Biogeochemical controls on oxygen depletion across multiple scales in estuaries and the coastal ocean

Jeremy Testa
Chesapeake Biological Laboratory
Solomons, Maryland

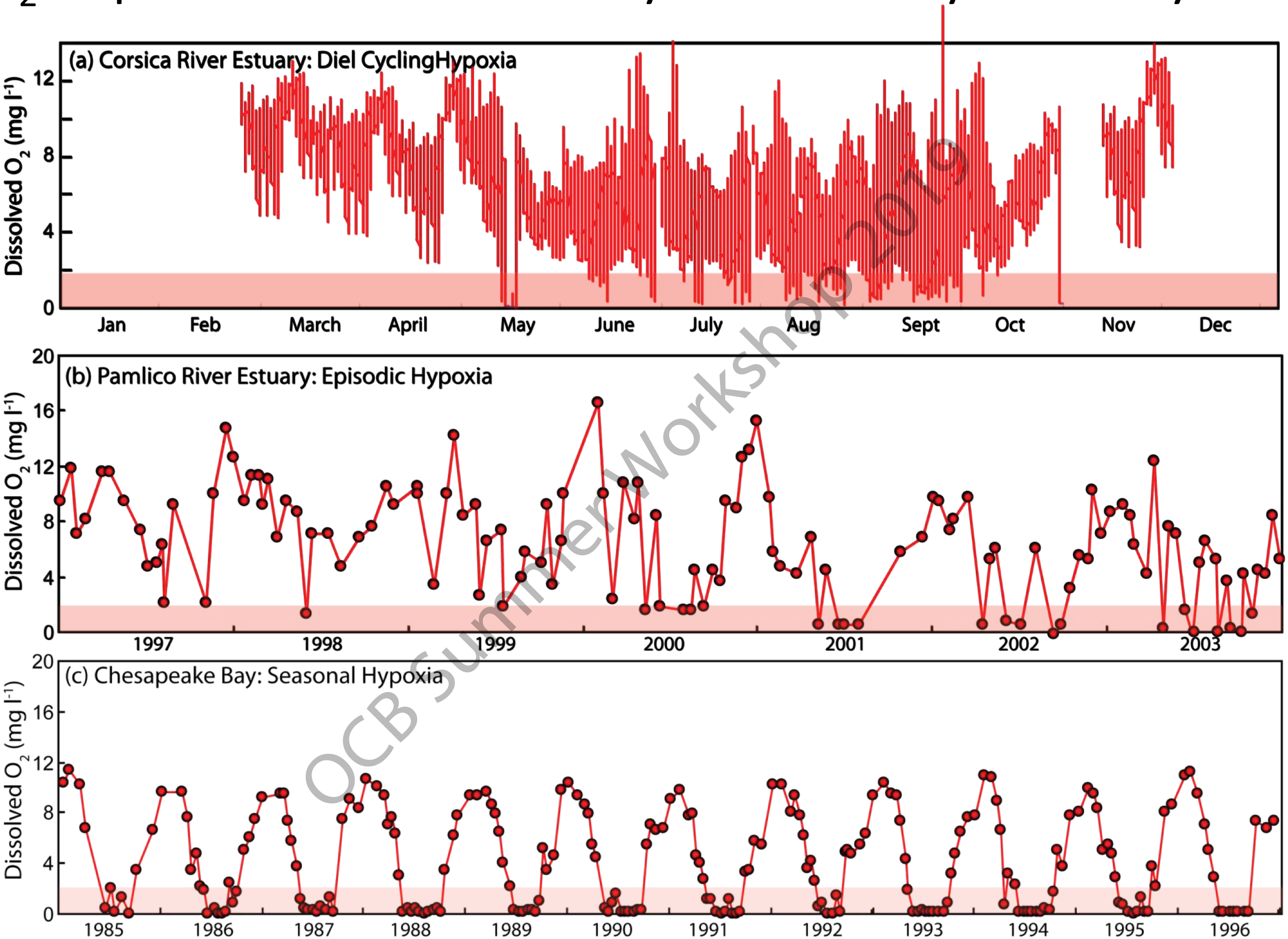
University of Maryland
CENTER FOR ENVIRONMENTAL SCIENCE

Collaborators: Katja Fennel, Lora Harris, Walter Bo

Approach and Considerations

- **Approach**: Perform a synthesis of oxygen uptake rates and potential replenishment rates across diverse coastal ecosystems, quantify a metric that balances the two controls
- There are a diversity of time scales of oxygen depletion in coastal and marine ecosystems (permanent, seasonal, episodic, diel)
- The degree of oxygen depletion depends on the magnitude of the biogeochemical oxygen consumption rates relative to physical replenishment
- Oxygen consumption is driven by a variety sources, including watershed and wetland C inputs, nutrient-fueled autochthonous organic matter, reduced chemical species

O_2 Depletion Time Scales Vary Substantially Across Systems



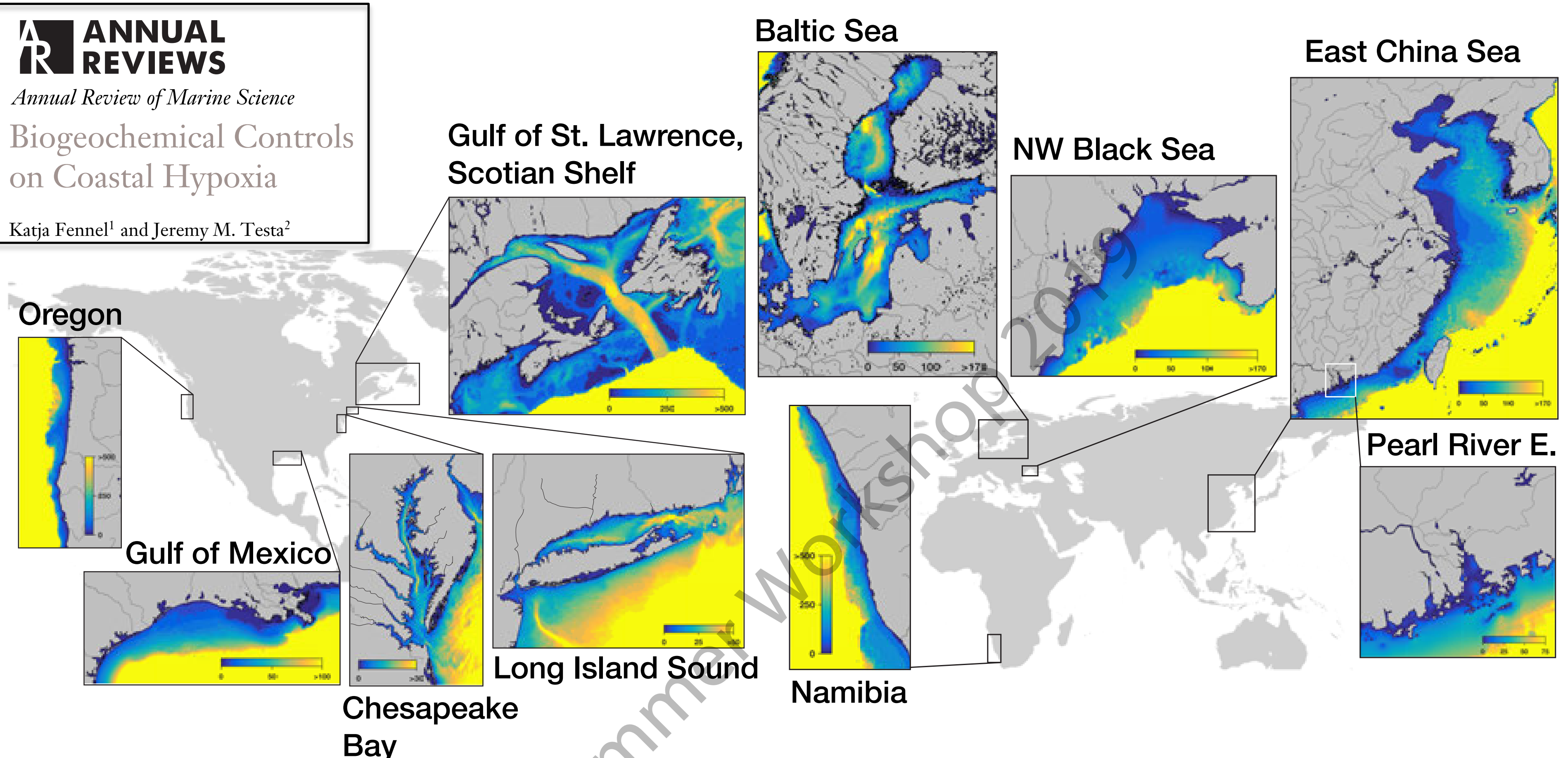
(Testa and Kemp 2011)

ANNUAL REVIEWS

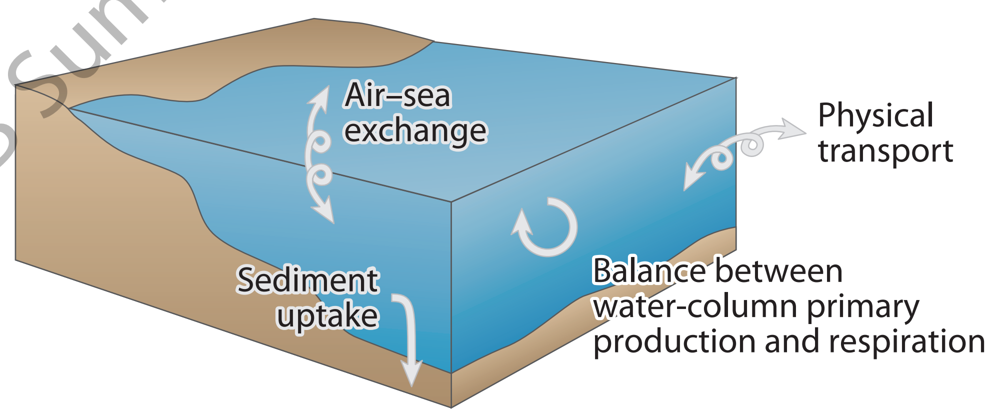
Annual Review of Marine Science

Biogeochemical Controls on Coastal Hypoxia

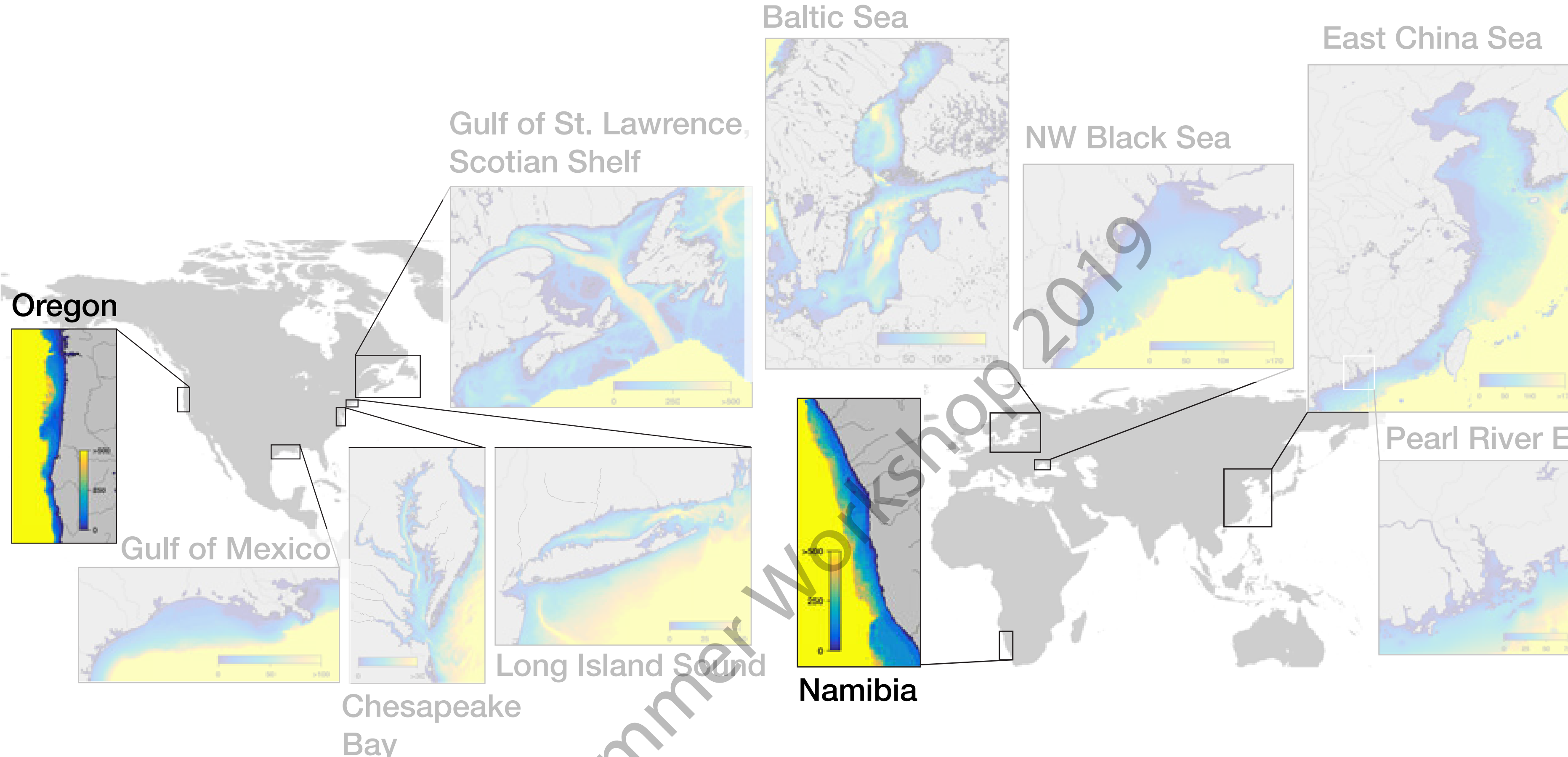
Katja Fennel[1] and Jeremy M. Testa[2]



Despite the substantial differences in these systems, the same processes affect oxygen availability.



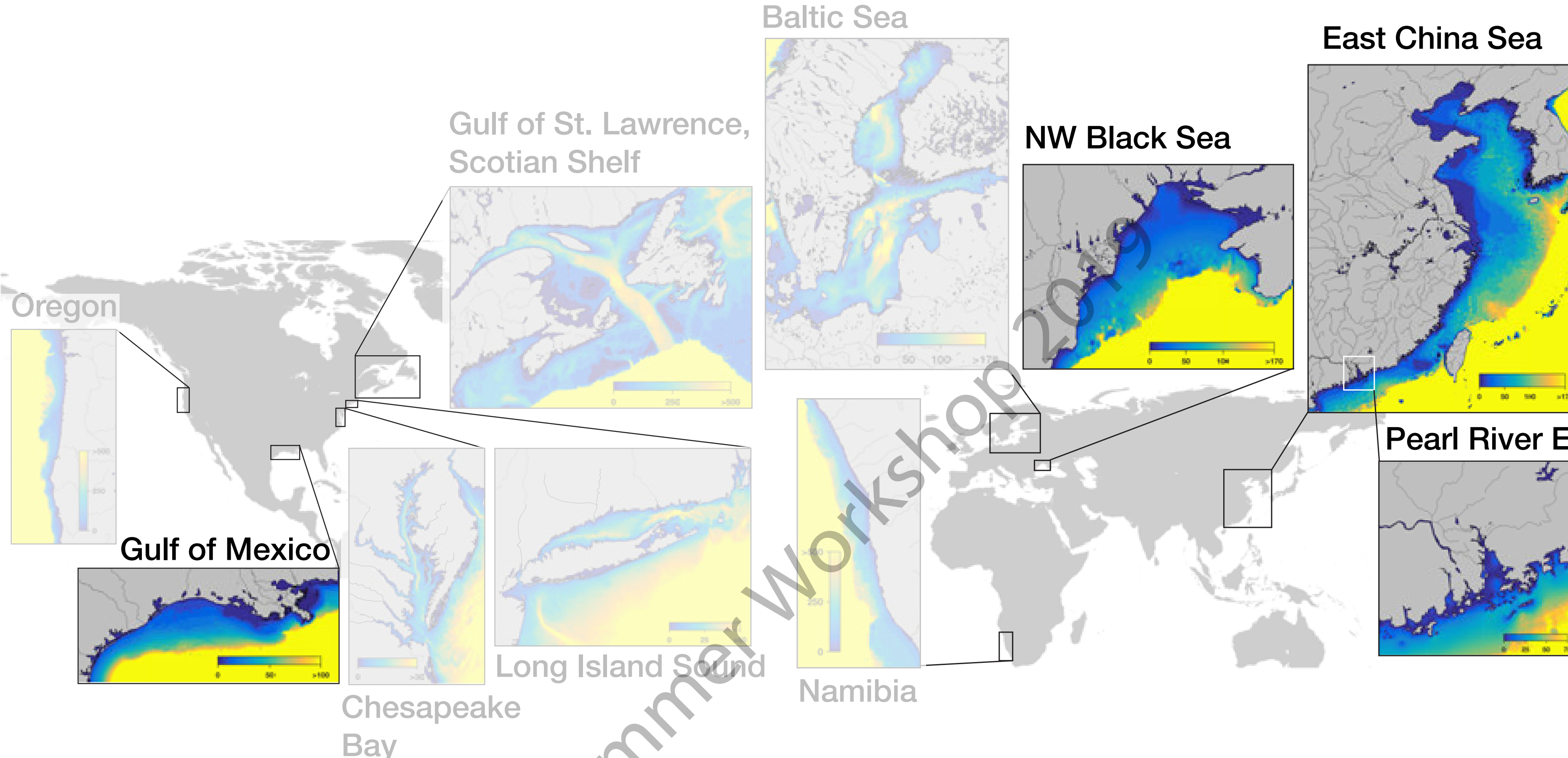
Fennel & Testa, *ARM*



Upwelling shelves Oregon, Namibia

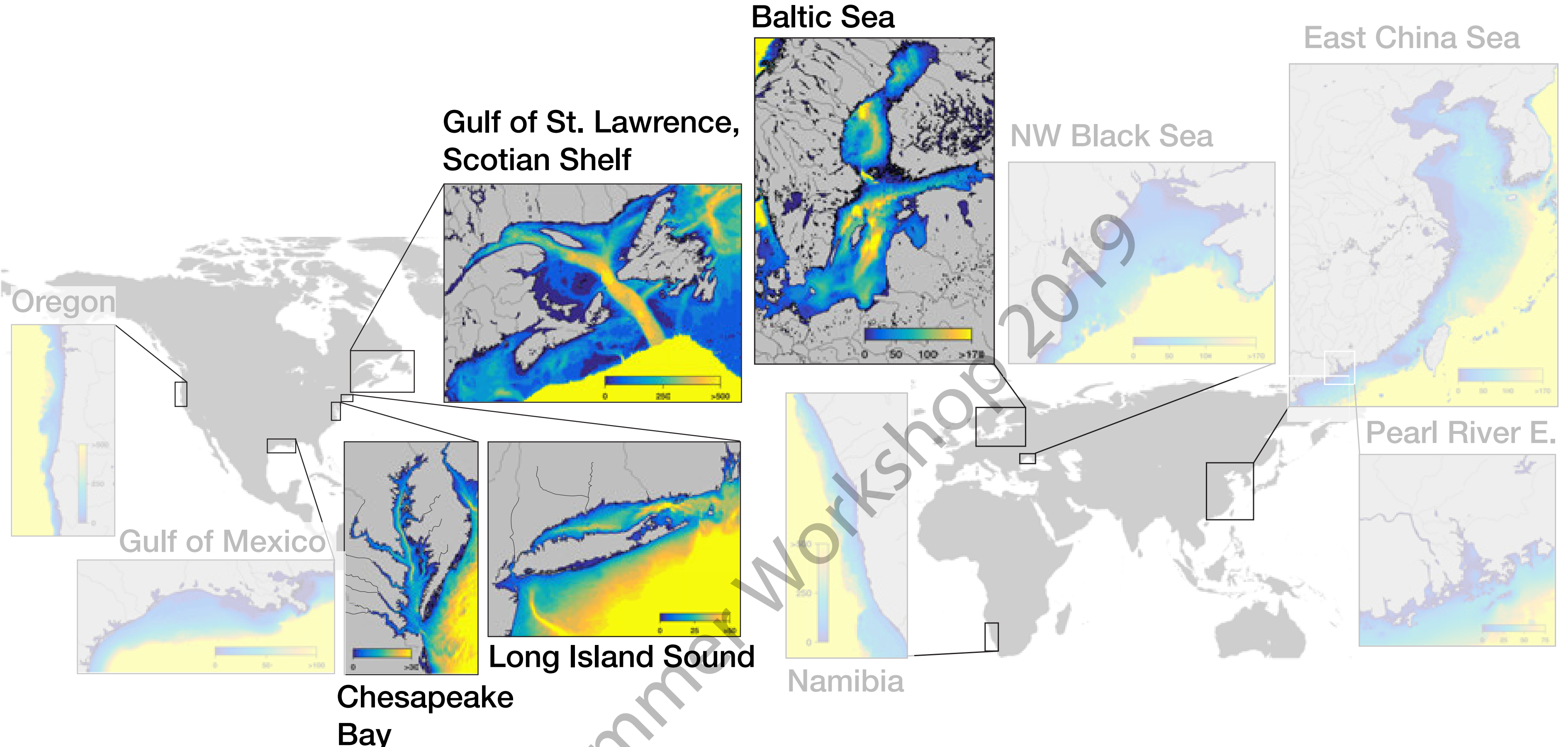
open boundaries,
rivers may be minor,
low oxygen is naturally driven

Fennel & Testa, *ARMS* (2019)



River-dominated shelves & estuaries	Gulf of Mexico, NW Black Sea, East China Sea, Pearl River Estuary	broad shelves, major rivers, low oxygen is anthropogenically driven in combination with climate effects

Fennel & Testa, *ARMS* (2019)

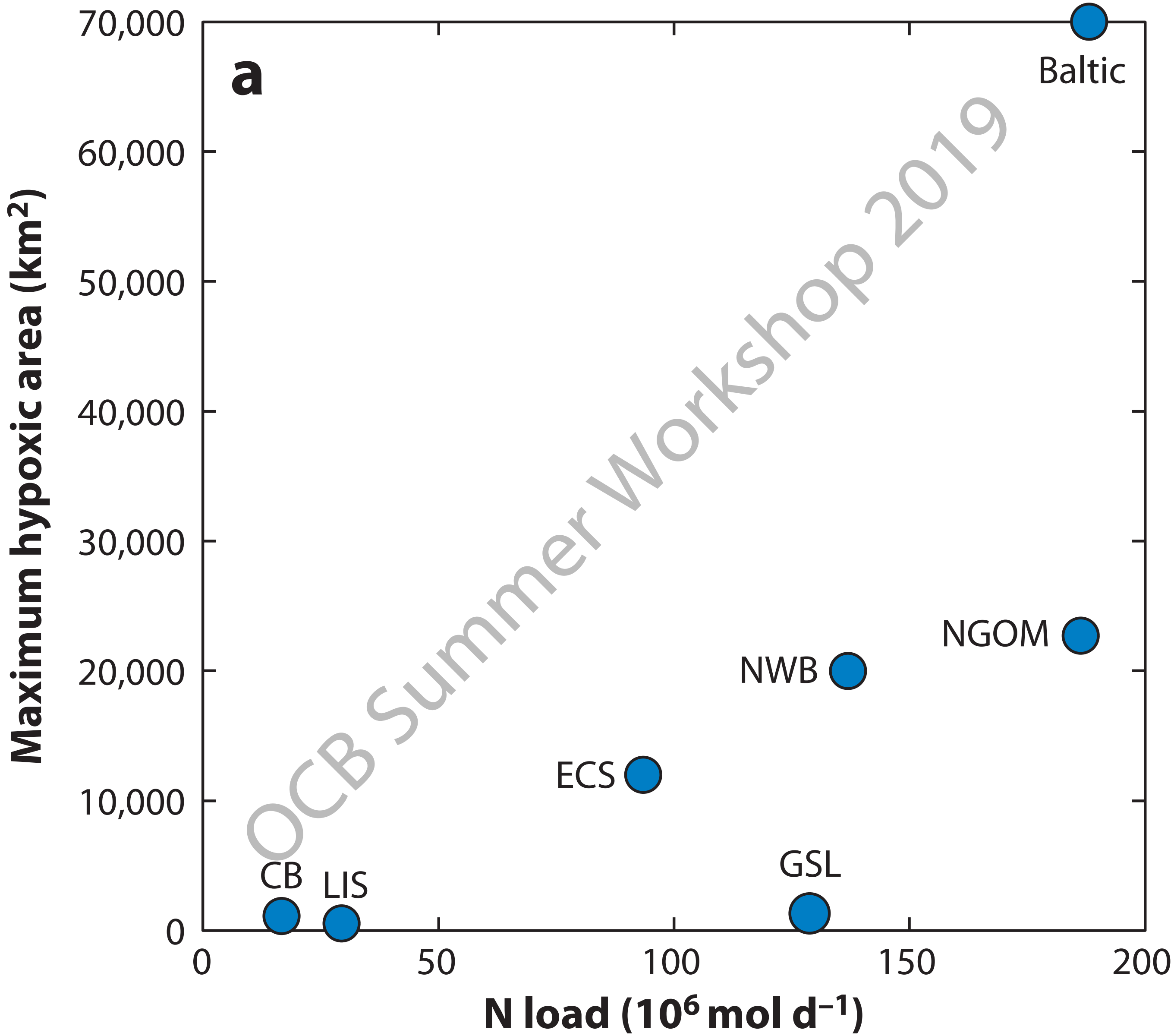


Retentive systems Chesapeake Bay, Long Island Sound, Baltic Sea, Gulf of St. Lawrence & Scotian Shelf

moderate inputs, restricted circulation, anthropogenic influence varies

Fennel & Testa, *ARMS* (2019

Nitrogen Load and Hypoxic Area



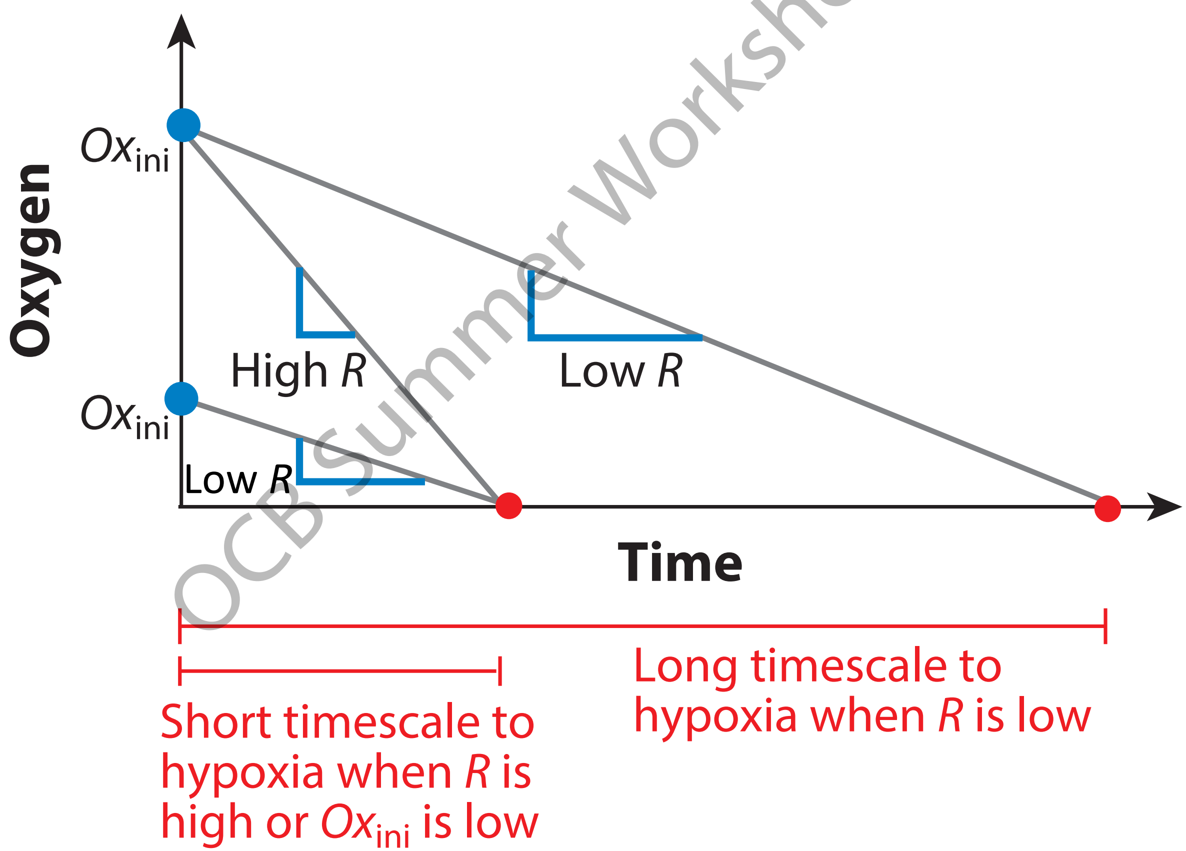
Fennel & Testa, *ARM*

Time scale of hypoxia occurrence (in days)

$$\tau_{hyp} = \frac{Ox_{ini}}{R}$$

initial oxygen concentration (mmol m^{-3})

net oxygen consumption rate (mmol m^{-3} d^{-1})



Fennel & Testa, *ARM*

Time scale of hypoxia occurrence (in days)

$$\tau_{\text{hyp}} = \frac{Ox_{\text{ini}}}{R}$$

initial oxygen concentration (mmol m^{-3})

net oxygen consumption rate (mmol m^{-3} d^{-1})

$$\gamma = \frac{\tau_{\text{hyp}}}{\tau_{\text{res}}}$$

nondimensional number that relates time scale of hypoxia occurrence to residence time

Hypothesized that this number (γ) needs to be *less than 1* for hypoxia to occur.

Fennel & Testa, *ARM*

Table 1 Cross-system comparison of selected estuaries and river-dominated shelves

Chesapeake Bay
Pearl River
Baltic Sea
Long Island Sound
Gulf of St. Lawrence

N Gulf of Mexico
East China Sea
NW Black Sea

Residence time (d)

180
4
3,100
75
730

30
11
150

	Hypoxic-layer thickness	Maximum hypoxic area (mean)	Water-shed area	Discharge (m^3 s^{-1})	N load (10^6 mol d^{-1})	P load (10^6 mol d^{-1})	Resid… tim… (τ_{res})	…diment …xygen …sumption …mol O_2 …$^{-3}$ d^{-1})	Sediment fraction of total consumption (%)	Hypoxia timescale (τ_{hyp}) (d)
Es…										
Ch…			…0[a]	1,100[c]	17[c]	0.39[c]	180	20[f]	11	19
Pe…			…0[h]	10,000[i]	77[h]	0.82[h]	4[h]	66[j]	33	4
Bal…			…00[m]	14,000[n]	190[o]	4.1[o]	3,10…	8[q]	17	600
Lo…			…0[t]	670[u]	29[v]	0.99[v]	75	19[r]	8	20
Gu… L…			…00[z]	15,000[α]	130[β]	1.7[β]	730	9.7[x]	64	1,500
Ri…										
No… M…			…00[z]	17,000[ε]	190[h]	3.6[h]	30	20[θ]	33	15
Eas…			…00[h]	29,000[λ]	93[μ]	1.4[μ]	11	23[ξ]	3	8
No… B…			…00[σ]	8,900[σ]	140[σ]	1.6[σ]	150	…6.8[ρ,χ]	30	89

The characteristics of each system are compiled from the literature sources cited in the footnotes below. For the calculation of the fraction of oxygen consumption by the sediment, the total oxygen consumption is the sum of water-column consumption integrated over the hypoxic layer and sediment oxygen consumption. The definition of the hypoxia timescale is given in Section 2; for this calculation, we used an initial oxygen concentration of 225 mmol O_2 m^{-3}. Abbreviations: N, nitrogen; ND, no data; P, phosphorus.

[a]Kemp et al. 2005; [b]Testa et al. 2014; [c]Q. Zhang et al. 2015; [d]Du & Shen 2016; [e]Smith & Kemp 1995; [f]Boynton et al. 2018; [g]Yin et al. 2004; [h]Rabouille et al. 2008; [i]Cai et al. 2004; [j]Zhang & Li 2010 (modeled); [k]Wulff & Stigebrandt 1989; [l]Carstensen et al. 2014; [m]Wulff et al. 2014; [n]Johansson 2018; [o]Nausch et al. 1999; [p]Pers & Rahm 2000; [q]Noffke et al. 2016; [r]Welsh & Eller 1991; [s]US Environ. Prot. Agency 2017; [t]Wolfe et al. 1991; [u]Gay et al. 2004; [v]J. Donnell, unpublished data; [w]Bricker et al. 2007; [x]Lehmann et al. 2009; [y]Belley et al. 2010; [z]Howarth et al. 1996; [α]Saucier & Chasse 2000; [β]Howarth et al. 1996; [γ]Bourgault et al. 2012; [δ]Fennel et al. 2016; [ε]Natl. Park Serv. 2017; [ζ]K. Fennel, unpublished data; [η]Murrell et al. 2013; [θ]Yu et al. 2015b; [κ]Chen et al. 2007; [λ]Chen et al. 2009; [μ]C.-C. Chen, unpublished data; [ξ]Zhou et al. 2017; [π]Cannaby et al. 2015; [ρ]Capet et al. 2013; [σ]Ludwig et al. 2009 (estimated for the Danube, Dnieper, and Dniester); [φ]A. Capet, unpublished data; [χ]Capet et al. 2016.

Fennel & Testa, *ARM*

Table 1 Cross-system comparison of selected estuaries and river-dominated shelves

	Water-shed area	Discharge (m^3 s^{-1})	N load (10^6 mol d^{-1})	P load (10^6 mol d^{-1})	Residence time (τ_{res}) (d)	Water-column oxygen consumption (mmol O_2 m^{-3} d^{-1})	Sedim oxyge consump (mmol m^{-3} d	poxia escale (yp) (d)
Es								
Ch	0[a]	1,100[c]	17[c]	0.39[c]	180[d]	11[e]	20[f]	19
Pe	0[h]	10,000[i]	77[h]	0.82[h]	4[h]	35[j]	66[j]	4
Bal	00[m]	14,000[n]	190[o]	4.1[o]	3,100[k]	0.3[p]	8[q]	600
Lo	0[t]	670[u]	29[v]	0.99[v]	75[w]	9.6[r]	19[r]	20
Gu L	00[z]	15,000[α]	130[β]	1.7[β]	730[γ]	0.05[x]	9.7[x]	1,500
Ri								
No M	00[z]	17,000[ε]	190[h]	3.6[h]	30[ζ]	10.0[η]	20[θ]	15
Eas	00[h]	29,000[λ]	93[μ]	1.4[μ]	11[h]	28[λ]	23[ξ]	8
No B	00[σ]	8,900[σ]	140[σ]	1.6[σ]	150[ρ]	1.8[φ]	6.8[ρ]	89

Chesapeake Bay
Pearl River
Baltic Sea
Long Island Sound
Gulf of St. Lawrence

N Gulf of Mexico
East China Sea
NW Black Sea

Hypoxia time scale (d)

19
4
600
20
1,500

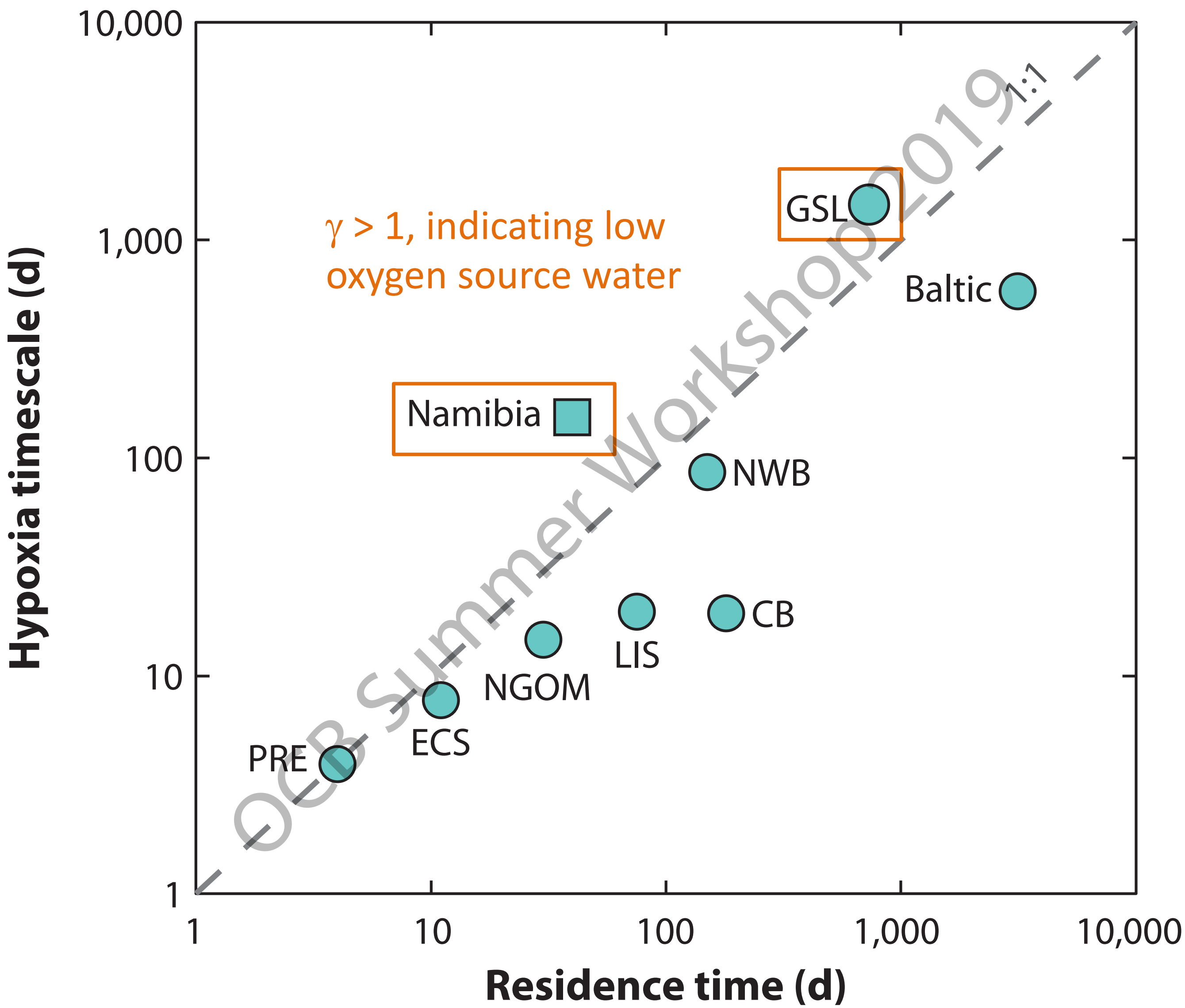
15
8
89

The characteristics of each system are compiled from the literature sources cited in the footnotes below. For the calculation of the fraction of oxygen consumption by the sediment, … sum of water-column consumption integrated over the hypoxic layer and sediment oxygen consumption. The definition of the hypoxia timescale is given in Section 2; for this calculation, … ion of 225 mmol O_2 m^{-3}. Abbreviations: N, nitrogen; ND, no data; P, phosphorus.

[a]Kemp et al. 2005; [b]Testa et al. 2014; [c]Q. Zhang et al. 2015; [d]Du & Shen 2016; [e]Smith & Kemp 1995; [f]Boynton et al. 2018; [g]Yin et al. 2004; [h]Rabouille et al. 2008; [i]Cai et al. 2004; [j]Zhang & Li 2010 (modeled); [k]Wulff & Stigebrandt 1989; [l]Carstensen et al. 2014; [m]Wulff et al. 2014; [n]Johansson 2018; [o]Nausch et al. 1999; [p]Pers & Rahm 2000; [q]Noffke et al. 2016; [r]Welsh & Eller 1991; [s]US Environ. Prot. Agency 2017; [t]Wolfe et al. 1991; [u]Gay et al. 2004; [v]J. Donnell, unpublished data; [w]Bricker et al. 2007; [x]Lehmann et al. 2009; [y]Belley et al. 2010; [z]Howarth et al. 1996; [α]Saucier & Chasse 2000; [β]Howarth et al. 1996; [γ]Bourgault et al. 2012; [δ]Fennel et al. 2016; [ε]Natl. Park Serv. 2017; [ζ]K. Fennel, unpublished data; [η]Murrell et al. 2013; [θ]Yu et al. 2015b; [κ]Chen et al. 2007; [λ]Chen et al. 2009; [μ]C.-C. Chen, unpublished data; [ξ]Zhou et al. 2017; [π]Cannaby et al. 2015; [ρ]Capet et al. 2013; [σ]Ludwig et al. 2009 (estimated for the Danube, Dnieper, and Dniester); [φ]A. Capet, unpublished data; [χ]Capet et al. 2016.

Fennel & Testa, *ARM*

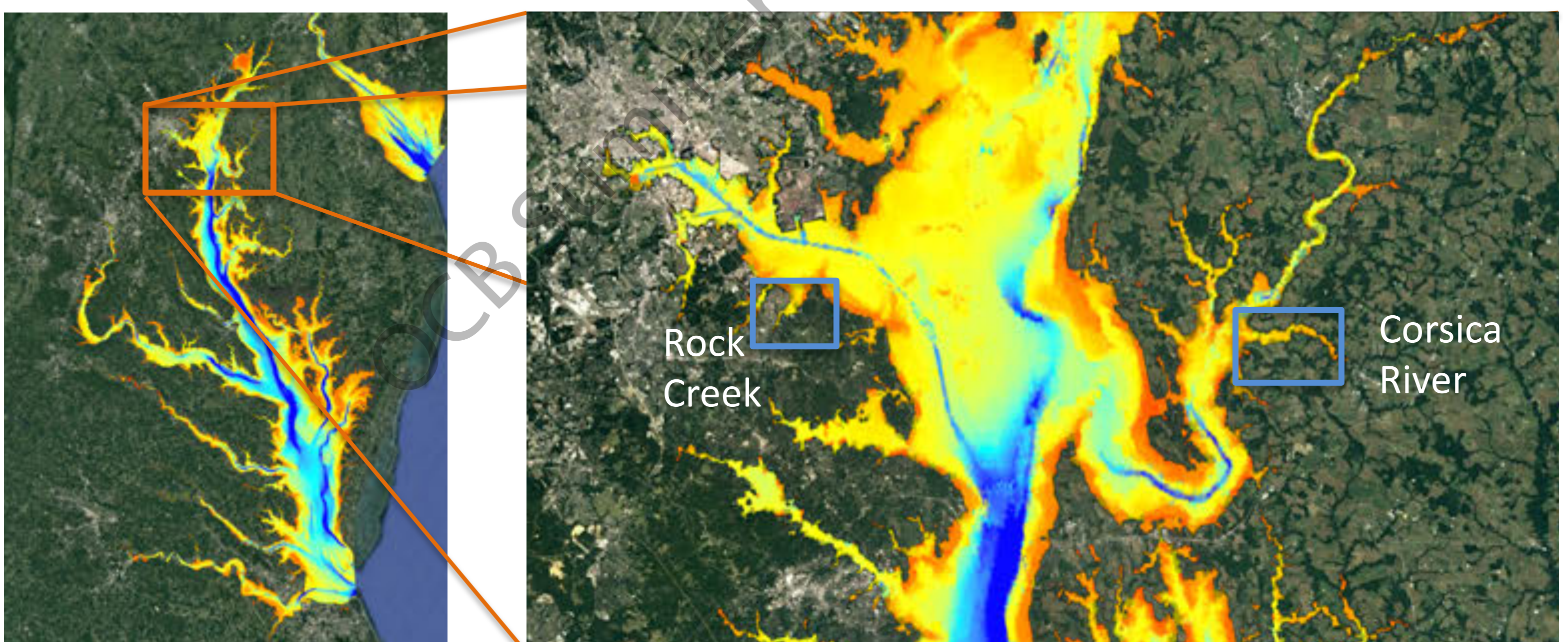
For Most Hypoxic Systems, γ <1



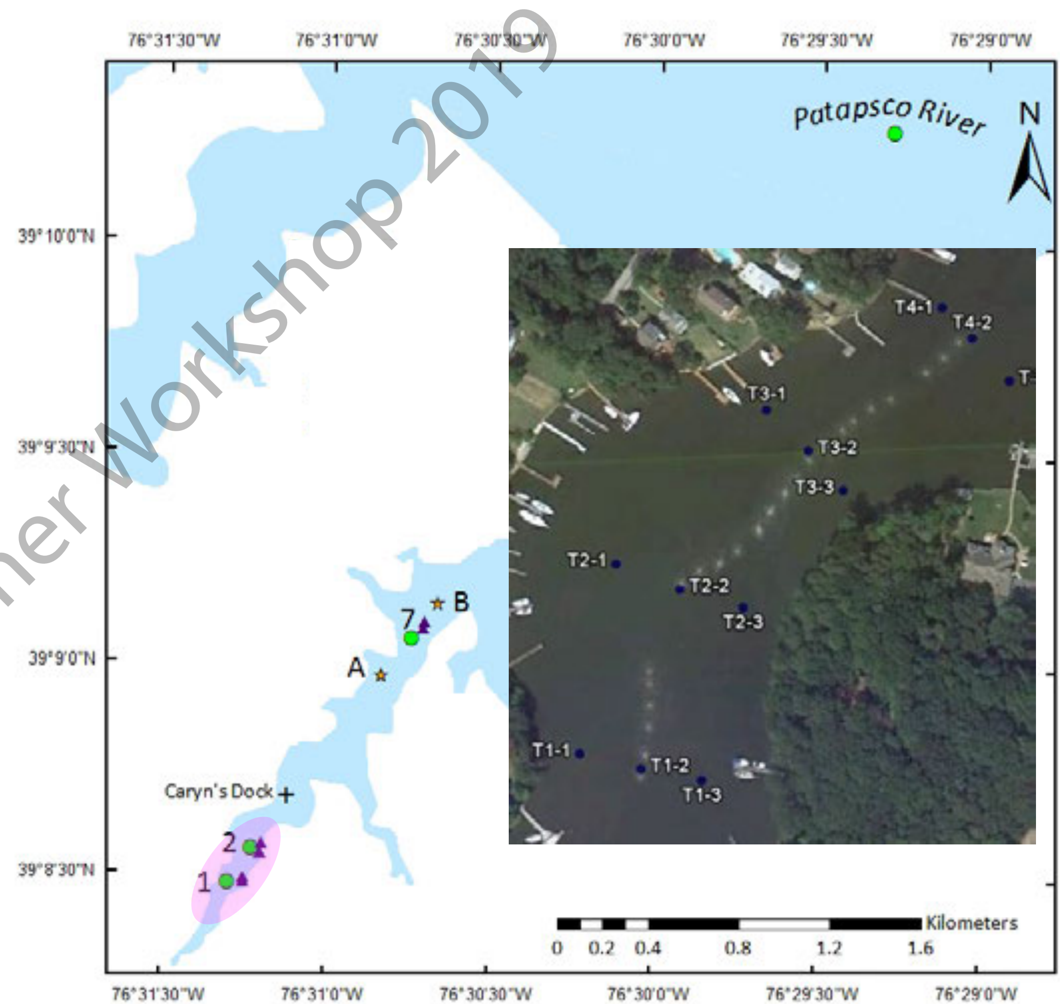
Fennel & Testa, *ARM*

What Can we Learn from Smaller Time and Space Scales?

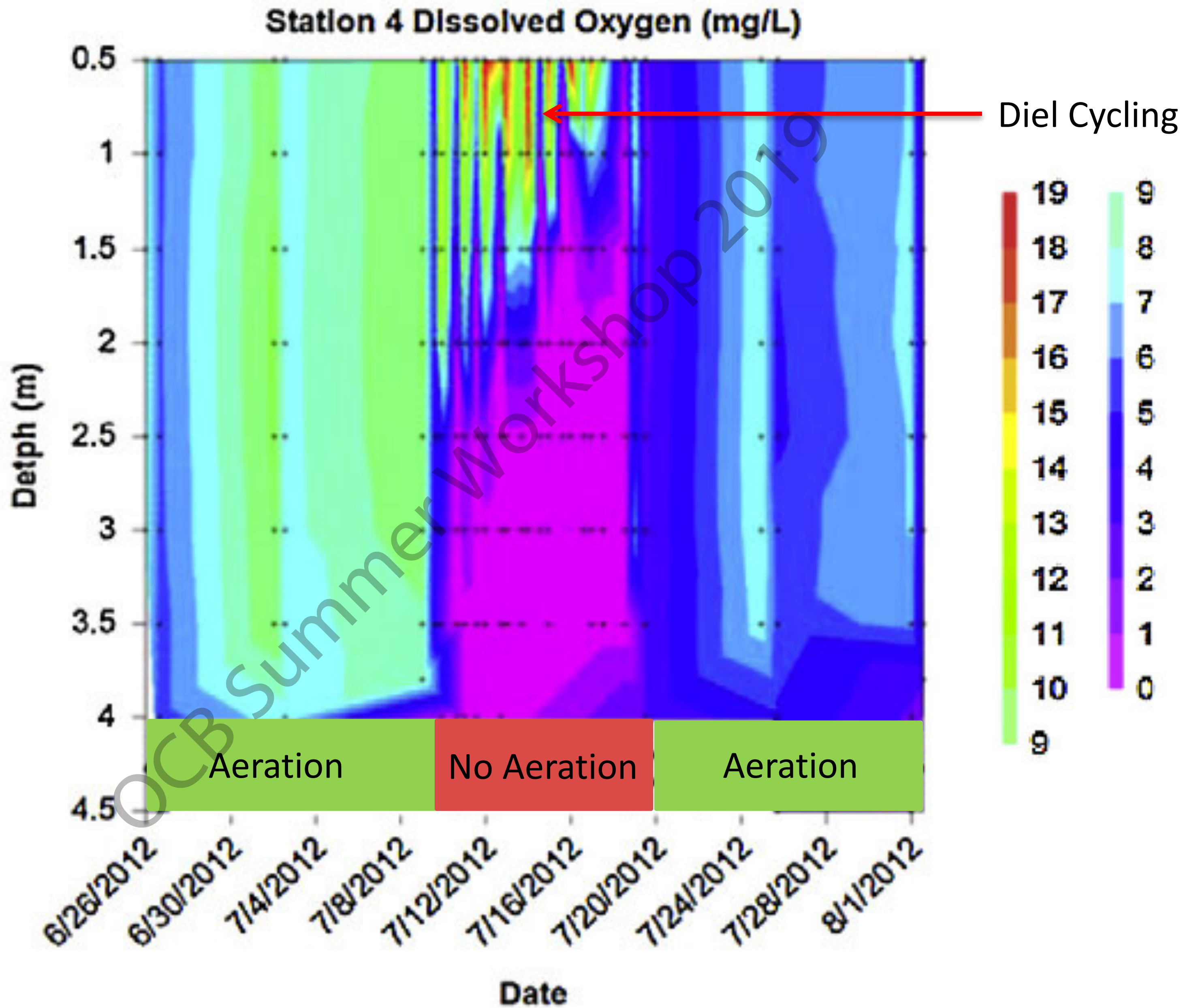
	Corsica River Estuary, MD	Rock Creek, MD
Depth (m)	1	2-3
~Area Hypoxic (km^2)	4	0.5
Chlorophyll (μg/L)	80 to >150	50 to >300
Observed τ_{hyp} (days)	**1-2**	**1-5**



Rock Creek, MD: A Highly-Eutrophic Creek Managed by Aeration

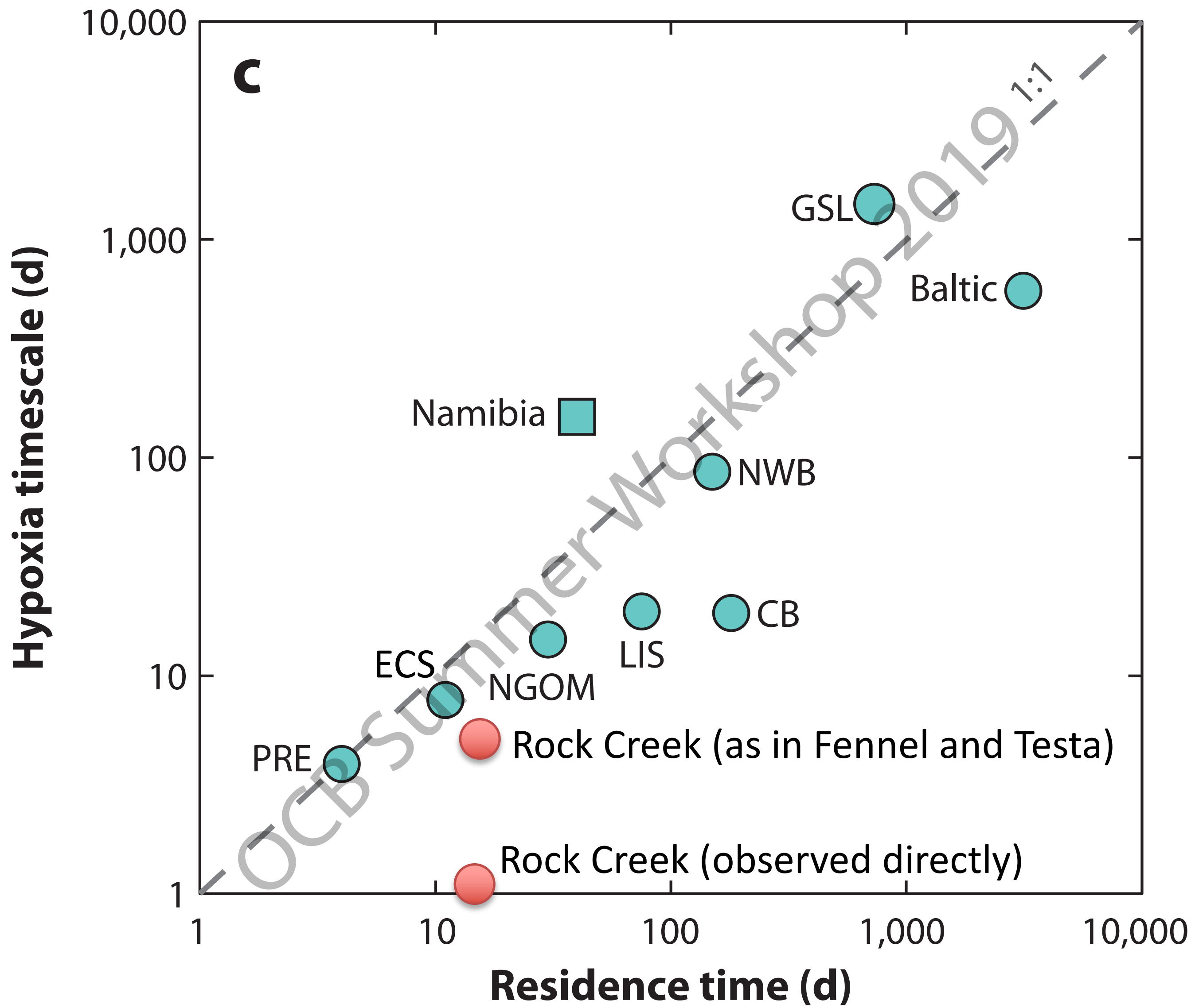


Anoxia Upon Experimental Shutdown of Aerators



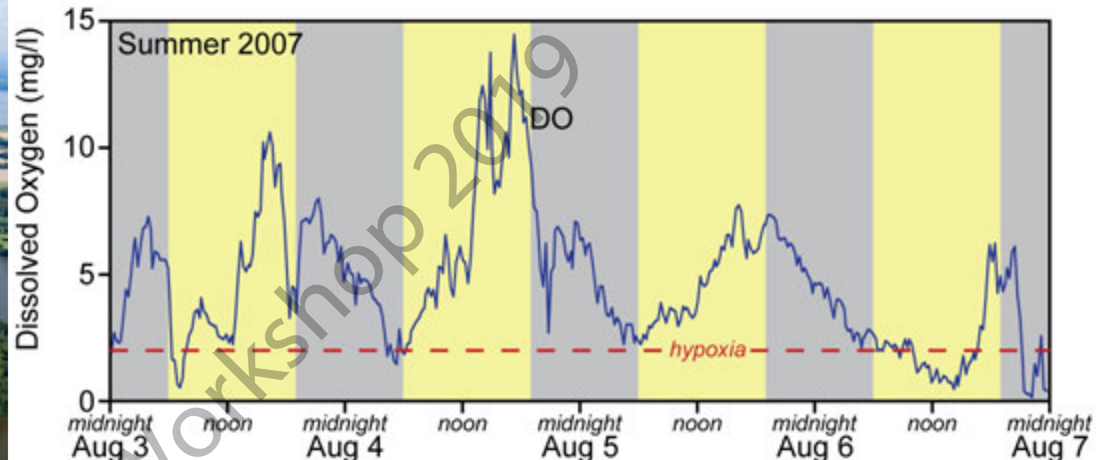
Harris et al. 2015

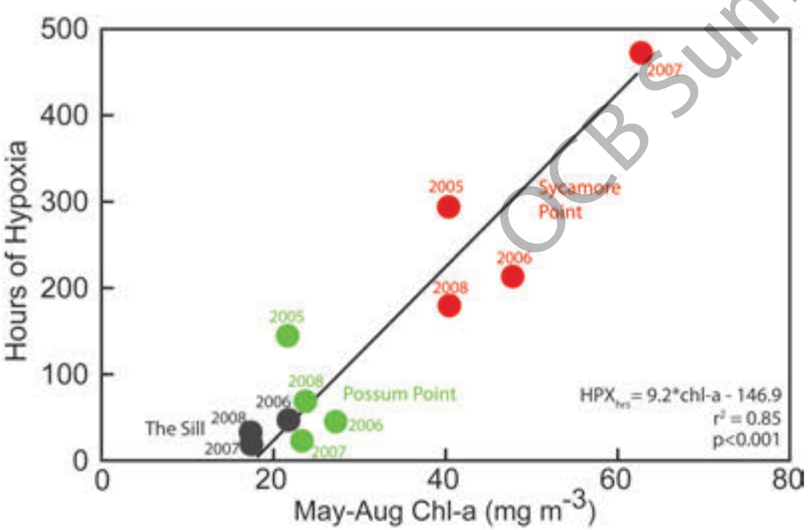
γ <<1 for Rock Creek, Less Than Predicted

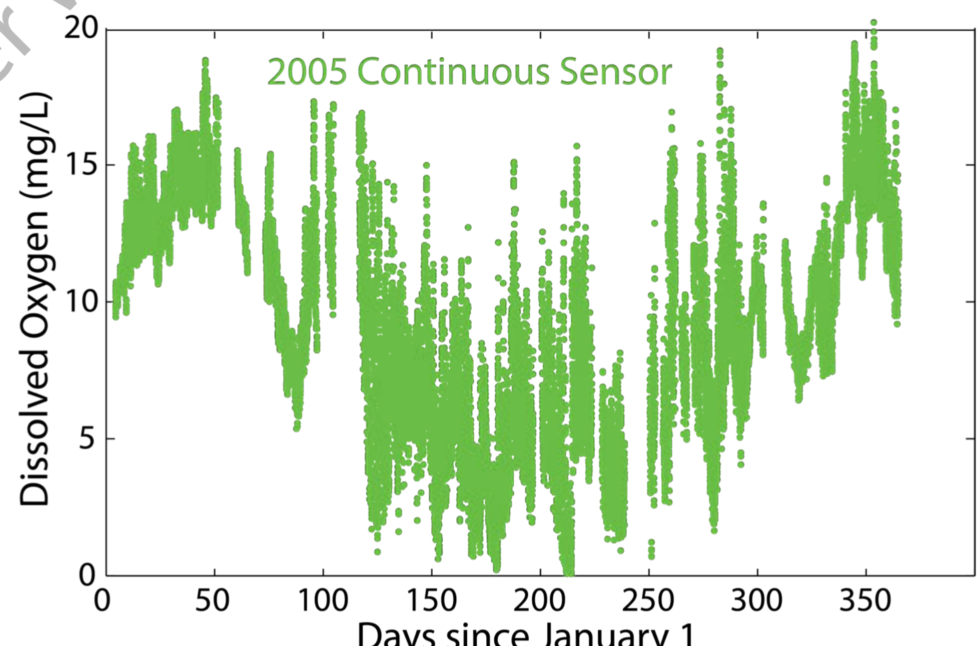


Corsica River Estuary, MD: A Highly-Eutrophic Creek with Diel Cycling Hypoxia

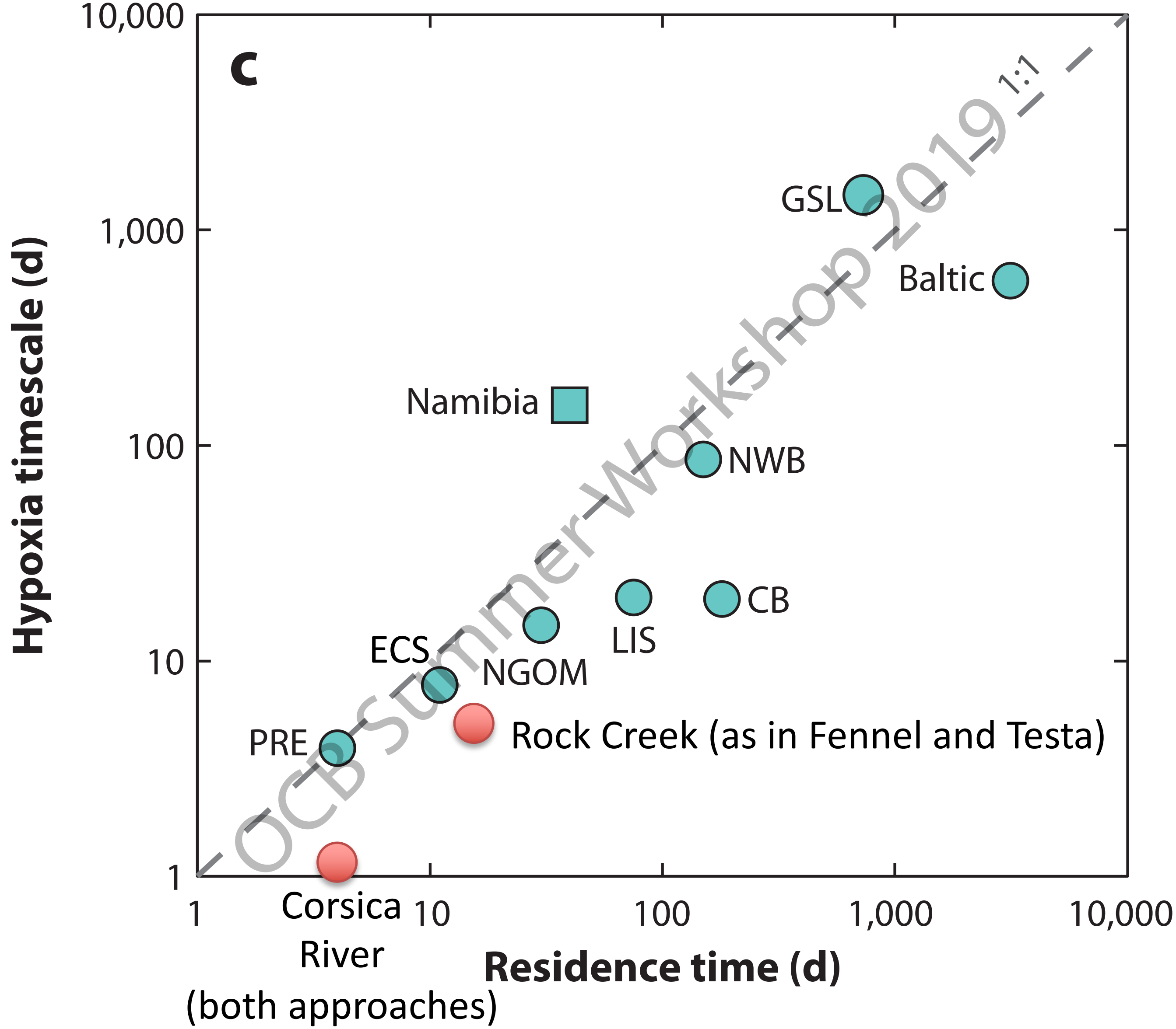
Photo credit: Will Parsons, Chesapeake Bay Program







γ <<1 for Eutrophic, Shallow sites



Fennel & Testa, *ARM*

Summary

Great diversity among coastal systems experiencing hypoxia. Same processes at play but relative importance varies.

Even at low rates of oxygen consumption hypoxia can occur if residence time is long or source water is oxygen-poor.

Ratio of hypoxia time scale and residence time provides a framework for cross-system comparisons $\gamma = \frac{\tau_{\mathrm{hyp}}}{\tau_{\mathrm{res}}}$

In river-dominated systems hypoxic zone size scales with nutrient load.

Very shallow and productive systems develop hypoxia at the timescale of a few days. These types of systems are likely common in eutrophic systems.
Future increases in temperature should increase τ_{hyp}, but other climatic changes relevant

Thank You