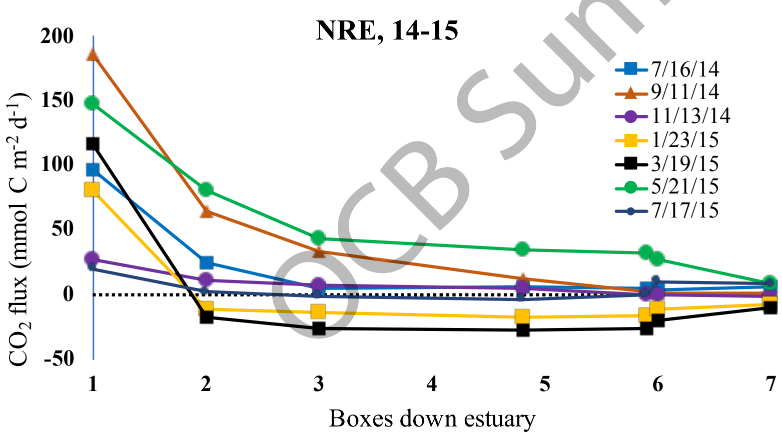
<u>Grab samples</u>
- DIN, DON, DIP
- DIC, DOC
- TSS
- Chl *a*
- CDOM
- ^{18}O

<u>Equilibrator</u>
- Temp
- Pressure

<u>CO_2 Analyzer</u>
- $xCO_{2(ambient\ air)}$
- $xCO_{2(equilibrated\ air)}$

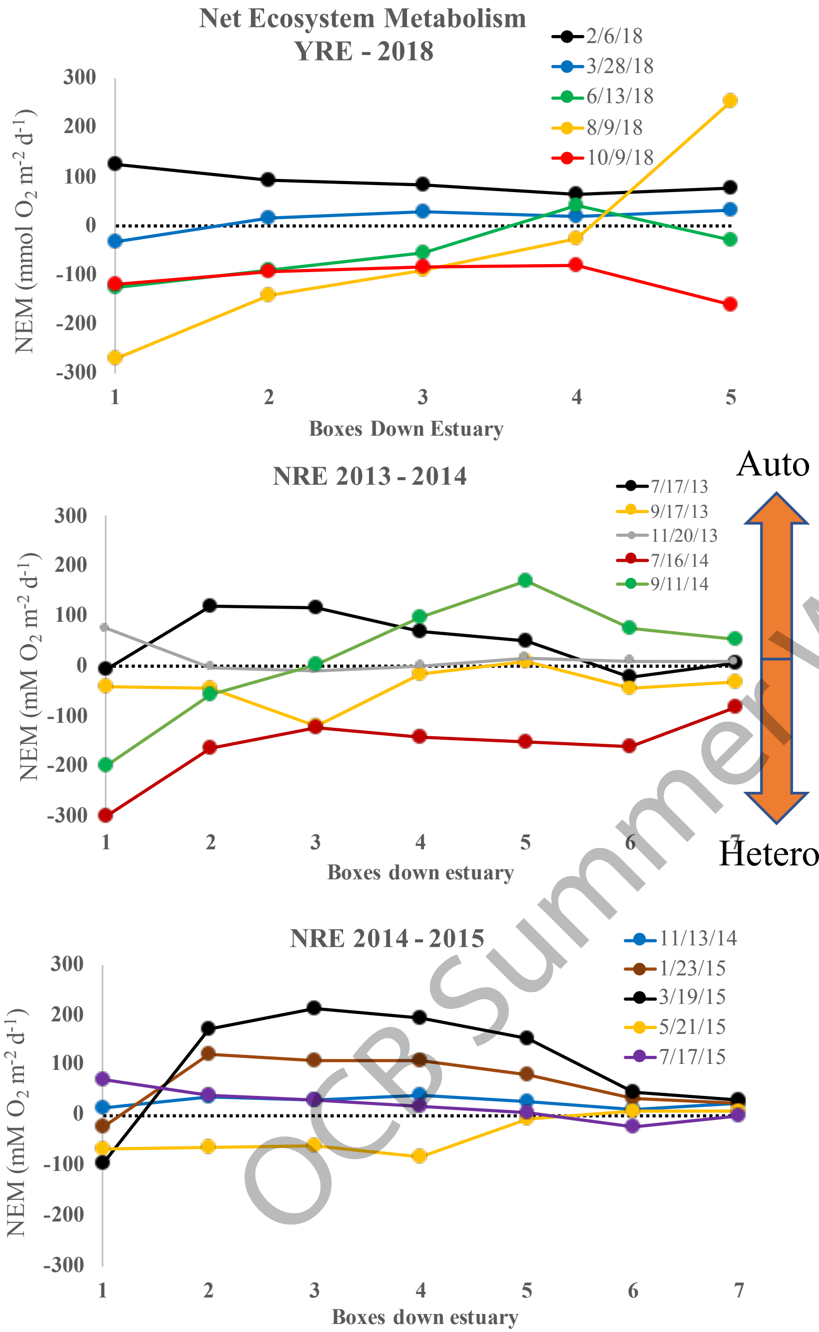






CO_2 Fluxes varied with FW discharge

- In YRE highest CO_2 emissions from June - October with higher than average FW discharge. In Feb and March there was net uptake of CO_2.
- In NRE (2013-14) with lower than average FW discharge net emissions mainly at head of the estuary with net uptake or balance in other boxes.
- In NRE (2014-15) with slightly higher than average FW discharge net emissions in most boxes during May and September with net or zero uptake during the rest of the year.

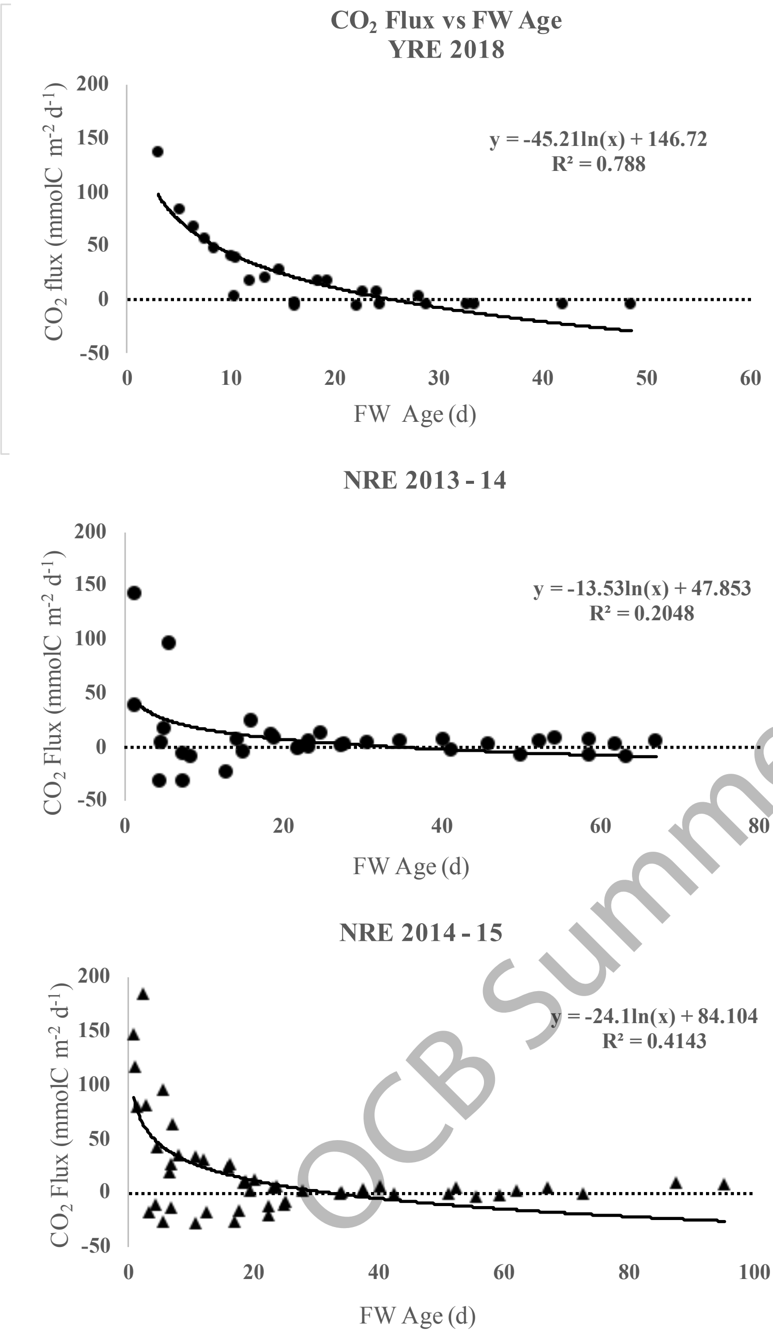


NEM shifted from net heterotrophy to net autotrophy depending on FW discharge

- In Feb and March the YRE was net autotrophic due to low discharge and cold temperatures. From June – November with high FW discharge most of the estuary was net heterotrophic.

- NEM in the NRE (2013 -14), with lower than average discharge, displayed no clear trends.

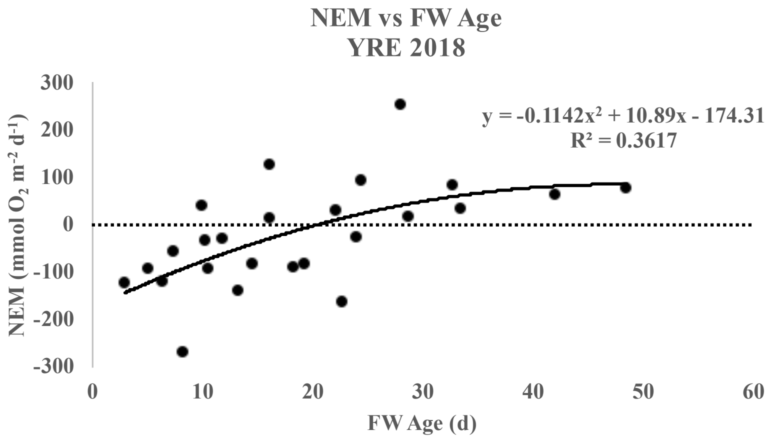
- In 2014 – 15 the NRE with slightly greater than average FW discharge was mainly net autotrophic.

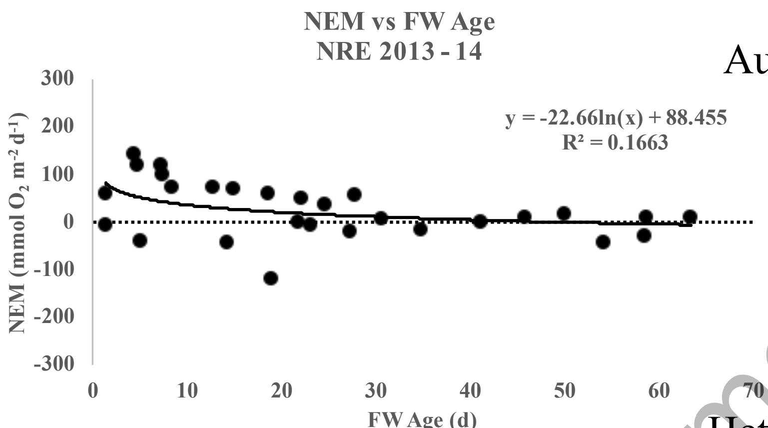


CO_2 Fluxes were highest at short FW Ages

- In all sites CO_2 fluxes decreased with increasing FW Age.
- At a FW age of approximately 20 – 25 d net fluxes approached zero.

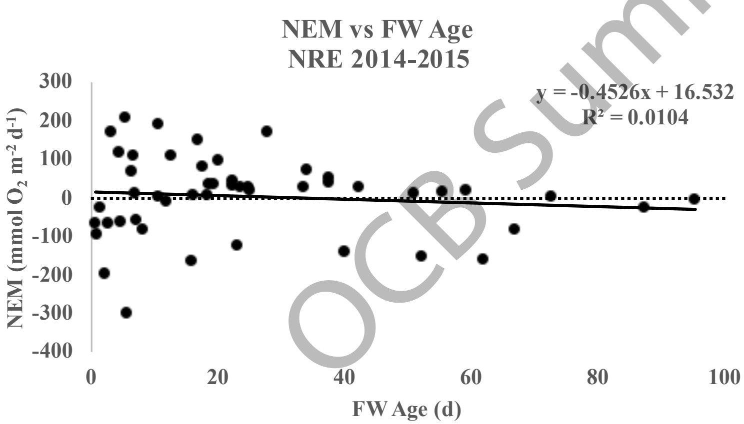
Net trophic status differed in the YRE and NRE and shifted with FW Age





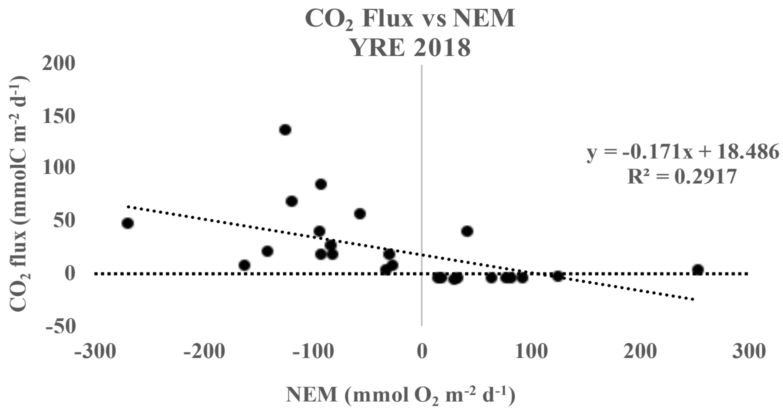
Net Autotrophic

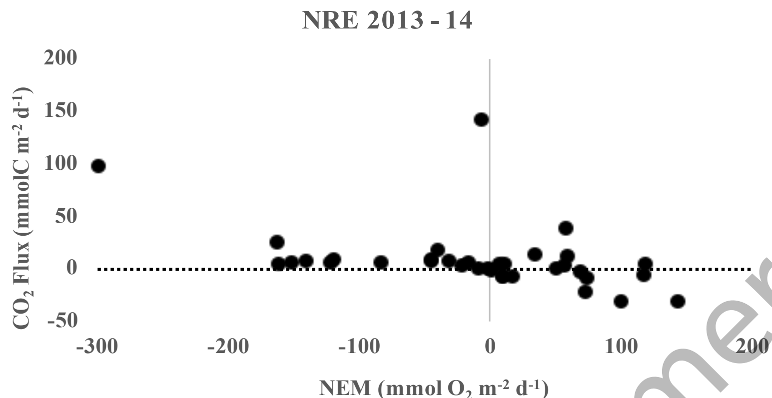
Net Heterotrophic

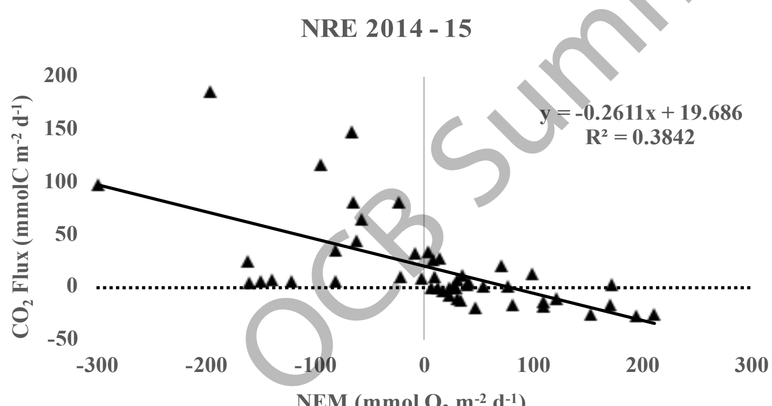


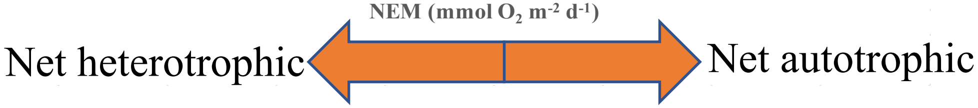
- YRE shifted from net heterotrophic to autotrophic with increased FW age.
- NEM in the NRE was weakly related to FW age but tended to shift from net autotrophic to heterotrophic or balance with increasing age.

The direction of CO_2 exchange varied with NEM



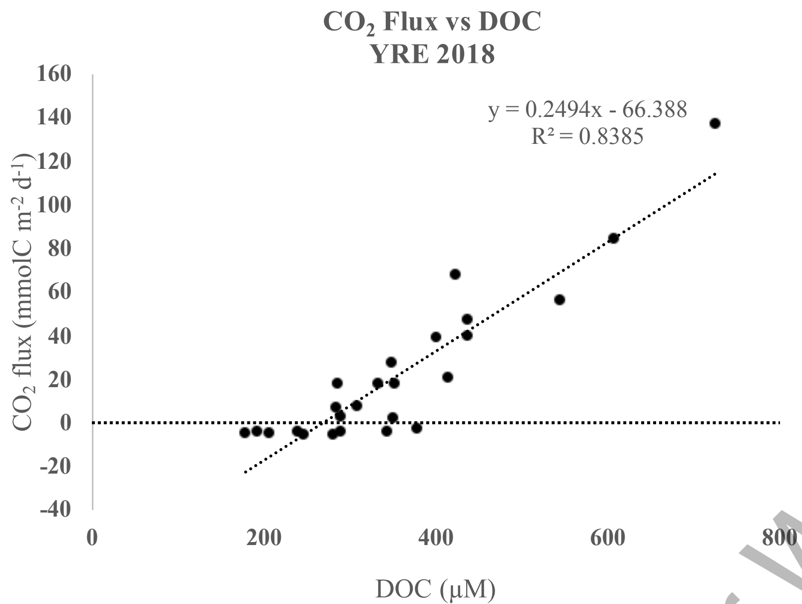


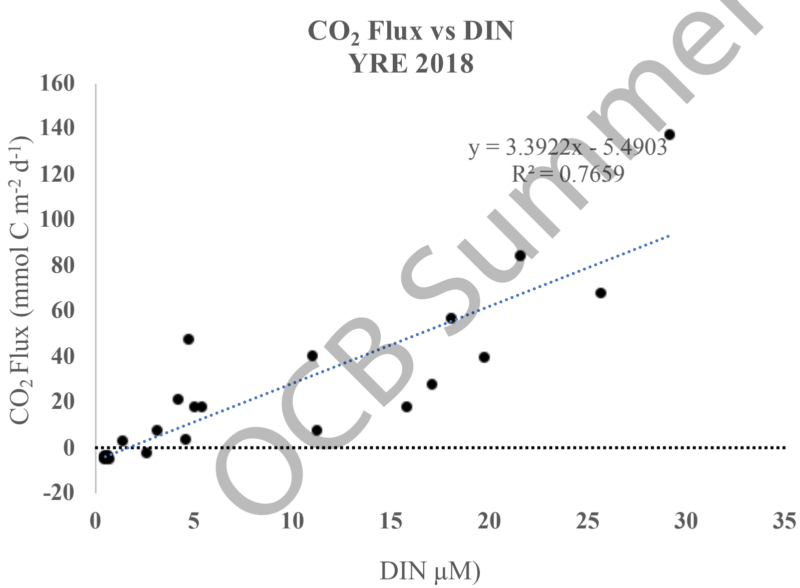




- Effluxes of CO_2 when net heterotrophic; uptake when net autotrophic

Other drivers that regulate CO_2 fluxes

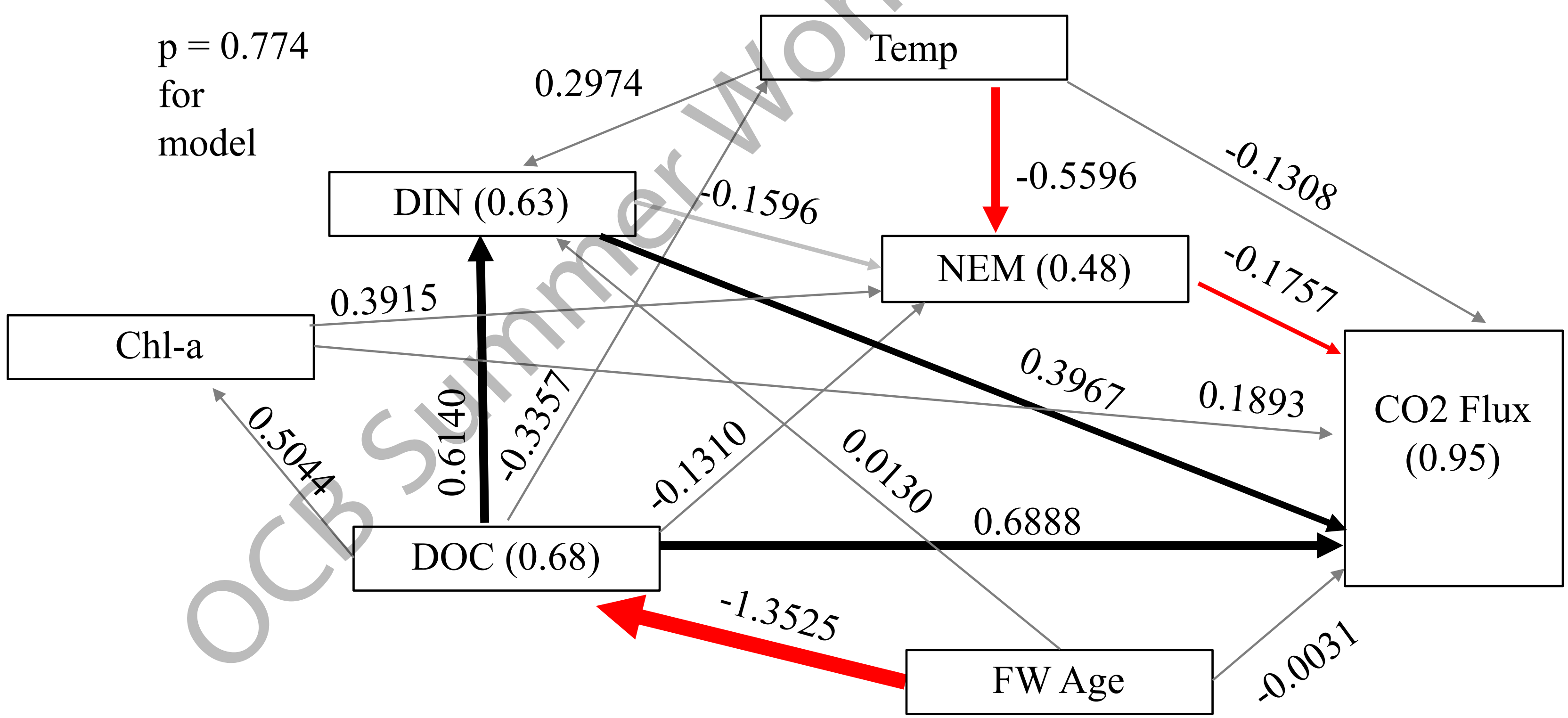




- In the YRE CO_2 fluxes strongly related to both DOC and DIN concentrations, highest at the heads of both the YRE and NRE and decreased linearly down estuary
- In the YRE and NRE chl-*a* was highest up estuary, weakly related to NEM but unrelated to CO_2 fluxes.

Structural equation models distinguished direct vs. indirect drivers of CO_2 fluxes in the YRE

Grey arrows represent non-significant pathways; black and red indicate significant positive and negative relationships. The correlation coefficient and size of each arrow corresponds to the relative strength of the relationship.



What sources of C support CO_2 evasion from YRE and NRE?

- DOC and DIC derived from riverine marshes
  - Estuarine DIC in excess of the C fixed plus DOC respired (Raymond et al, 2000)
  - Neubauer and Anderson (2003) determined that riverine marshes could supply approx. 47% of the excess DIC production in the YRE; DOC export negligible.
- Internally produced CO_2
  - VanDam et al (2018) demonstrated that in the NRE internal production of CO_2 more important than river derived DIC/CO_2

lateral C export (moles C m^{-2} y^{-1}) from marsh systems		
16.3	York R Estuary	Neubauer and Anderson, 2003
9.3 – 20.6	SC rivers	Neitch, 2000
24 – 30	Georgia rivers	Cai et al, 1999
17	Taskinas Cr, YRE	Knobloch et al (in prep)

A York River Comparison; slightly different conditions and interpretations

Raymond et al, (2000); 7/96 – 12/97

- Flushing time: 47.3 d
- Highest pCO_2 in summer and fall when residence time longest; lowest pCO_2 in winter and spring – low temperature, spring bloom, high discharge
- Highest heterotrophy head of estuary
- NEM: 8.3 moles C m^{-2} y^{-1}
- FCO_2: 6.3 moles C m^{-2} y^{-1}
- Net heterotrophy main driver of CO_2 evasion and DIC export

Anderson et al; 2/18 – 11/18

- Flushing time: 32.4 d
- Highest pCO_2 in June and August when residence time shortest; lowest pCO_2 in Feb and March – low temperature, spring bloom, low discharge
- Highest heterotrophy head of estuary
- NEM: 8.4 moles C m^{-2} y^{-1}
- FCO_2: 8.1 moles C m^{-2} y^{-1}*
- Net heterotrophy a driver but modulated by FW age

*Laruelle model estimated 8.1 moles C m^{-2} y^{-1}

How does FCO_2 vary from N to S in E. Coast estuaries; what are the drivers?

Estuaries	FCO_2(mmol m^{-2} y^{-1})	Drivers	Data source
Cocheco Bellalmy Oyster estuaries, NH	3.7 4.6 4.5	High nutrients, blooms, residence time, variable discharge	Hunt et al. 2011
Delaware Bay	2.4 ± 4.8	Upper - temperature Lower – NEM, mixing	Joessef et al, 2015
YRE (2018)	8.1	Very high FW discharge; NEM	Anderson et al
YRE (1996-97)	6.3	Net heterotrophy; allochthonous inputs	Raymond et al, 2000
NRE (2013-14) NRE (2014 – 2015) NRE (2014 –2016)	1.8 6.6 5.7 – 6.1	low FW discharge mid FW discharge mid FW discharge	Anderson et al; Crosswell et al, 2017 VanDam et al, 2018
Neuse (2009-10) Neuse (2014-16)	4.7 2.8-6.4	FW discharge,NEM allochthonous inputs;	Crosswell et al, 2012 VanDam et al, 2018
Altamaha, GE Sapelo GE Doboy Sound GE Satilla GE	25.3 10.5 10.7 42.5	High FW discharge Marsh inputs DIC Marsh inputs DIC	Jiang et al, 2008 Cai and Wang, 1998

How do observed vs. modelled estimates of FCO_2 and NEM in the mid-Atlantic region compare? (Laruelle et al, 2017)

Observed (molC m^{-2} y^{-1})		
NEM	FCO2	Site
-8.4	8.1	YRE
-4.5 1.8	1.8 6.6	NRE (2013-14) NRE (2014-15)
Modelled (Laruelle using CGEM)		
-7.4	11.1	Mid-Atlantic
Calculated FCO_2 based on Laruelle's Regression		
	11.3	YRE
	8.8 4.8	NRE (2013-14) NRE (2014-15)

Take home messages regarding regulation of CO_2 fluxes in estuaries

- Freshwater discharge transporting nutrients, pCO_2, DIC and DOC is the major driver controlling NEM, which in turn determines the magnitude and direction of $FCO_{2.}$
- The interannual variability in observed fluxes of CO_2 is likely due to differences in FW discharge. Extreme weather events are especially difficult to capture.
- Freshwater age determines the spatial variability in NEM and CO_2 fluxes.
- DIC derived from riverine marshes is likely responsible for the excess DIC and net heterotrophy inferred in many estuaries; DOC from marshes plays a lesser role.
- Transformations of carbon are spatially and temporally highly variable and difficult to simulate in models.

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