Blue carbon sequestration in the context of estuarine fish habitat restoration

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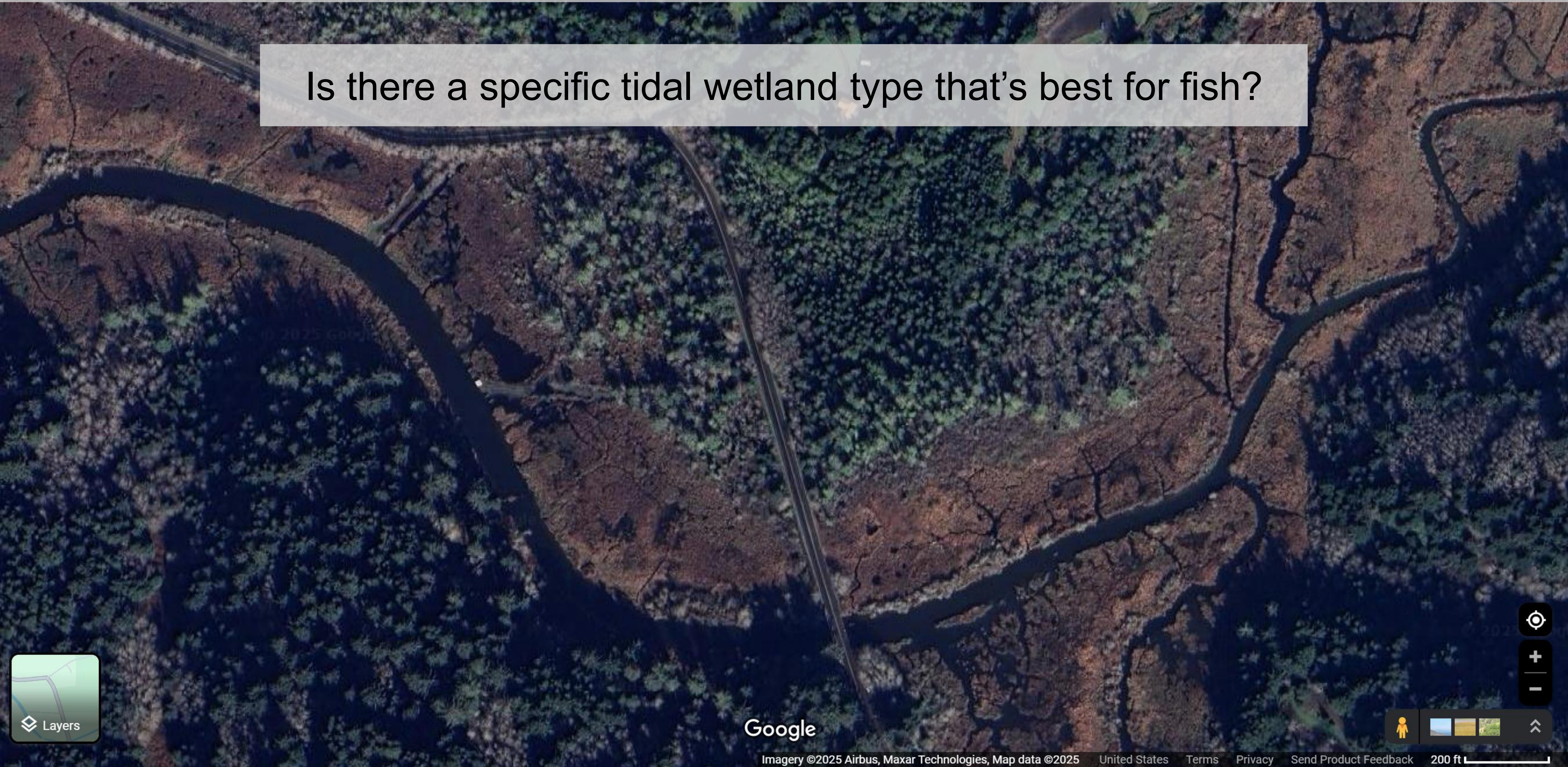
Roadmap

1. Fish habitat, carbon functions, and tidal wetland types
2. Sediment accretion and natural depositional processes
3. Salinity, methane and climate benefits
4. Restoration practices for fish, carbon and sea level rise resilience

Fish habitat functions and tidal wetland types

Is there a specific tidal wetland type that's best for fish?



Vegetated tidal wetland types (vegetation classes)

Lower intertidal:

- *Seagrasses*
- *Algae beds*
- *Tide flats*

Seagrass photo: Partnership for Coastal Watersheds

Upper intertidal:

Tidal marsh (herbaceous)

- Low marsh

- High marsh

Tidal swamp (woody-dominated)

- Forested tidal swamp

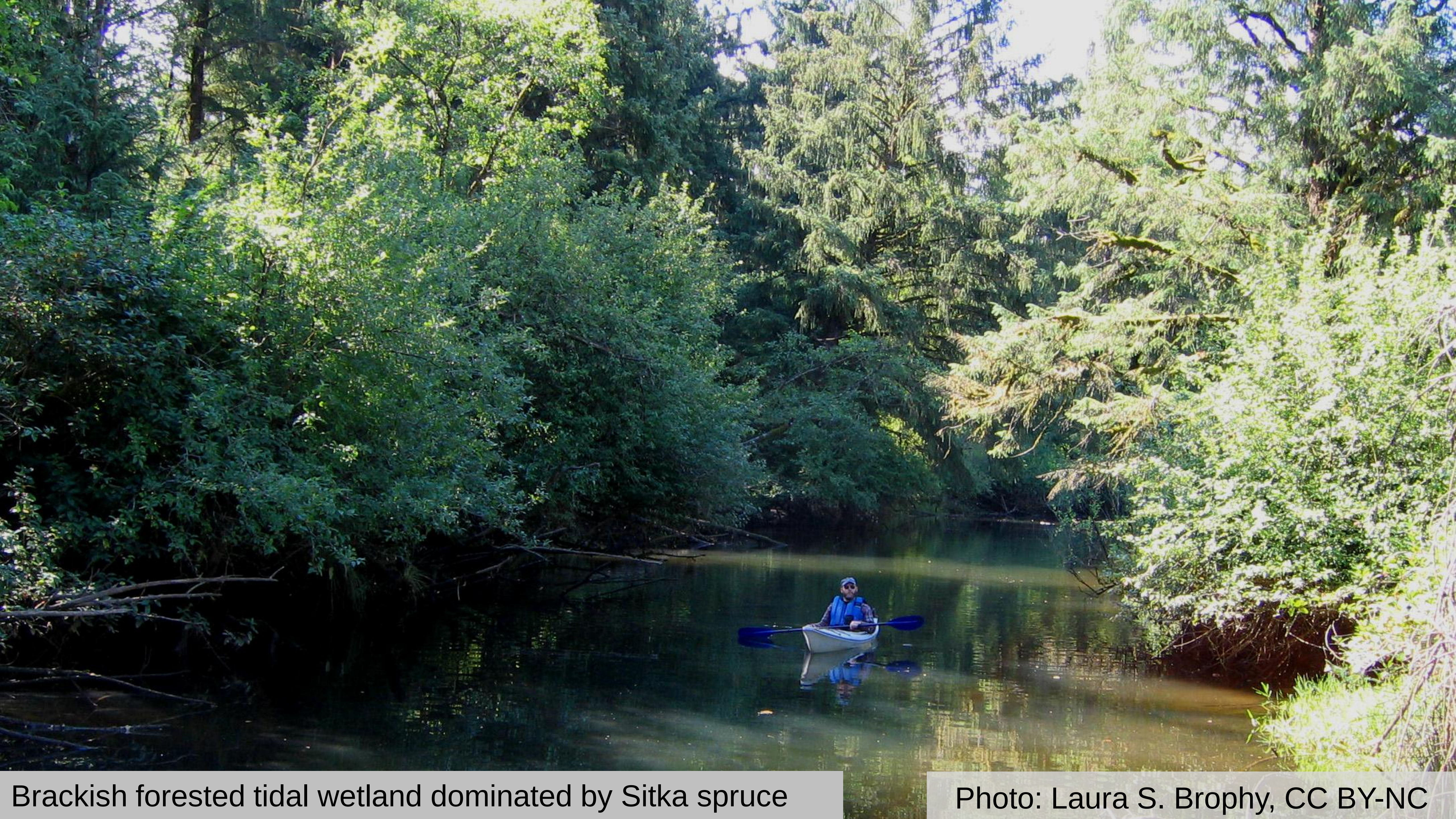
- Shrub tidal swamp

PNW brackish-tolerant Sitka spruce tidal wetlands

Typical dominants:
Trees: Sitka spruce (*Picea sitchensis*)
Shrubs: Pacific crabapple (*Malus fusca*), black twinberry (*Lonicera involucrata*).

Photo: Doug Firstbrook

Brackish forested tidal wetland dominated by Sitka spruce

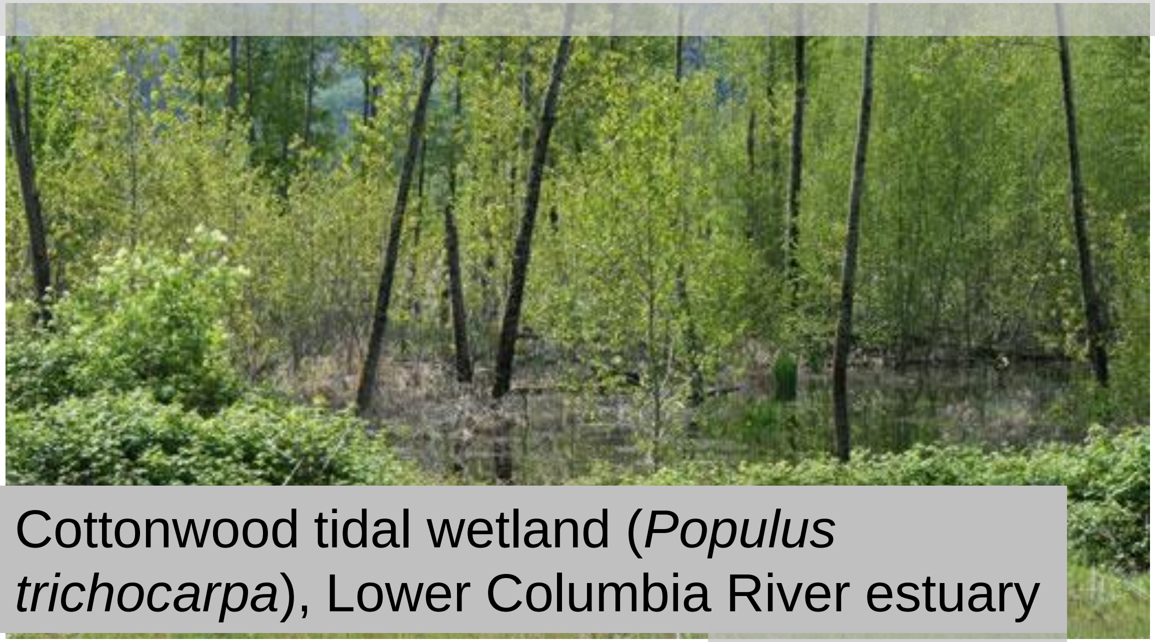


Brackish forested tidal wetland dominated by Sitka spruce

Photo: Laura S. Brophy, CC BY-NC

Brackish forested tidal wetland dominated by Sitka spruce

PNW freshwater forested tidal wetlands – hardwood-dominated



Cottonwood tidal wetland (*Populus trichocarpa*), Lower Columbia River estuary

Photo: USFWS

Oregon ash tidal wetland (*Fraxinus latifolia*), Lower Columbia River estuary

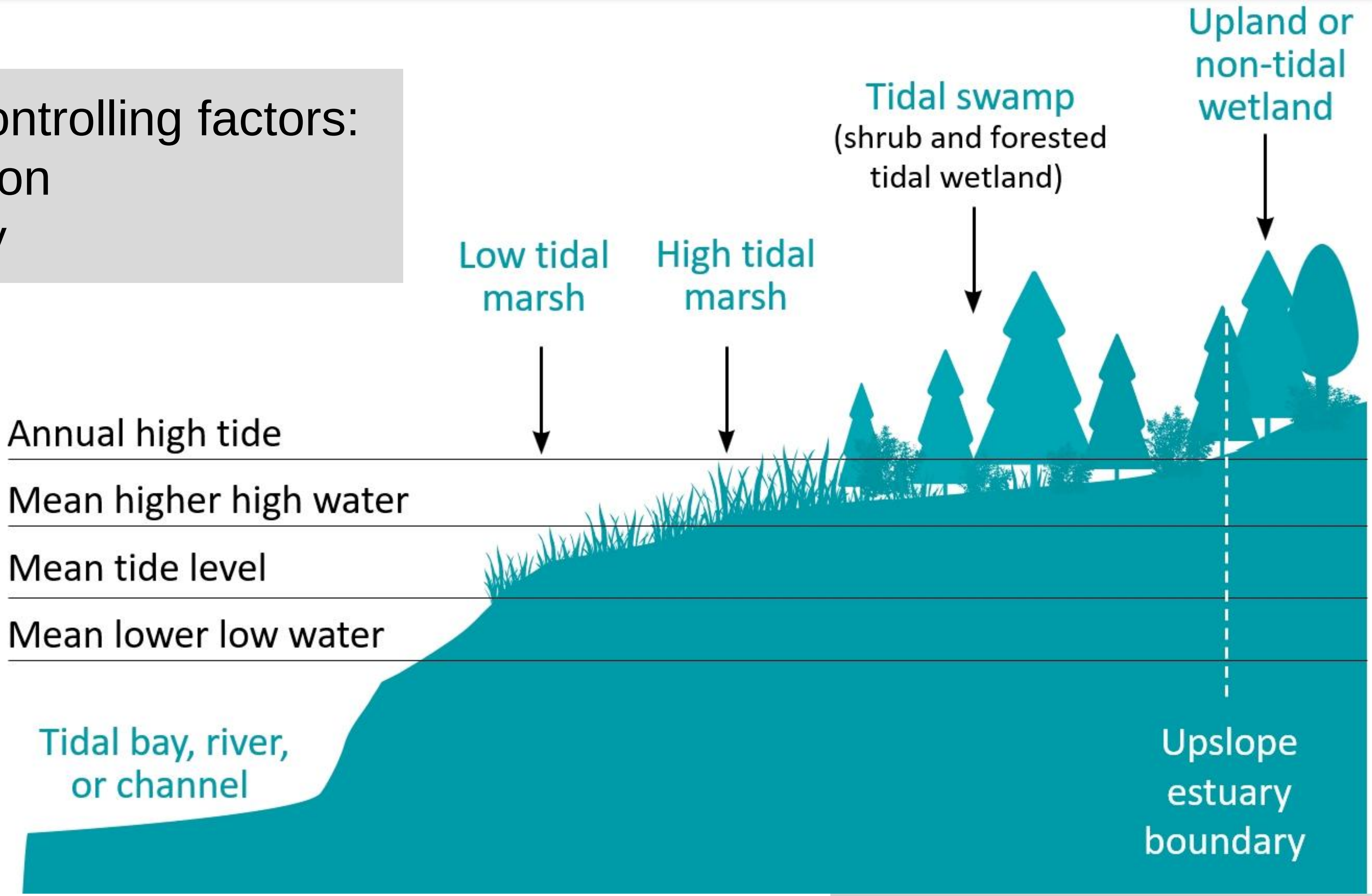
Photo: Laura S. Brophy, CC BY-NC

Red alder tidal wetland (*Alnus rubra*), Nisqually estuary

Photo: Laura S. Brophy, CC BY-NC

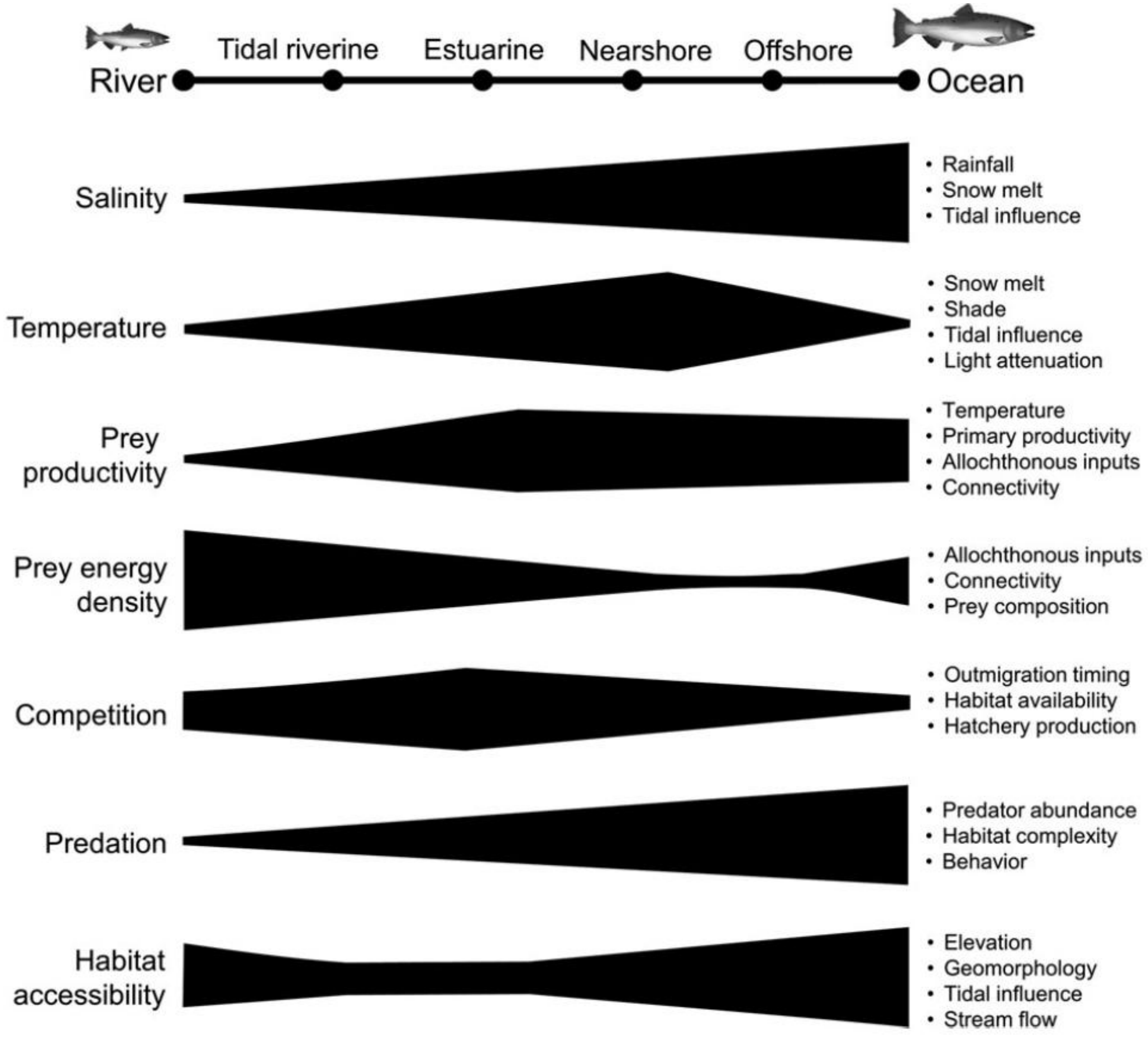
Distribution of PNW tidal wetland types

Primary controlling factors:
- Elevation
- Salinity



Fish habitat functions by estuary habitat

Functional characteristics



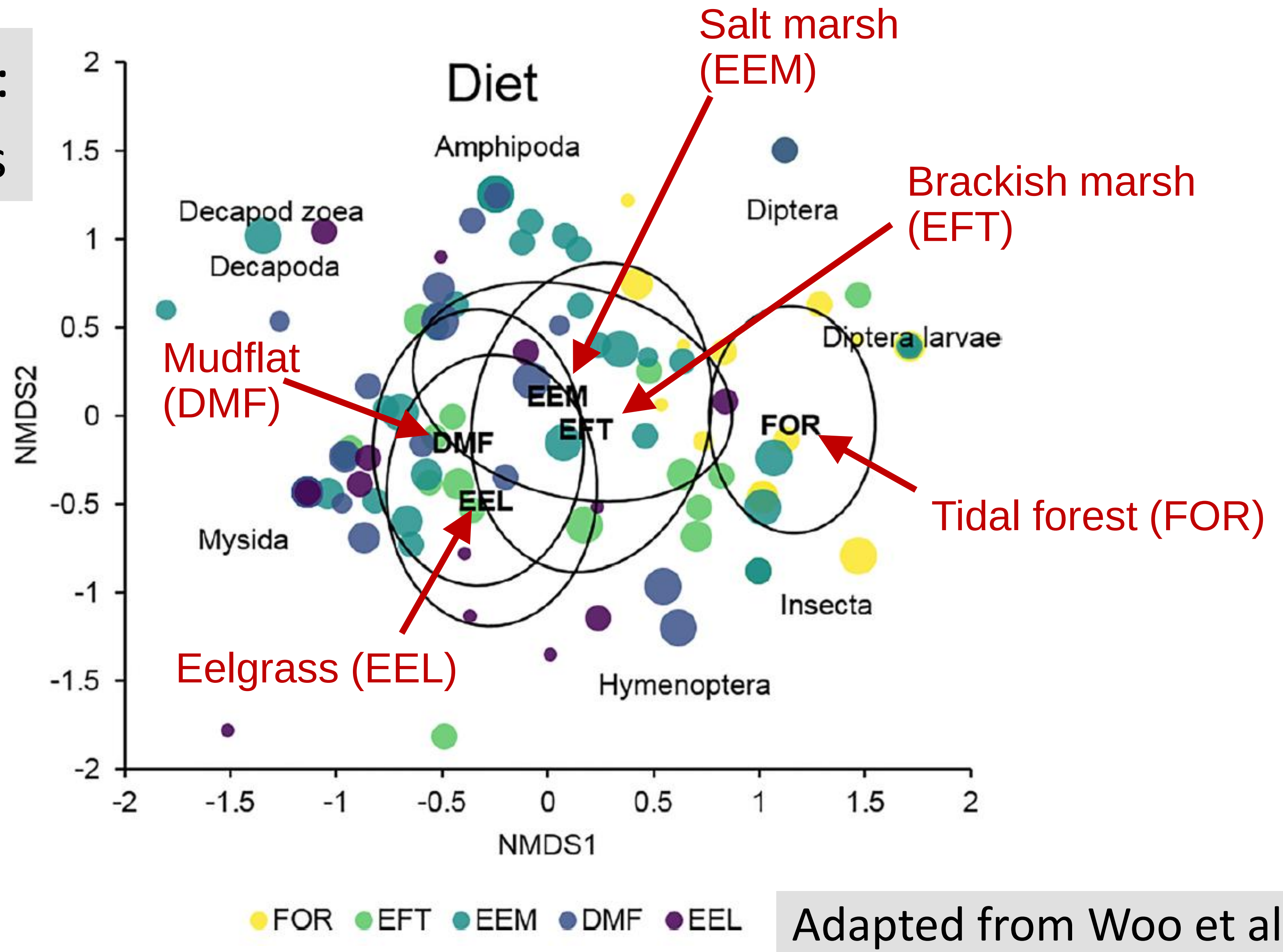
Physical and biological drivers

"No single habitat provides maximal benefits"

Source: Davis et al. 2019

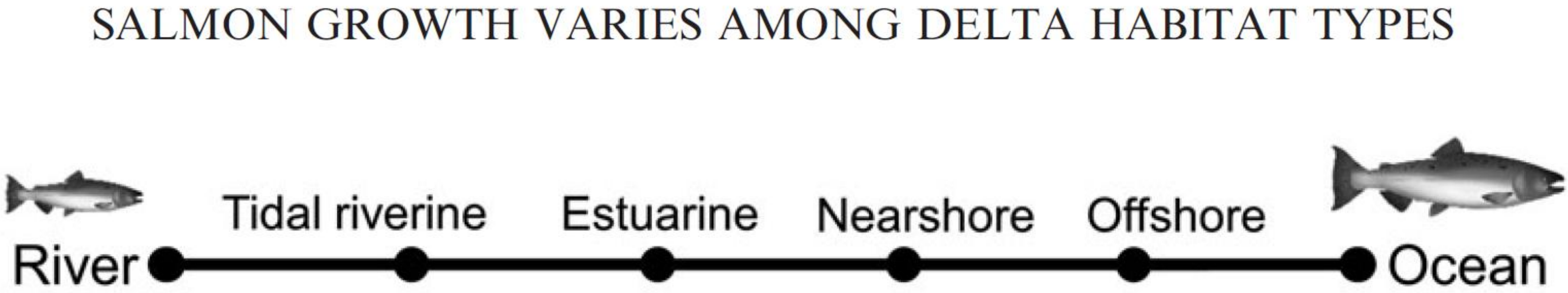
Fish diet varies across habitat types

Nisqually estuary, WA:
Juvenile Chinook diets



Adapted from Woo et al. (2019)

Forested tidal wetlands offer high salmon growth potential



Tidal forests provided higher-quality food and higher modeled growth potential for young salmon, compared to other estuary habitats.

Figure and paraphrased text from Davis et al. 2019

Fish habitat functions and tidal wetland types

Greene et al. (2021) modeled juvenile Chinook salmon growth potential in three habitat types across Puget Sound tidal deltas…

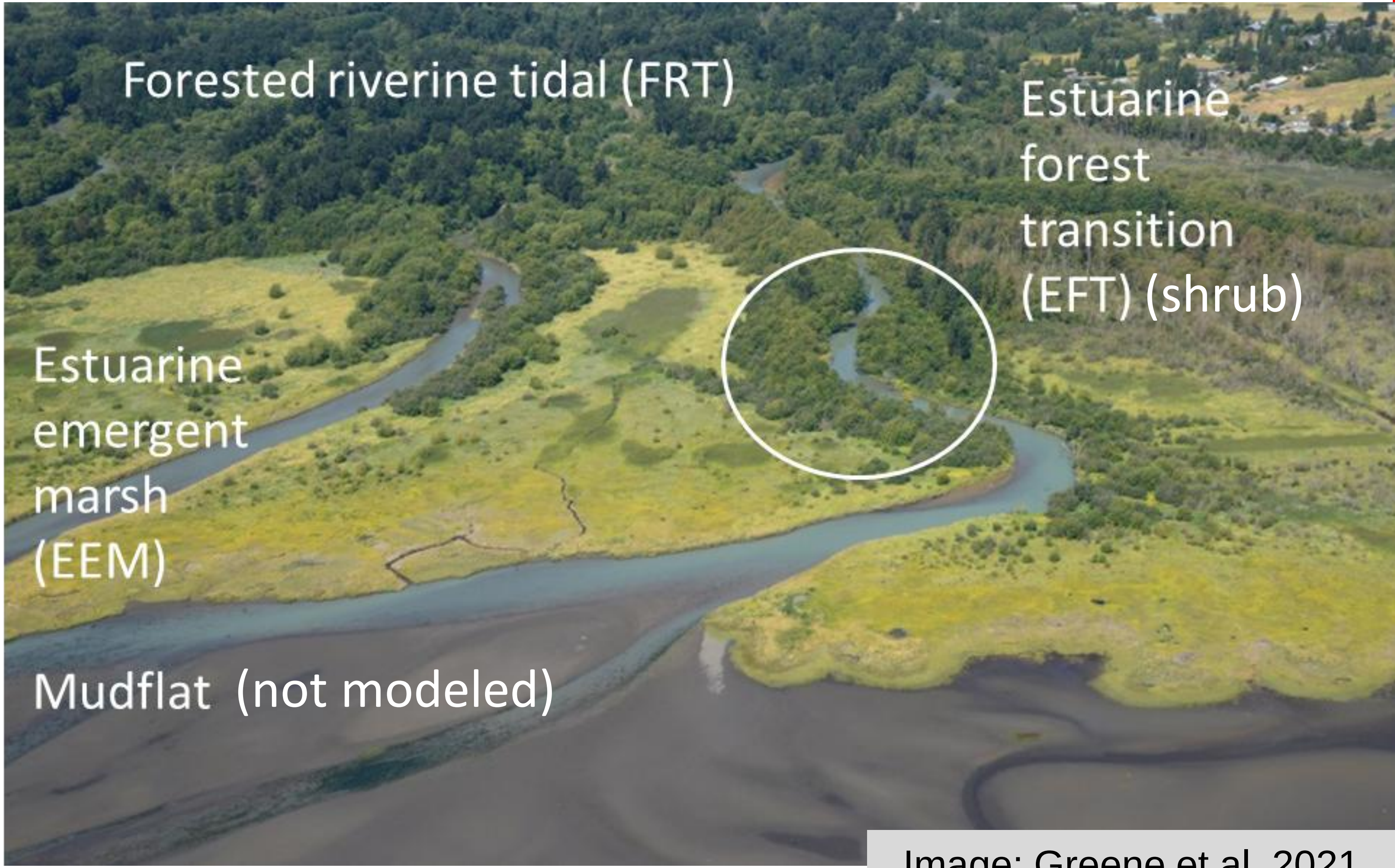
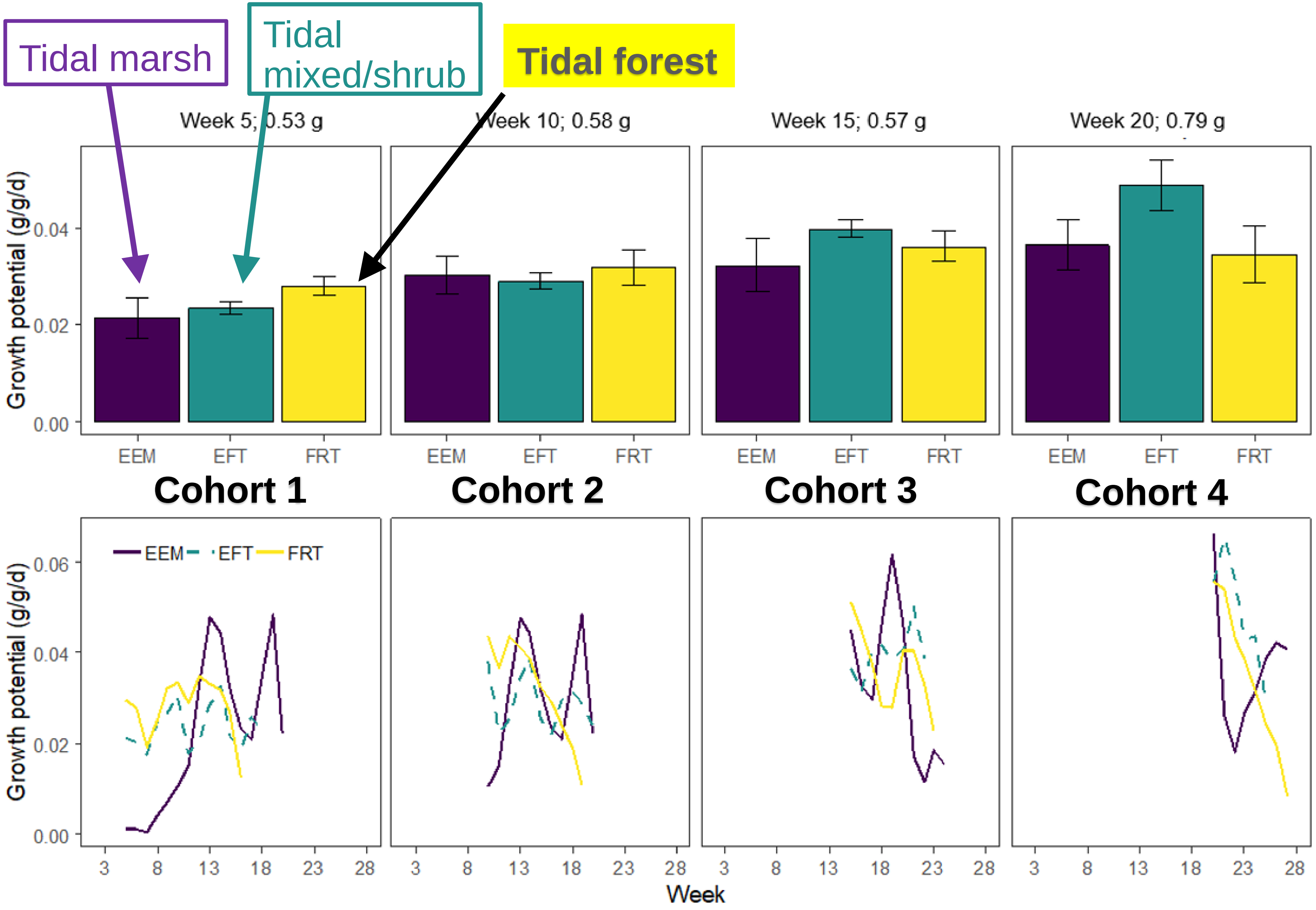


Image: Greene et al. 2021

Modeled juvenile Chinook salmon growth potential



Source: Greene et al. 2021

Fish habitat functions and tidal wetland types

Greene et al. 2021 conclusions:

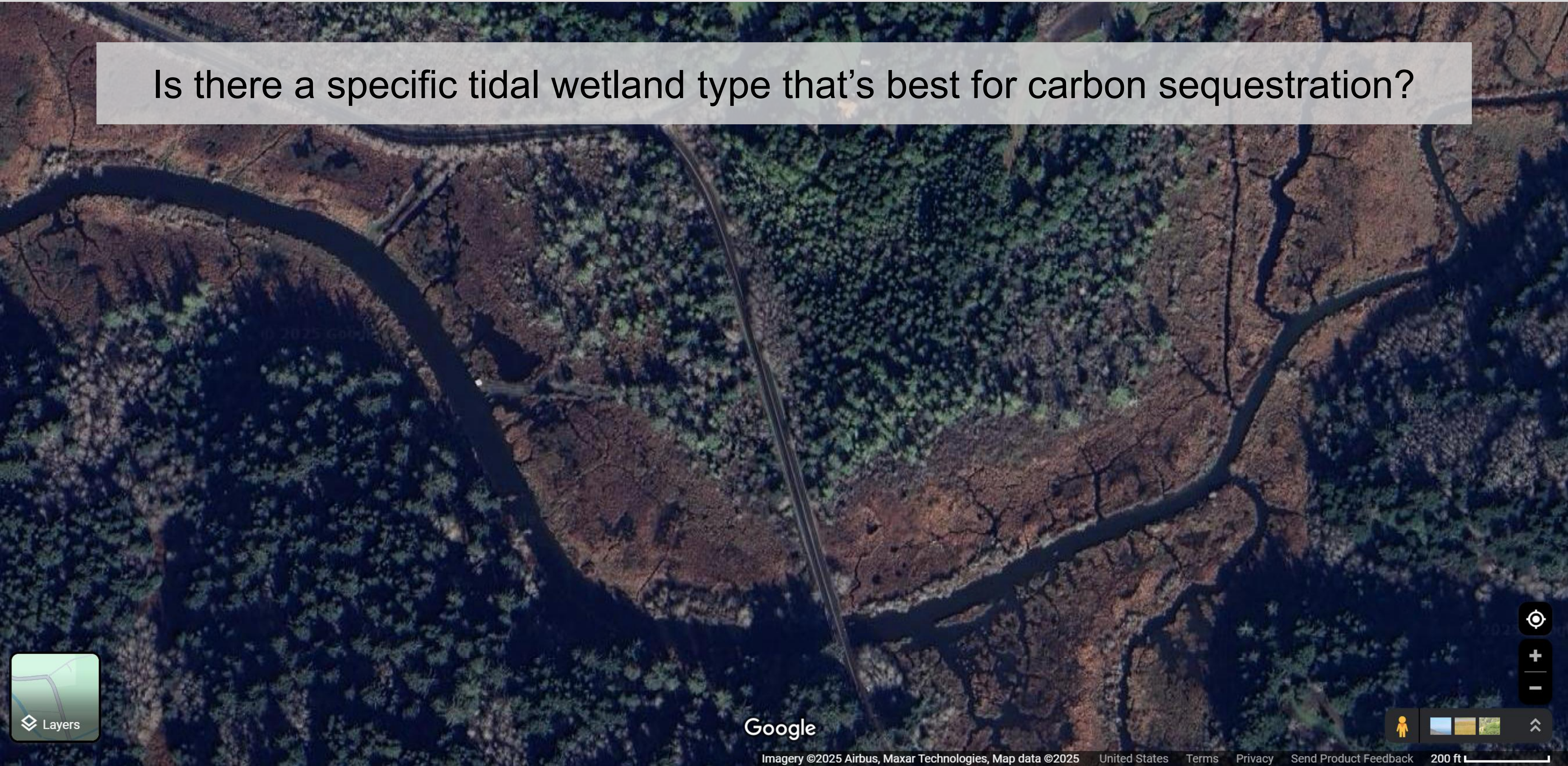
- Habitat diversity is important for maximizing juvenile Chinook salmon growth.
- Restoration planning should focus on habitat diversity as well as capacity, to support Chinook population recovery and resilience.

Source: Greene et al. 2021

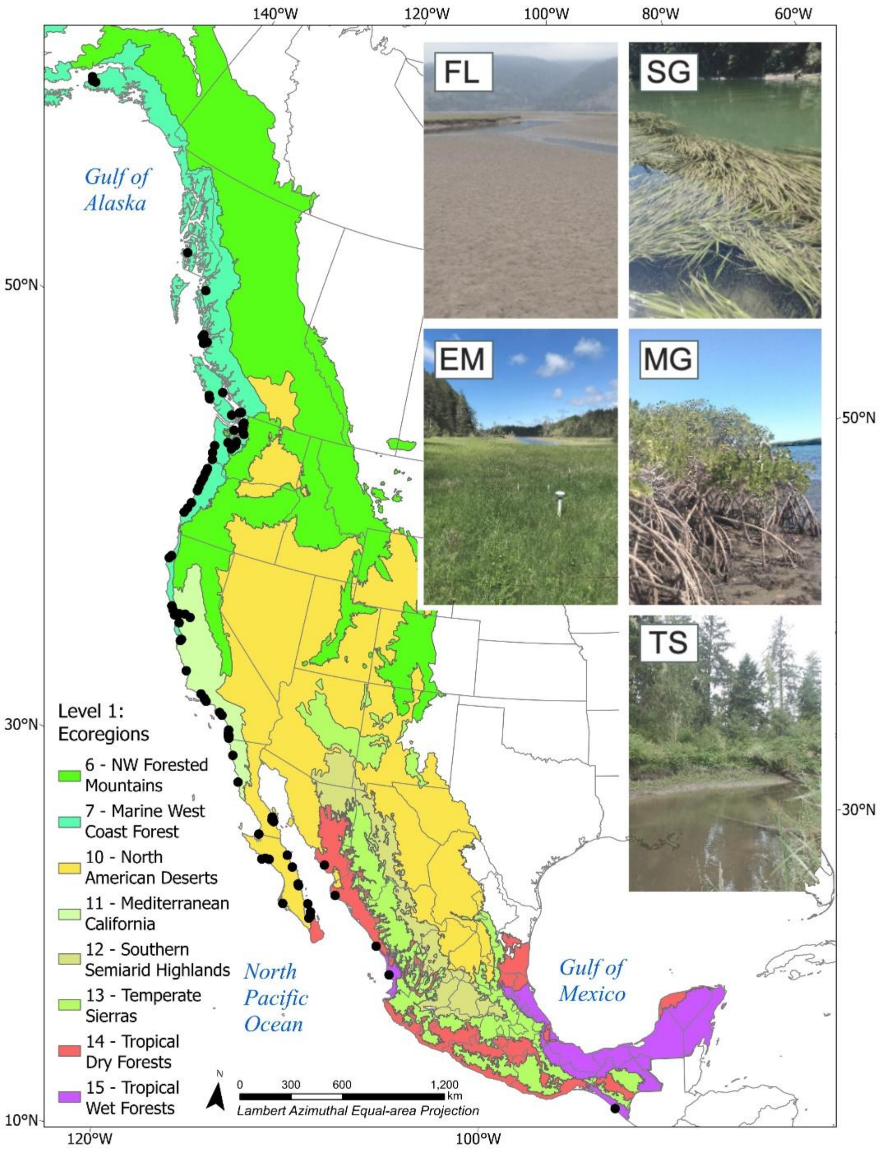
Photo: Laura S. Brophy CC-BY NC

Blue carbon functions and tidal wetland types

Is there a specific tidal wetland type that's best for carbon sequestration?



Carbon functions and tidal wetland types



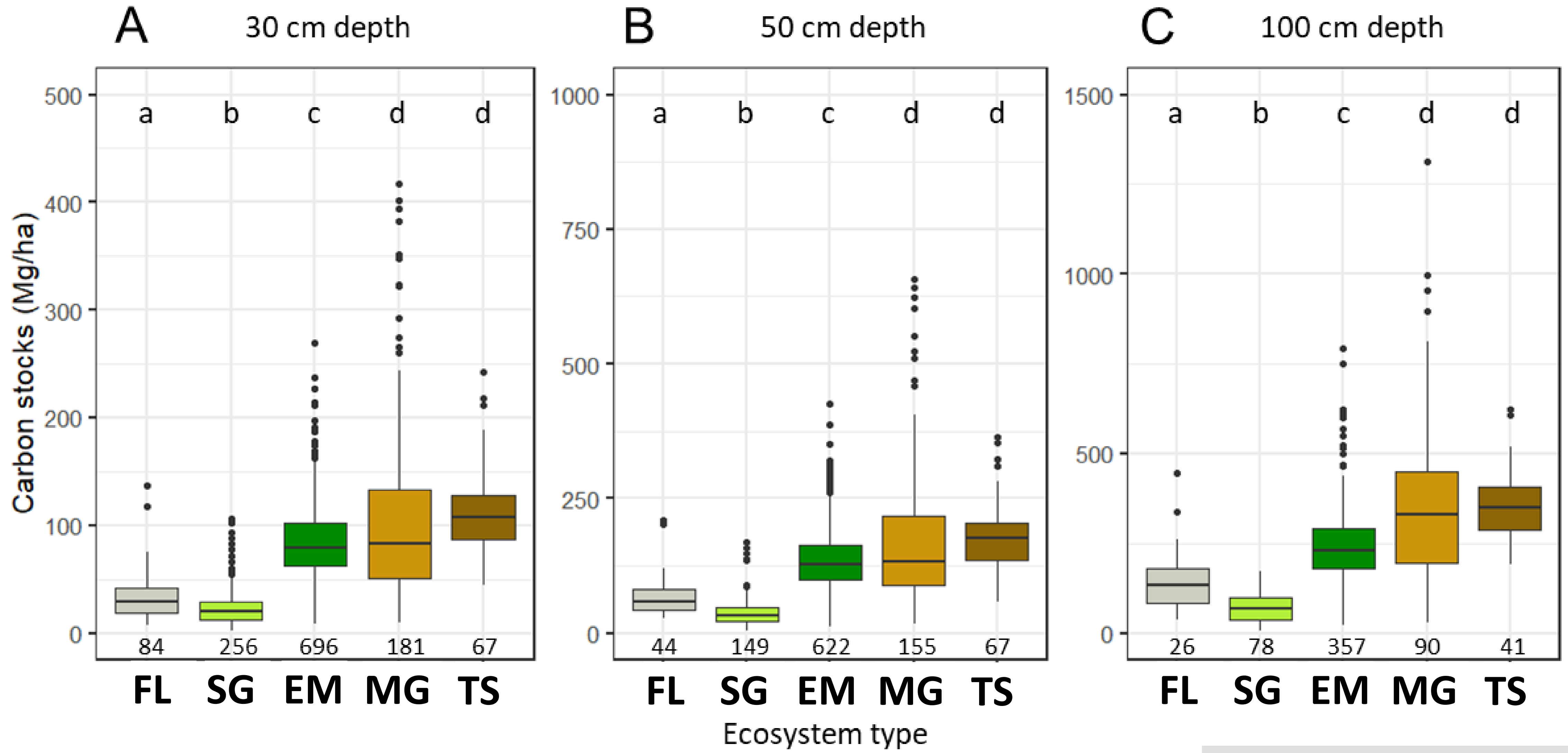
Janousek et al 2025

- Carbon stocks on the U.S. West Coast
- 69 data sources
- 1284 cores

Source: Janousek et al. 2025

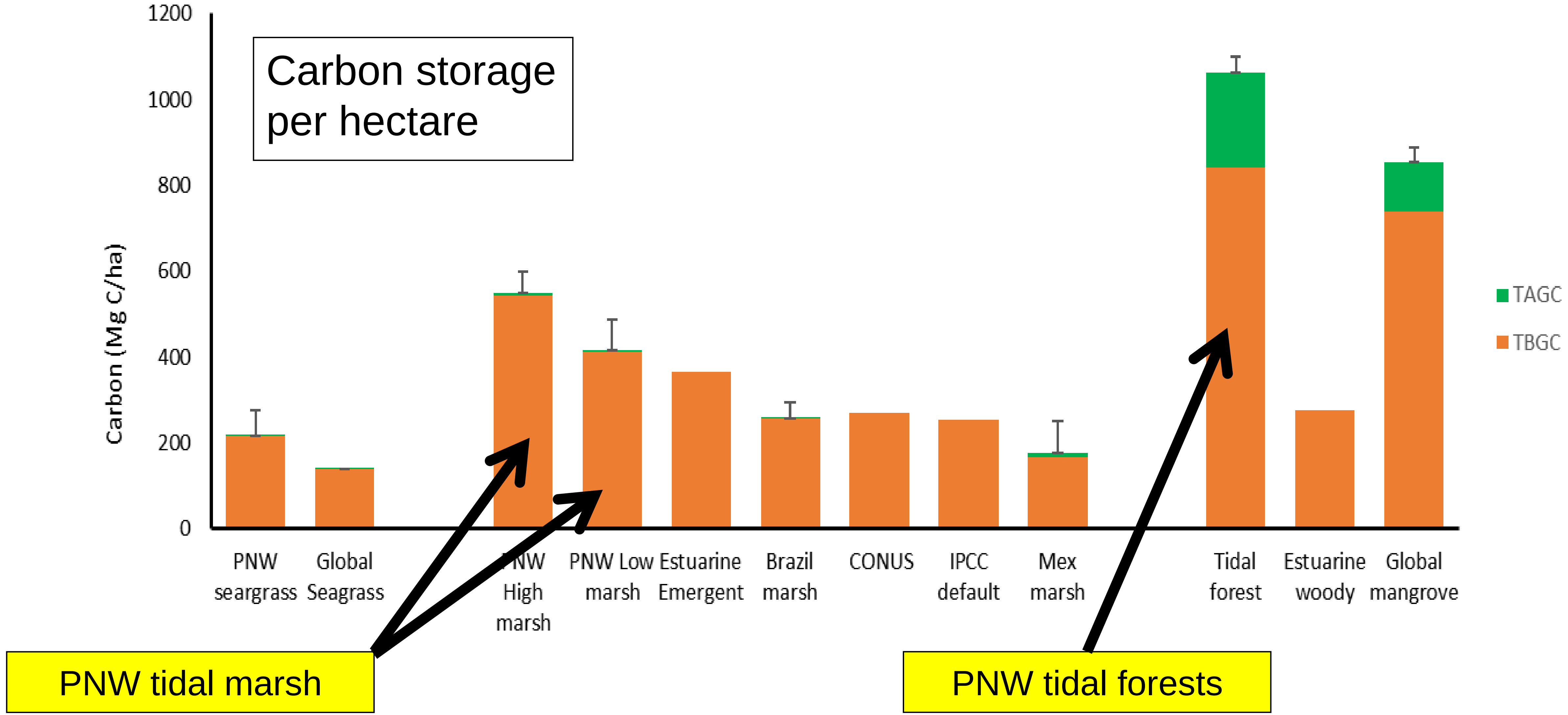
Carbon stocks by tidal wetland type

TS = tidal swamp (forested)
MG = mangrove SG = seagrass
EM = tidal marsh FL = mud flat



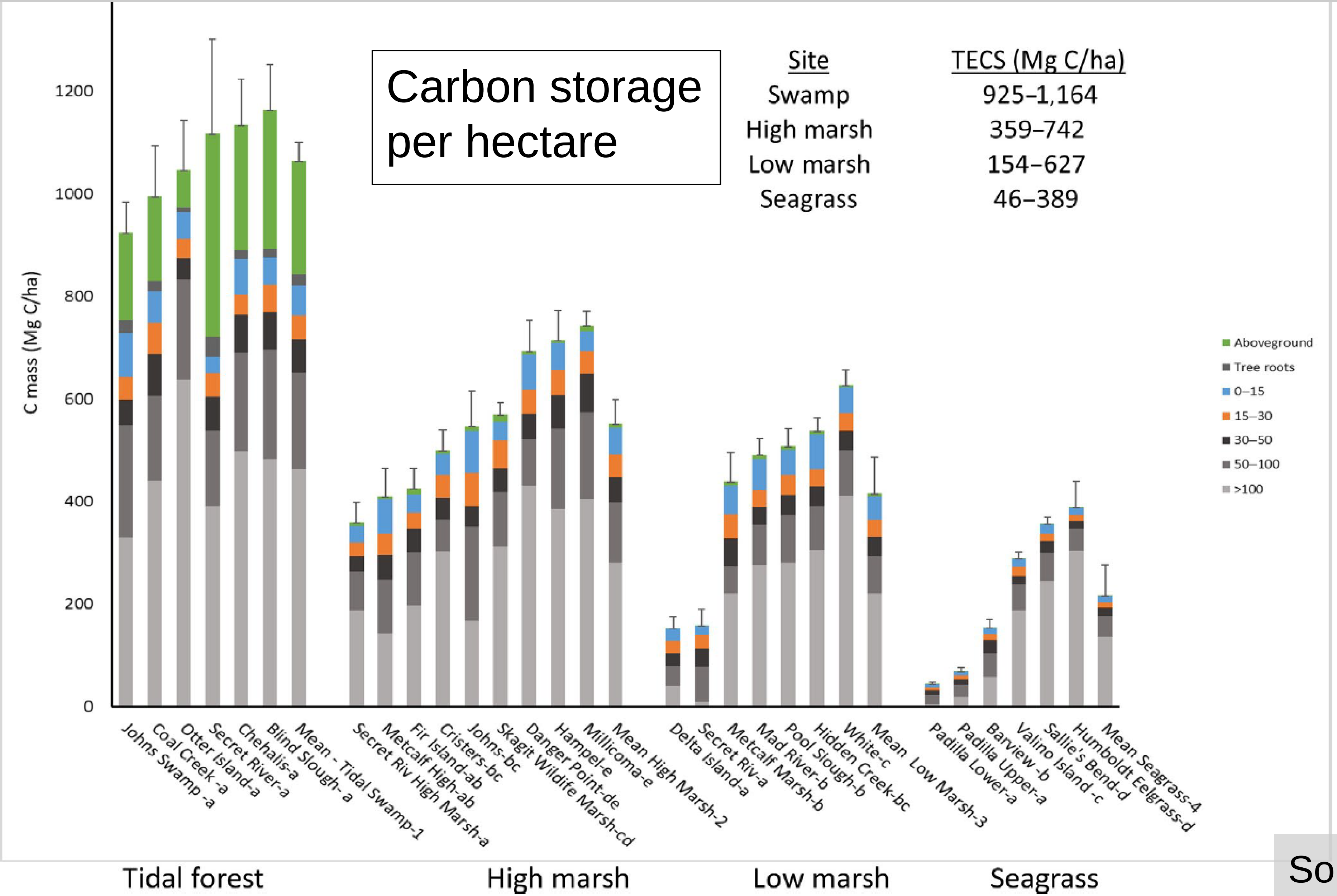
Source: Janousek et al 2025

Carbon stocks: PNW estuary habitats vs. global means (forested tidal wetlands are highest)



Source: Kauffman et al. 2020

Pacific NW tidal swamps store a _lot_ of carbon



Source: Kauffman et al. 2020

So, we have a winner… right?

Wait, what about us??

Seagrass photo: Partnership for Coastal Watersheds

Tidal marsh

Bravo, tidal swamp! 🎉 🎉 🎉

Tidal swamp

Tidal marsh and swamp photos: L. Brophy, CC BY-SA

Consider how blue carbon benefits are measured

Conservation of existing tidal wetlands

Benefits depend on carbon stocks

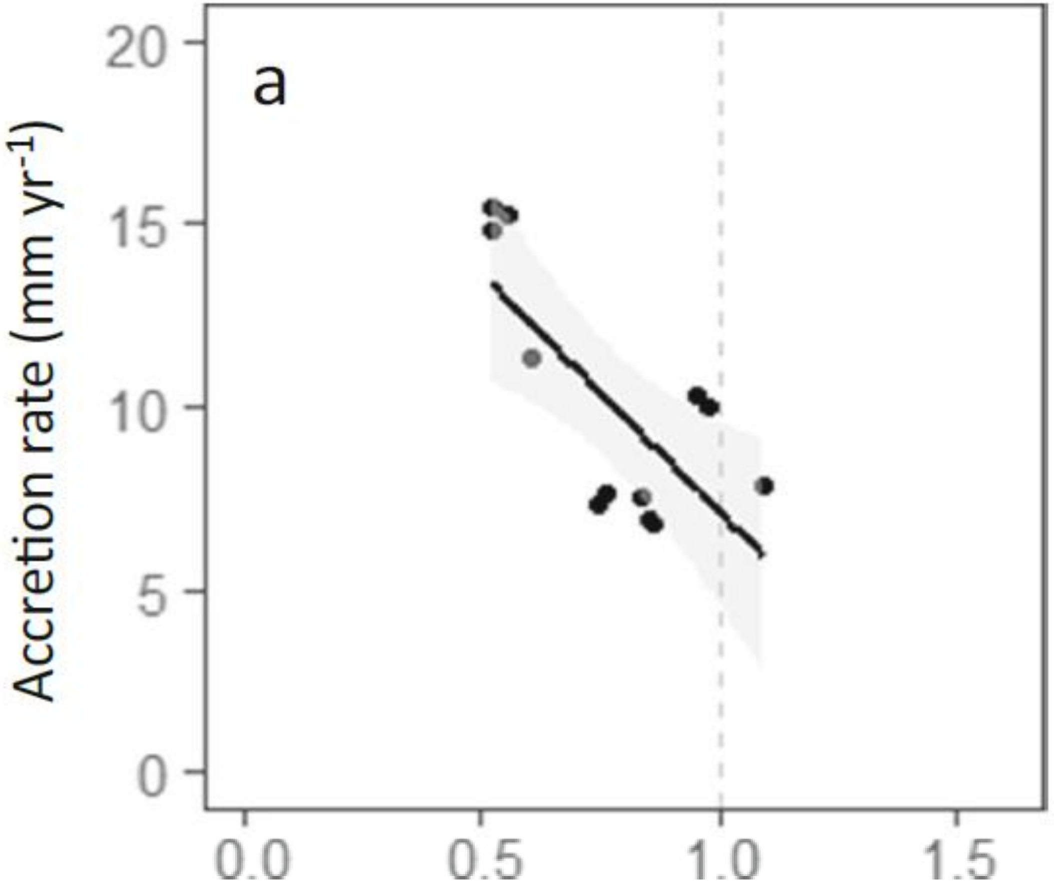
Tidal wetland restoration

Benefits depend on carbon storage rate

Photos: Laura S. Brophy, CC BY-NC

Carbon storage rates are usually higher at low elevations

Accretion at Southern Flow Corridor restoration site, Tillamook Bay, OR



Elevation (z*) (z* = 1.0 at MHHW, ~ 7.9 ft or 2.4 m NAVD88)

- Low marsh is inundated more often than high marsh, so receives more sediment
- More sediment accumulation means more carbon accumulation
- Vegetation traps sediment, produces organic matter
- Tide flats (lower than low marsh) accumulate less carbon

Sources: Janousek et al. 2020, 2025

Tillamook Bay estuary, Oregon

Layers
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Imagery ©2025 Airbus, Maxar Technologies, USDA/FPAC/GEO, Map data ©2025
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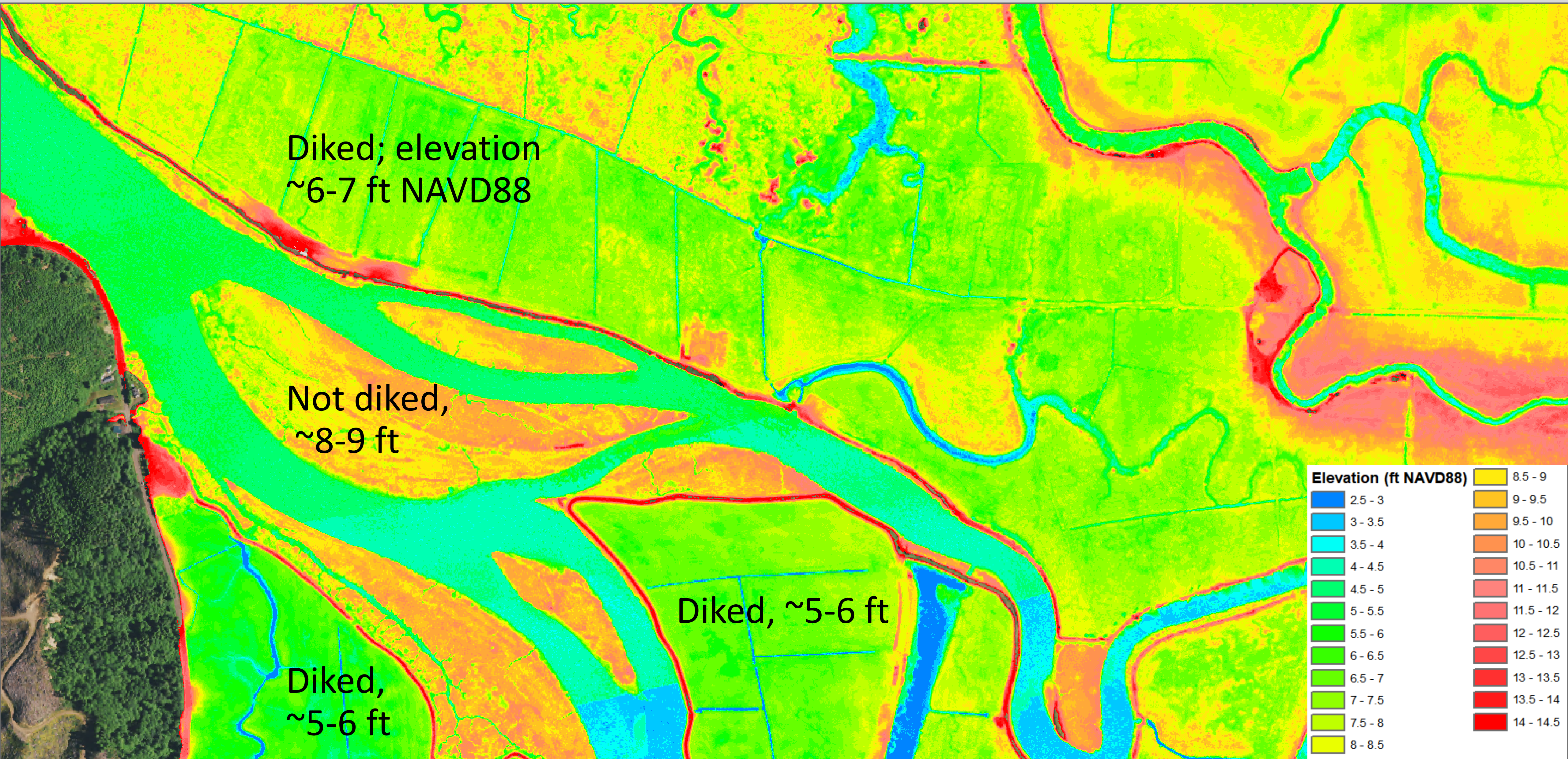
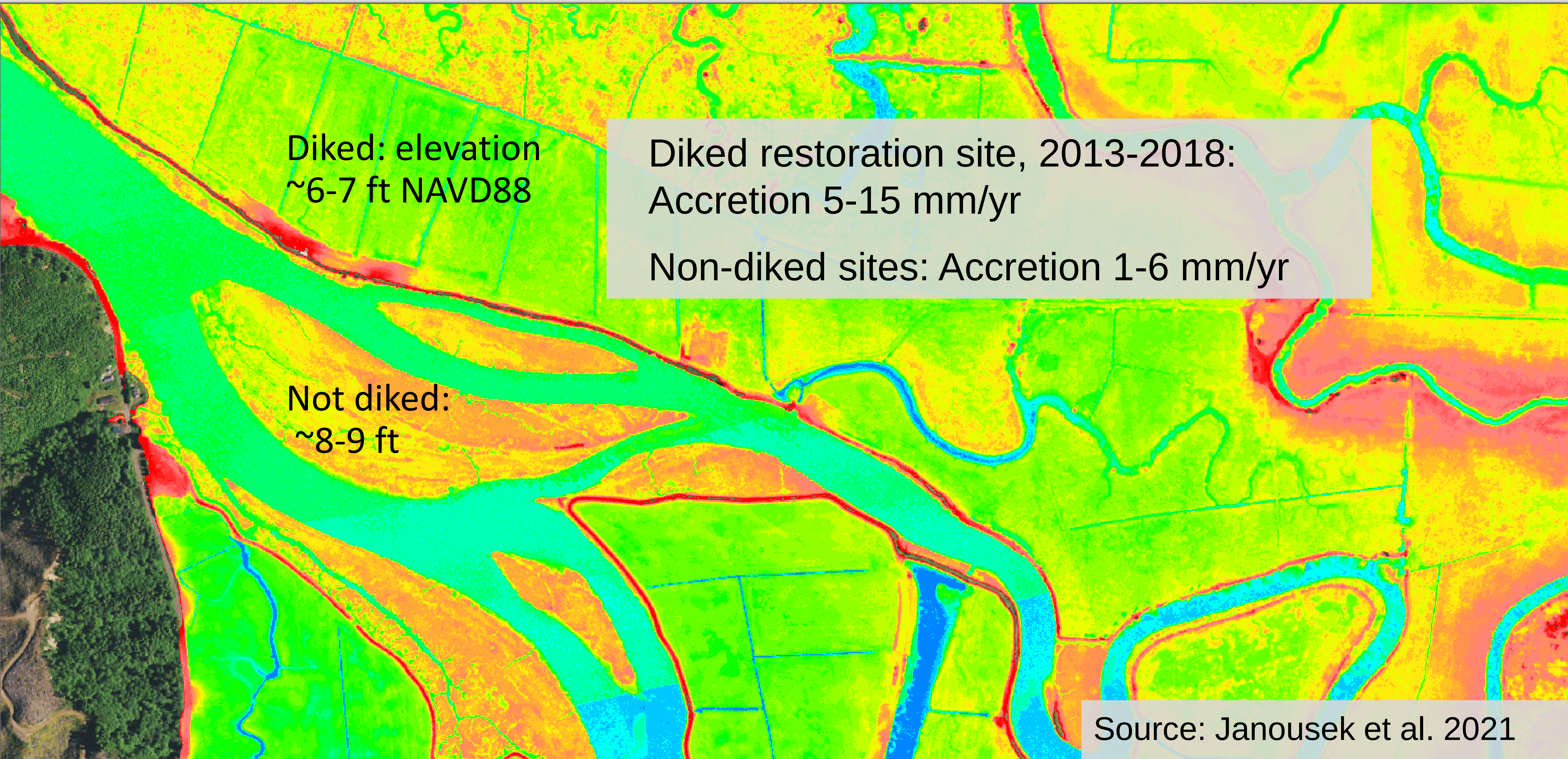
500 ft

Diked former tidal wetlands: subsided (now low elevation)



Accretion was higher in lower-elevation areas

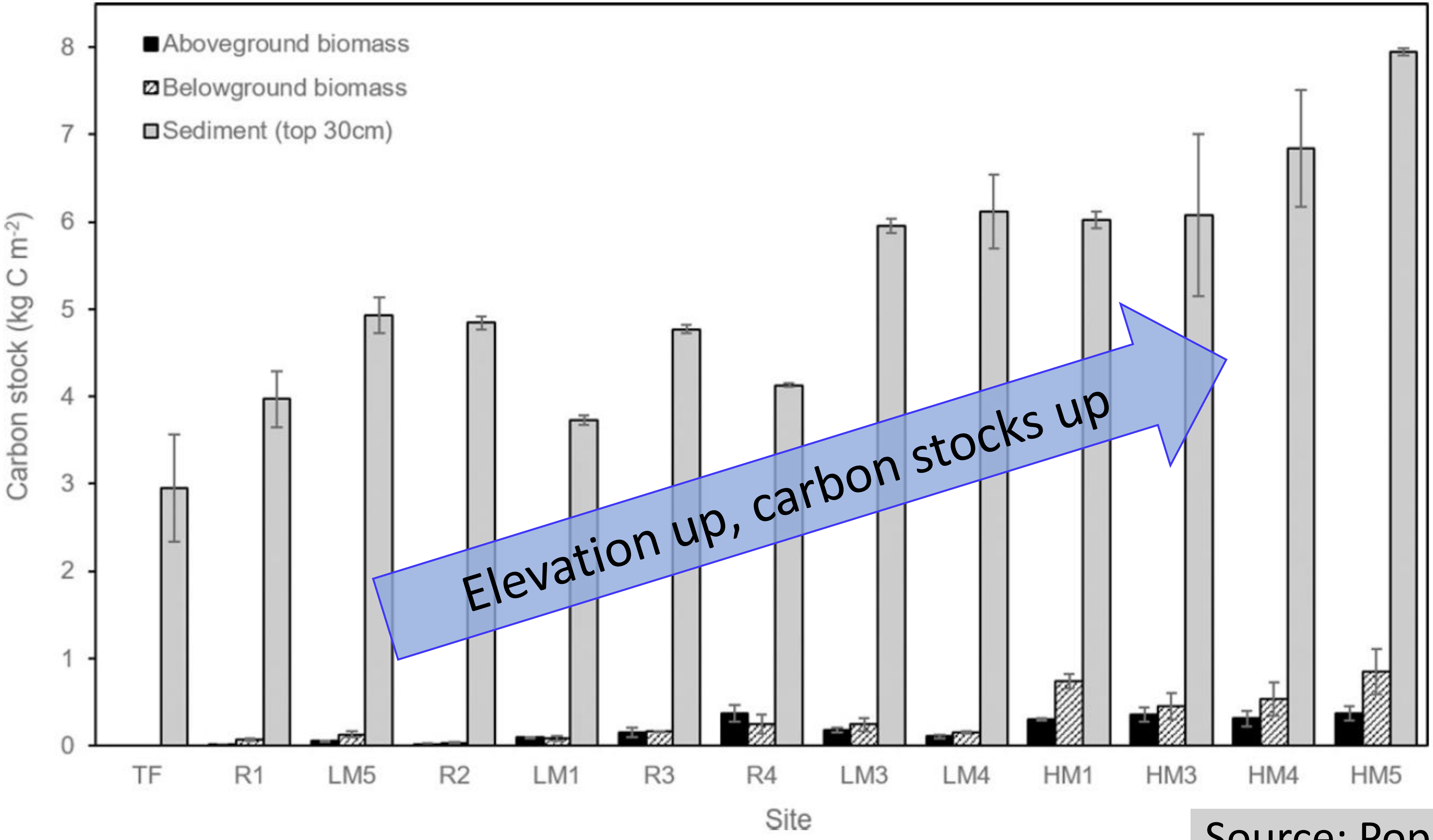


Accretion and carbon accumulation go hand-in-hand

Poppe and Rybczyk 2021 (Stillaguamish estuary, WA):
Carbon accumulation rates were controlled by accretion rates (Rank correlation $\rho = 0.97$, $P < 0.001$, $n = 13$)

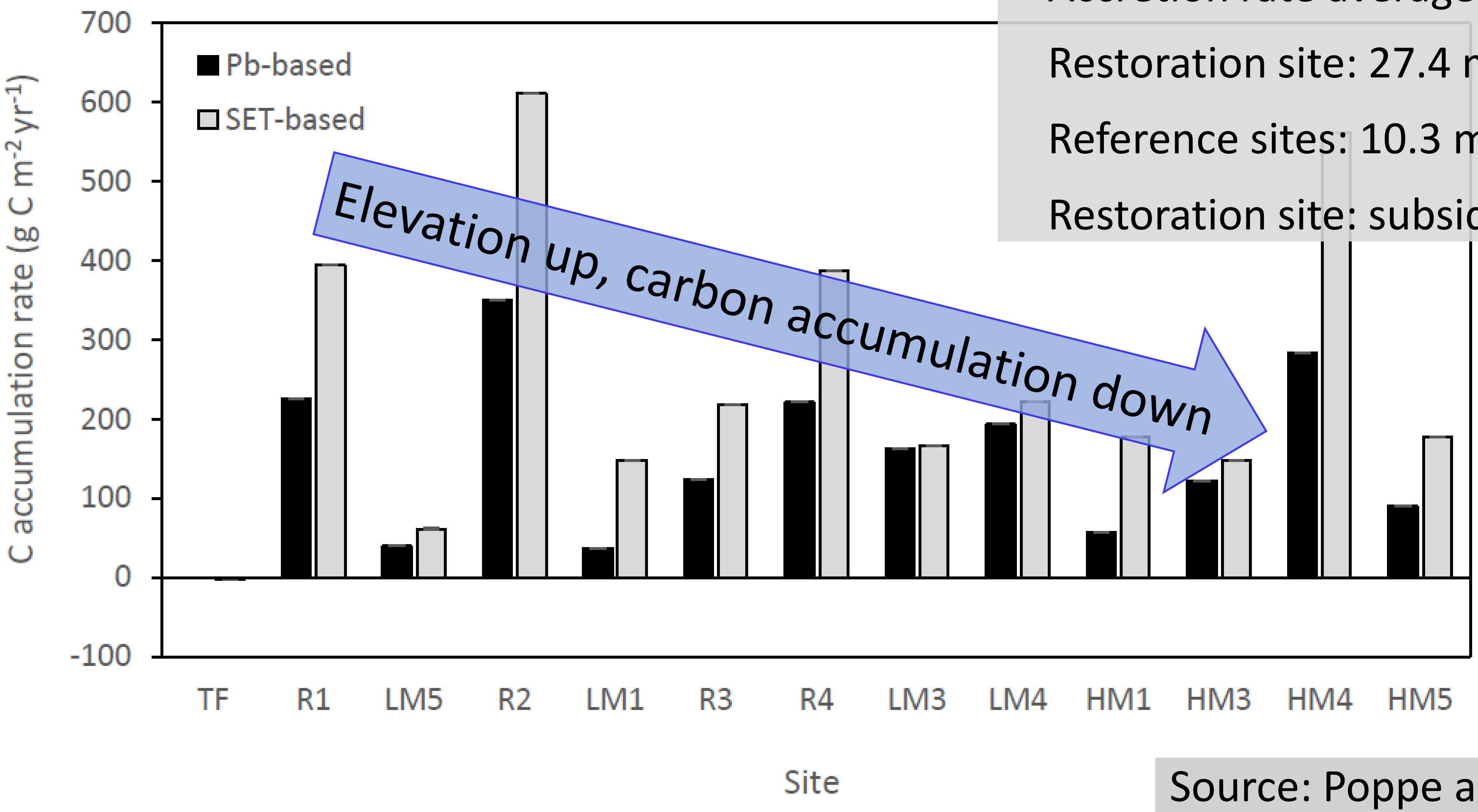
Peck et al. 2020 (7 Oregon estuaries): Carbon accumulation rates were controlled by sediment accretion rate (R2 = 0.49).

Carbon stocks: positive relationship to elevation



Source: Poppe and Rybczyk 2021

Carbon accumulation rates: negative relationship to elevation



Accretion rate averages:

Restoration site: 27.4 mm/yr

Reference sites: 10.3 mm/yr

Restoration site: subsided 0.5 – 1.0 m

Source: Poppe and Rybczyk 2021

So… do we have a new winner?

Low marsh stores lots of carbon fast! 🎉 🎉

Tidal marsh

Seagrass photo: Partnership for Coastal Watersheds

Tidal swamp

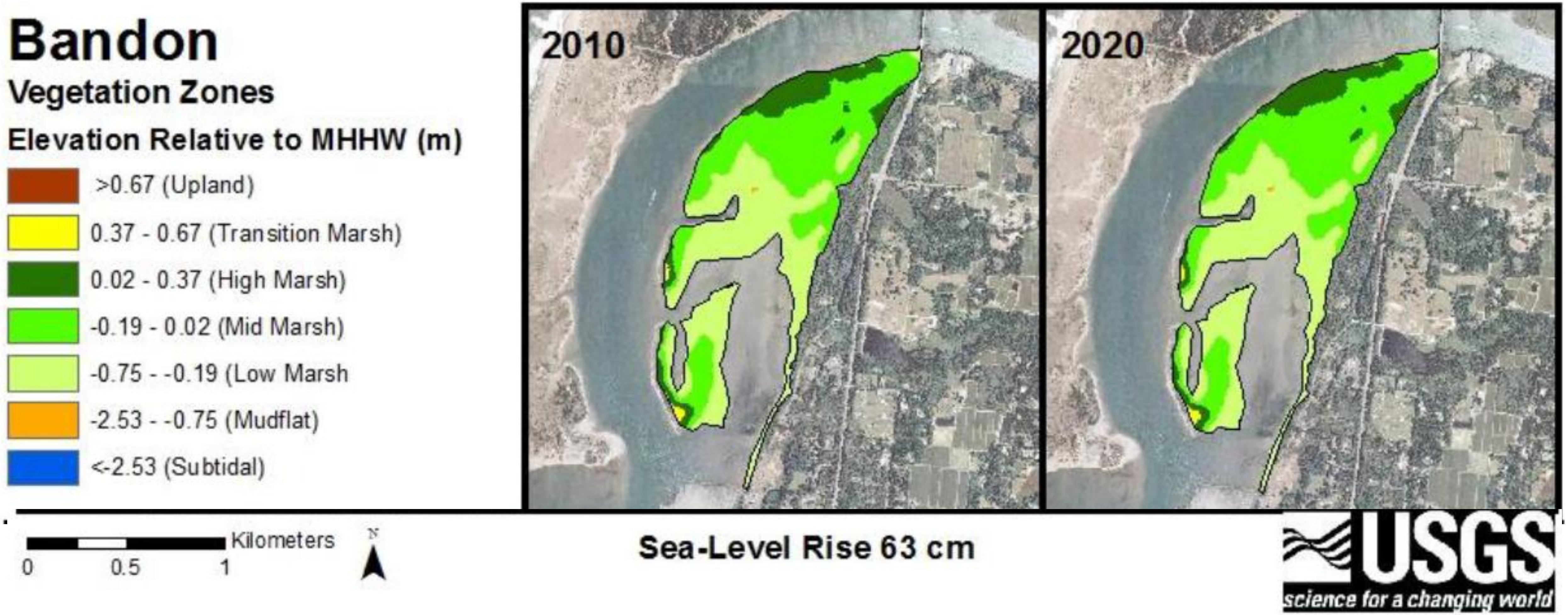
Tidal marsh and swamp photos: L. Brophy, CC BY-SA

But what about climate change and sea level rise?

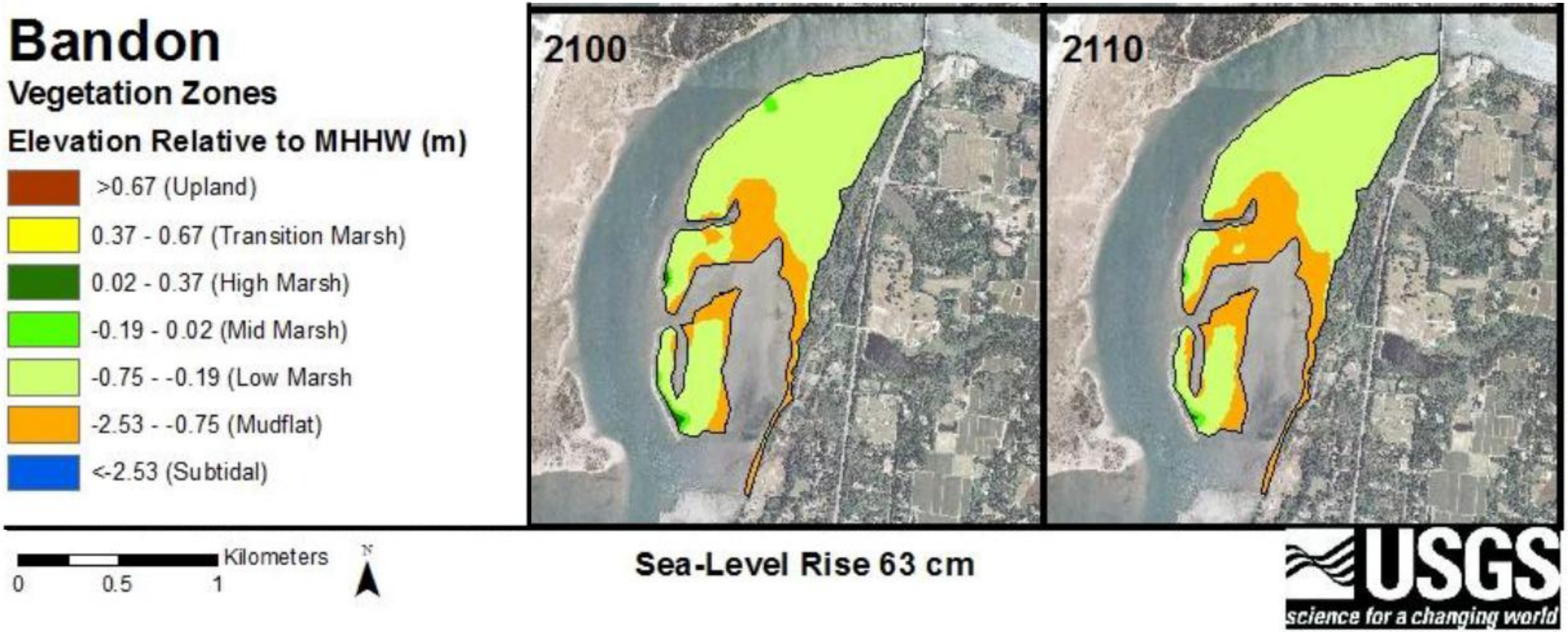
Current typical high tide

King tide: future typical high tide?

Low marsh may “drown” with rapid SLR



Source: Thorne et al. 2015



Source: Thorne et al. 2015

SLR resilience: highest in high marsh

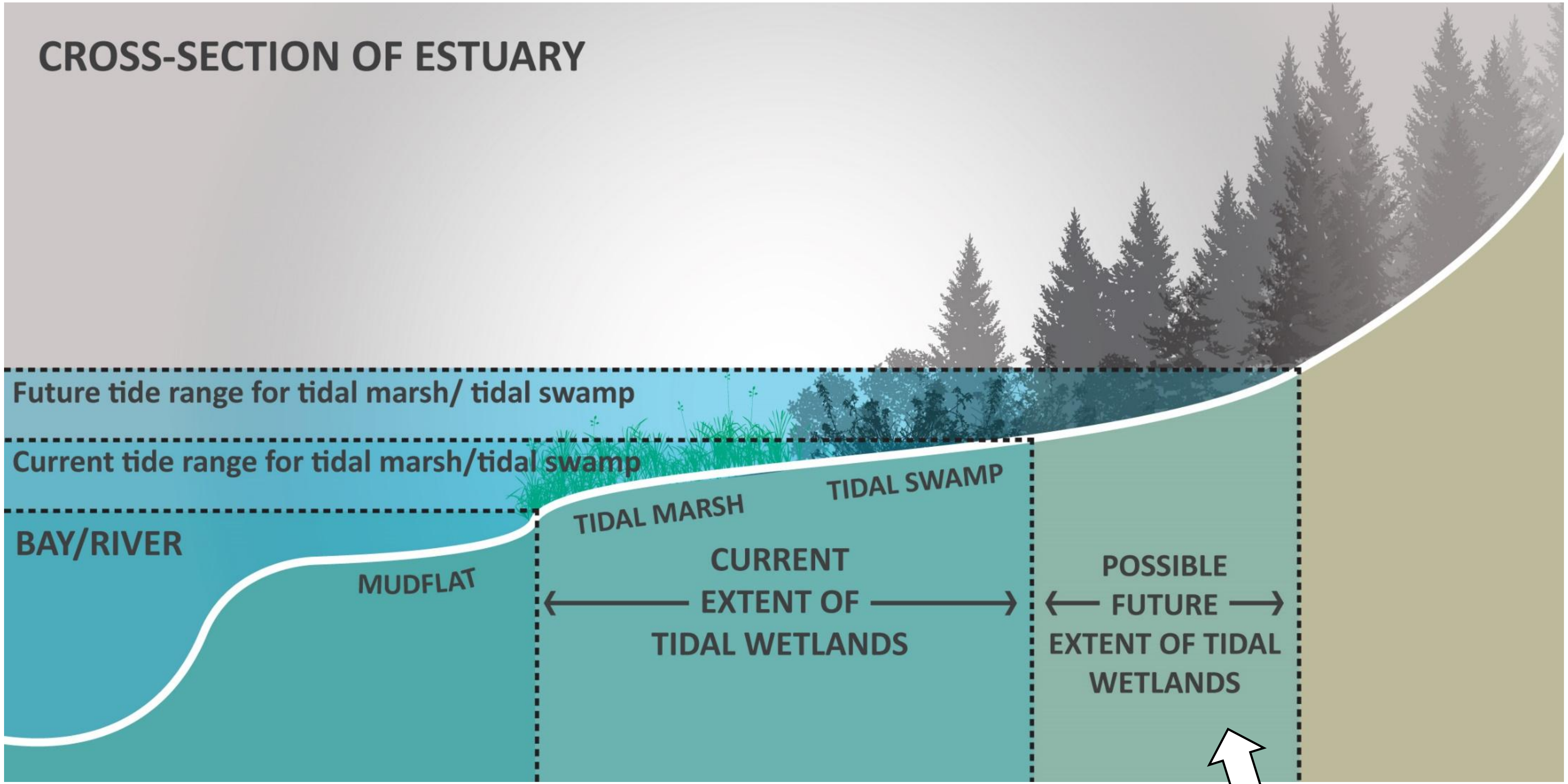
WARMER model, top factors affecting survival vs. drowning of tidal marsh:

- Amount of sea-level rise
- Initial elevation of the wetland

Variable	Relative influence (%)
Sea-level rise by 2110	40
Initial elevation (relative to MTL)	32
Sediment accumulation rate	17
Organic matter accumulation rate	6
Porosity	4
Tidal range	0.2
Refractory carbon	0.1

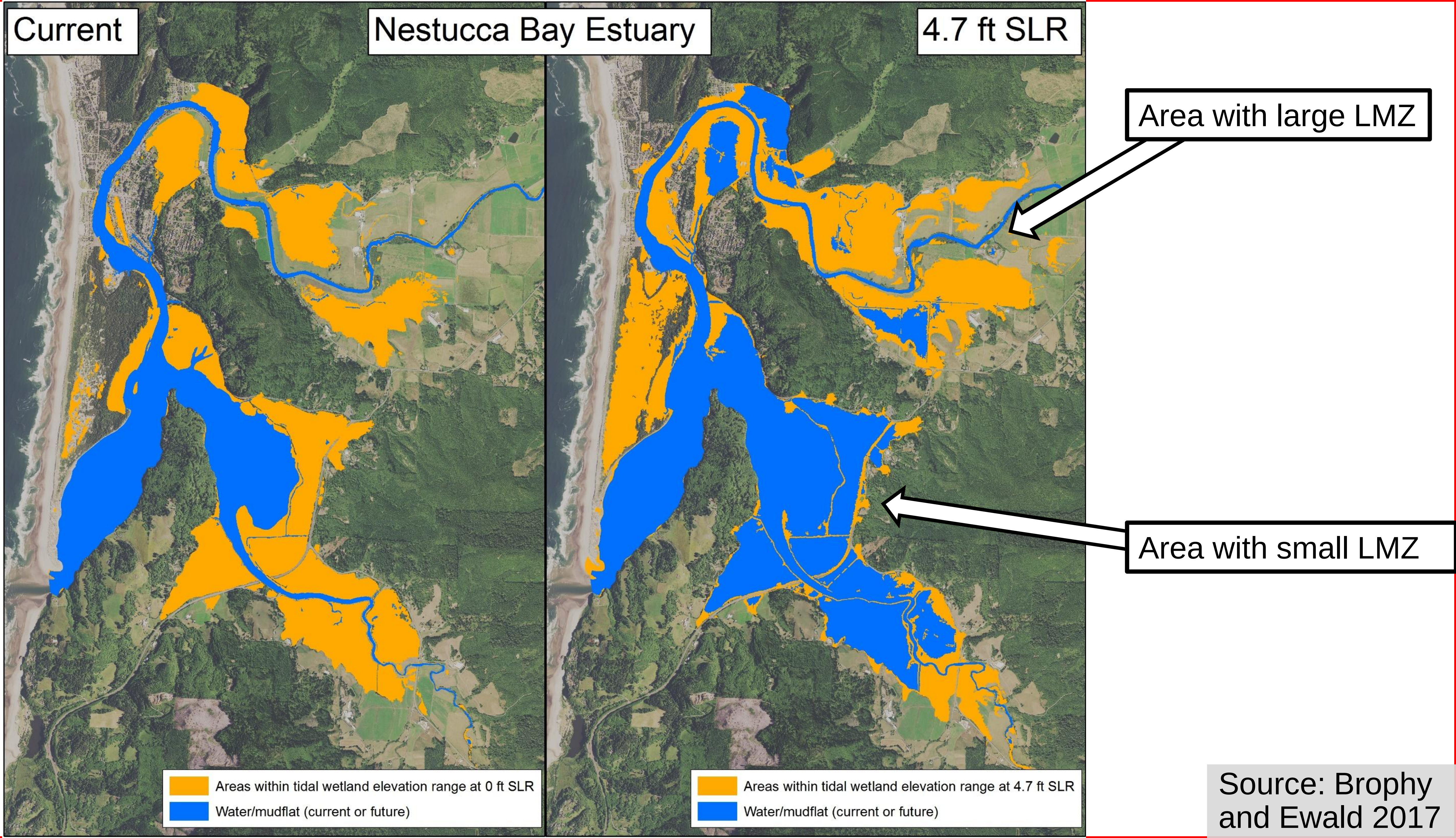
Source: Thorne et al. 2015

Landward migration zones are important



This is the Landward Migration Zone or "LMZ"

Source: Brophy et al. 2017



Source: Brophy and Ewald 2017

What does this mean to the restoration practitioner?

- Single-function prioritization should be avoided
- No single habitat type is best for fish – each is important at different times
- Higher-elevation tidal wetlands (high marsh, swamp): higher carbon stocks, more resilient to sea-level rise
- Low marsh: faster carbon accumulation, but more vulnerable to “drowning”
- Work towards a landscape array of habitats, to support wildlife resilience and diverse carbon opportunities
- Choose sites with landward migration space
- **Make sure to protect current tidal wetlands!**

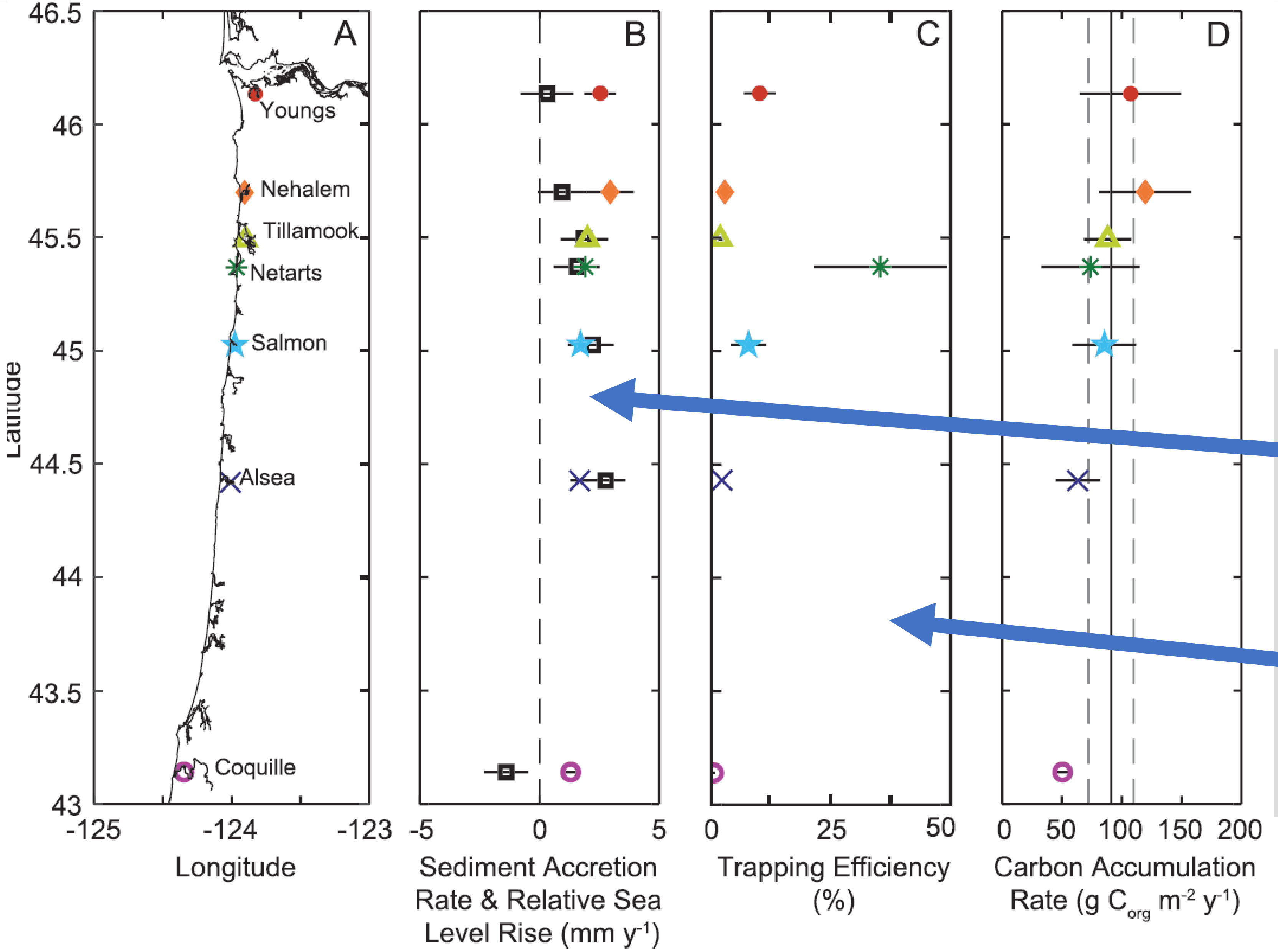
Sediment accretion and carbon storage

Peck et al. 2020 study of sediment and carbon burial in Oregon

- 72 cores in 7 Oregon estuaries
- Sediment accretion is a major control on carbon accumulation
- PNW estuaries have high sediment availability
- Most sediment is carried offshore
- Major river floods likely play a large role in sediment accretion
- These factors increase sea-level rise resilience

Source: Peck et al. 2020

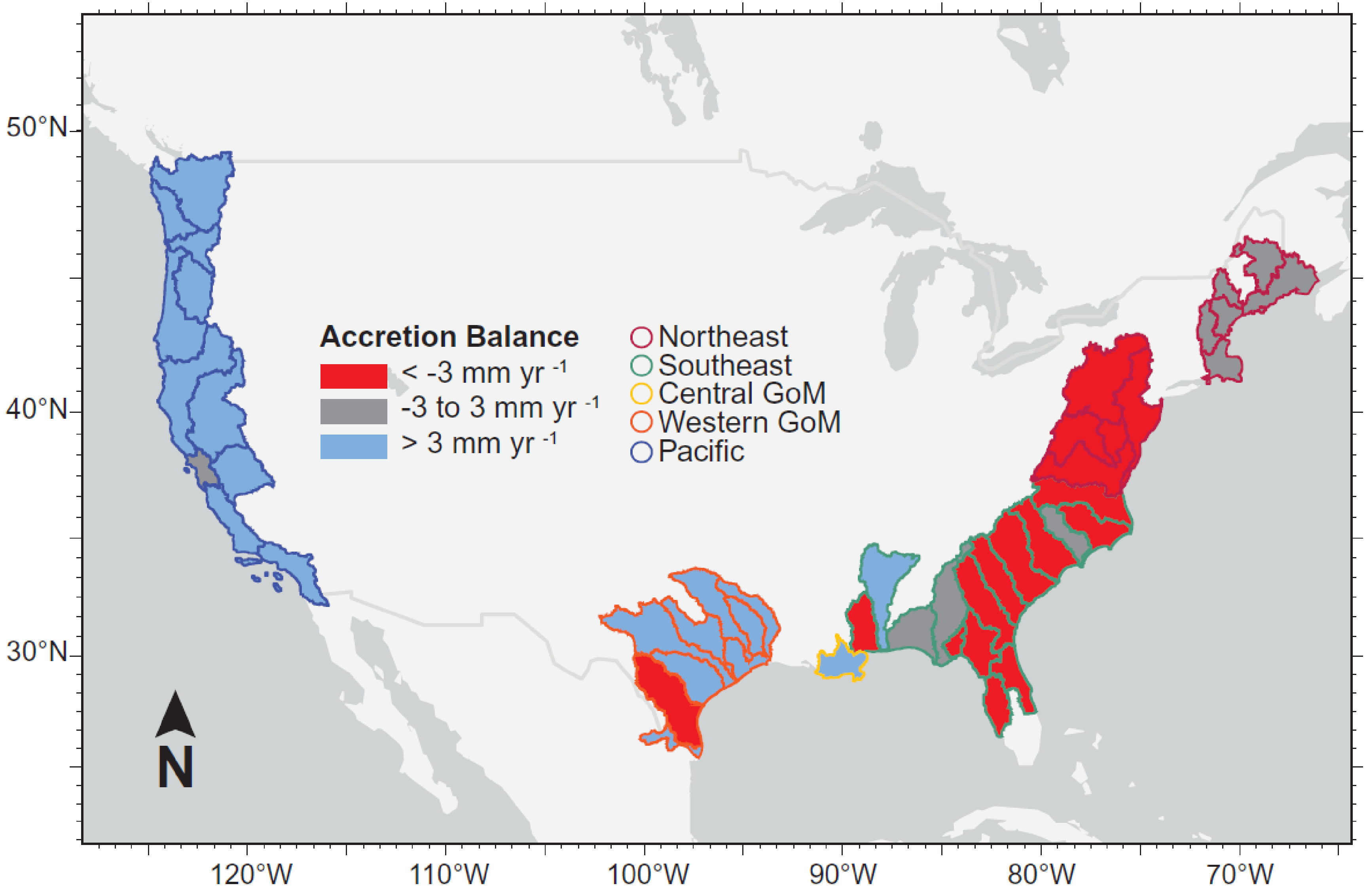
Sediment accretion vs. sea-level rise in Oregon high marsh



- Accretion is usually greater than sea-level rise
- Low "trapping efficiency" means lots of sediment is available

Source: Peck et al. 2020

Sediment supply vs. sea-level rise in the continental USA

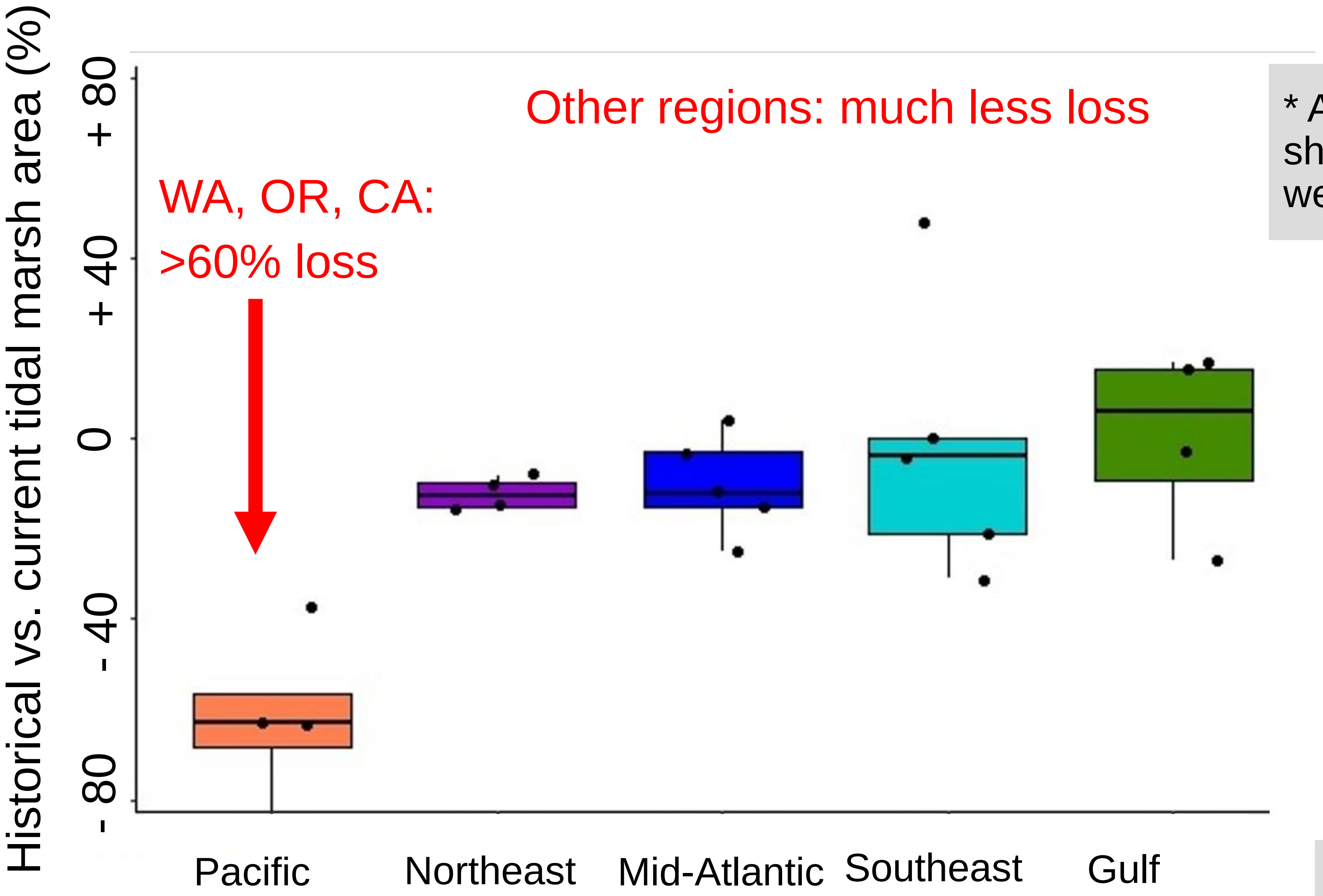


Blue color is good: accretion is greater than current rate of sea-level rise

Red: sea-level rise is higher than accretion rate

Source: Ensign et al. 2023

Past (historical) loss of tidal marsh* on U.S. coasts



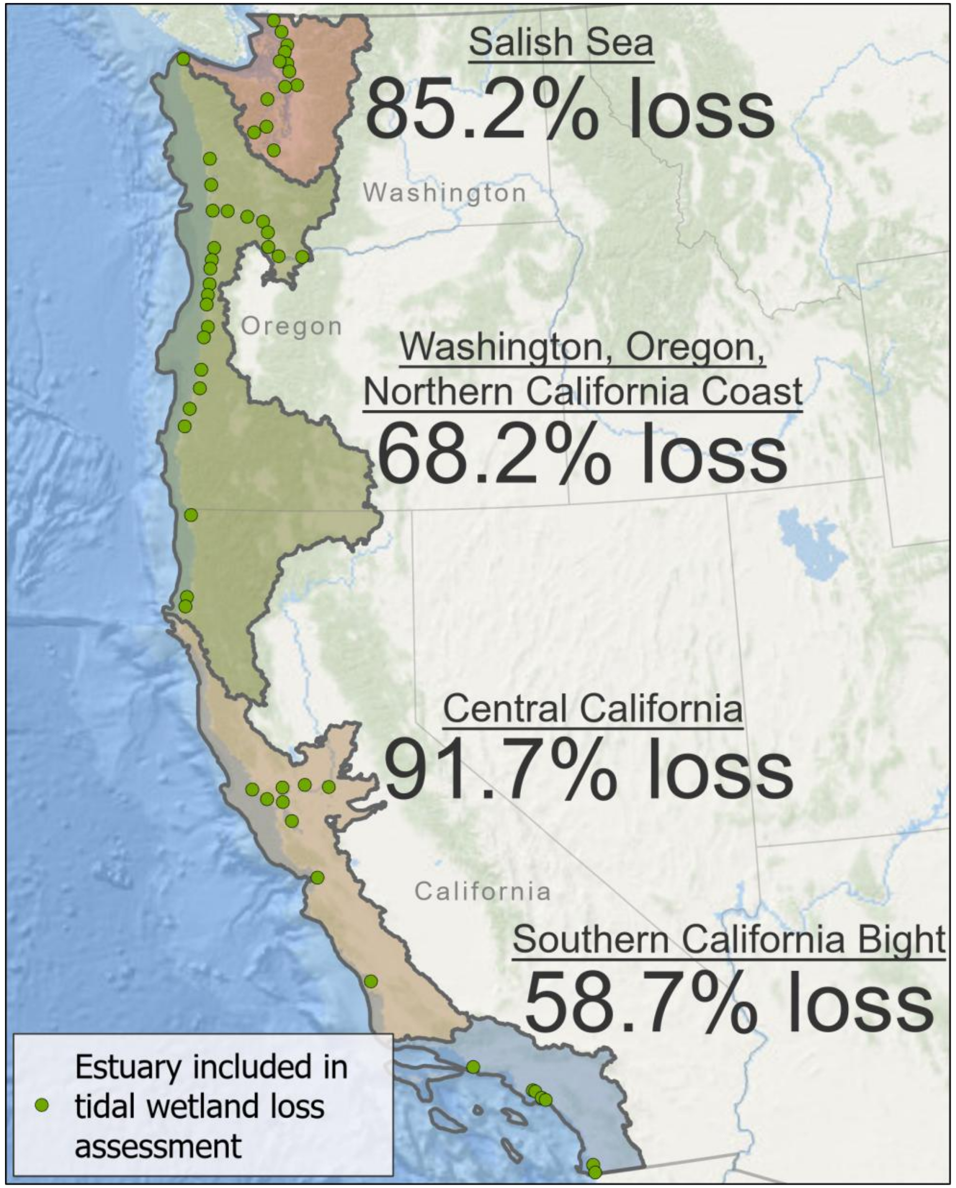
* Analysis does not include shrub or forested tidal wetlands.

Source: Endris et al. 2024

Past tidal wetland losses have been high on U.S. West Coast

- 85% of tidal wetlands have been lost from the U.S. West Coast

- Losses have been highest in Salish Sea and Central California



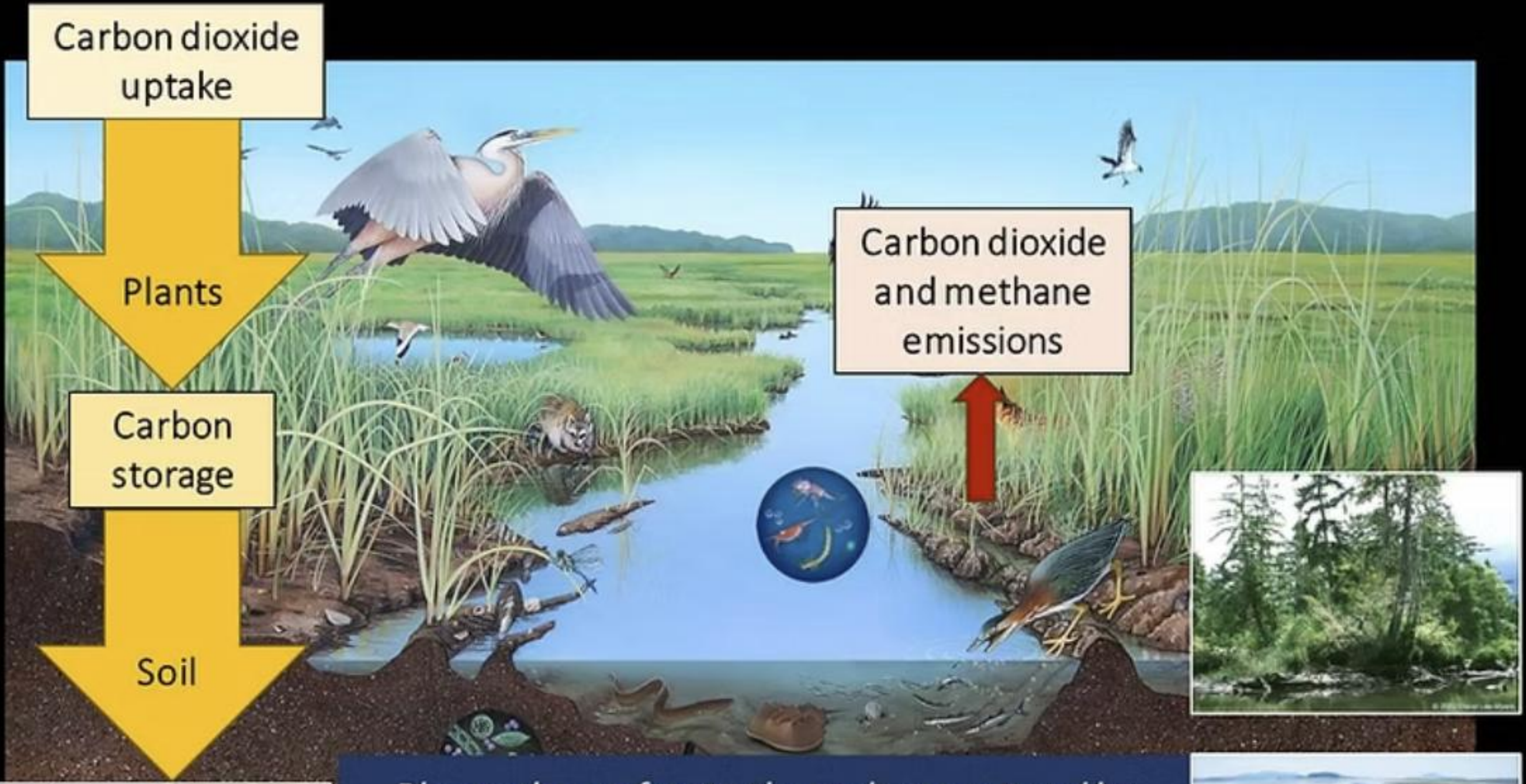
Source: Brophy et al. 2019

What does this mean to the restoration practitioner?

- Prioritize watersheds with intact natural processes (e.g. flood regimes)
- Work to remove offsite/basin-wide flow restrictions
- Funding applications: emphasize West Coast sediment supplies, intact natural processes, and tidal wetland losses
- Choose sites that can restore to high marsh / tidal swamp
- **Prioritize protection of existing tidal marsh and tidal swamp**
- Onsite, ensure natural processes are re-established
- Incorporate design elements to capture sediment

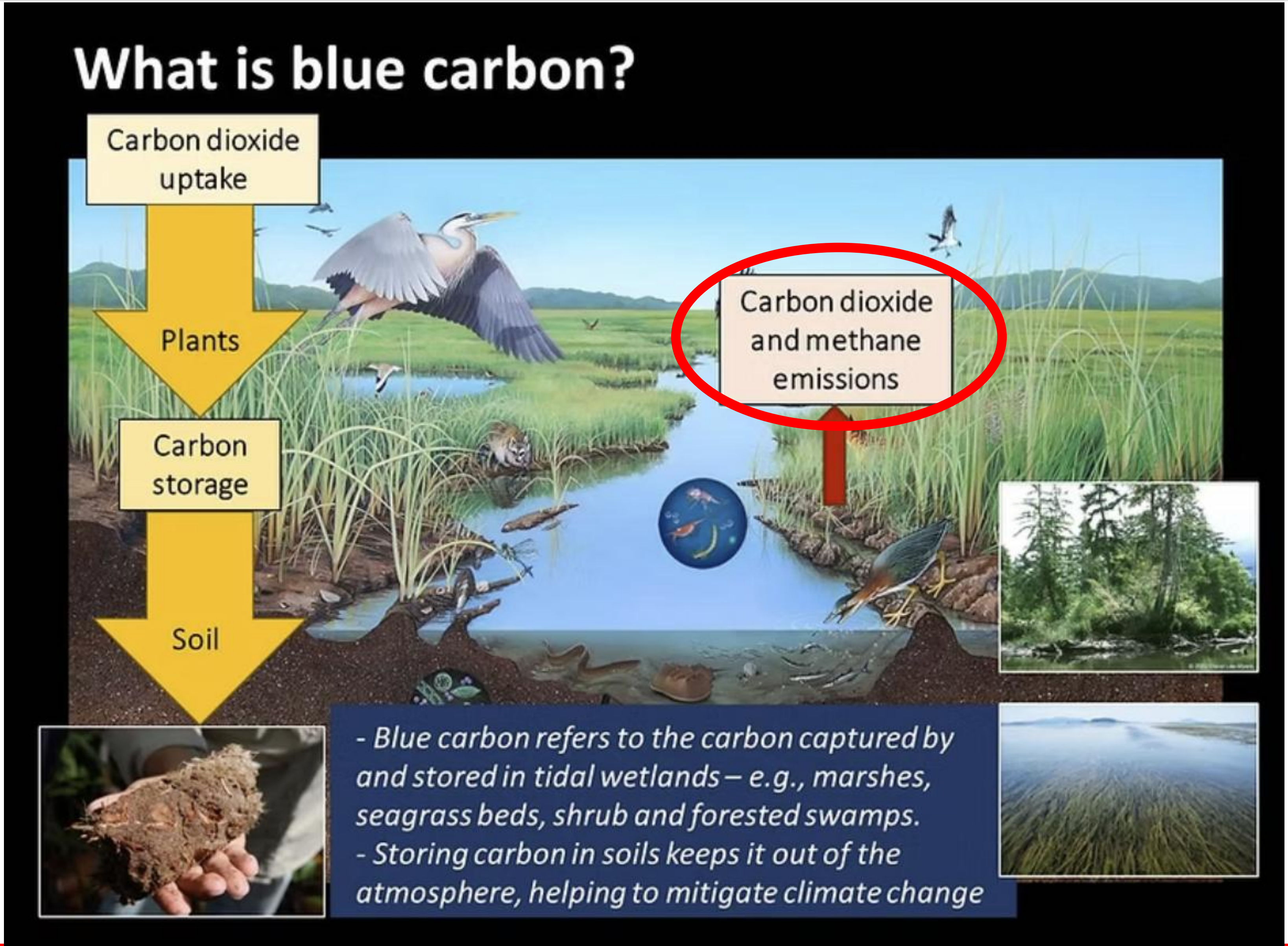
What about salinity and methane?

What is blue carbon?



- *Blue carbon refers to the carbon captured by and stored in tidal wetlands – e.g., marshes, seagrass beds, shrub and forested swamps.*
- *Storing carbon in soils keeps it out of the atmosphere, helping to mitigate climate change*

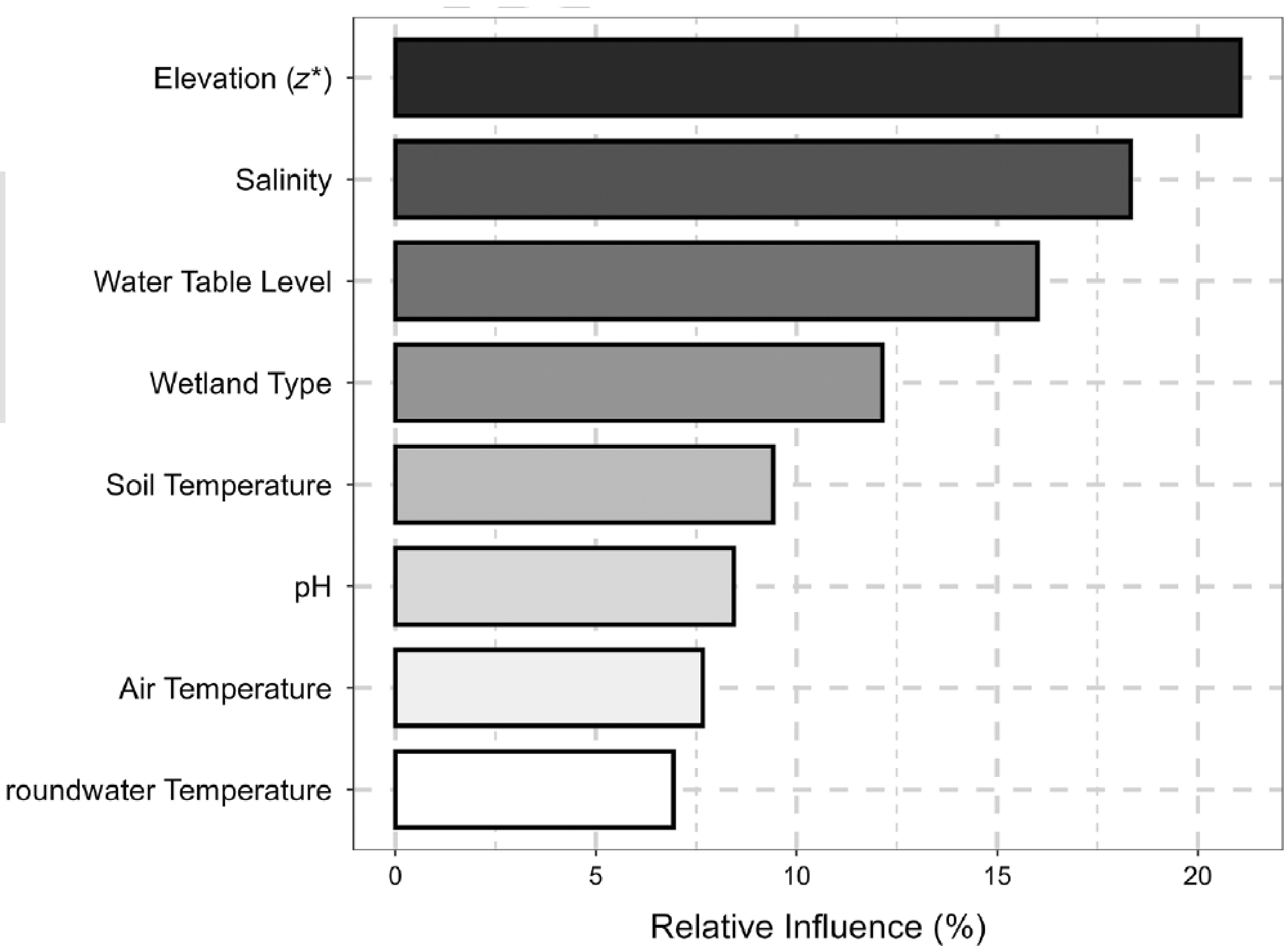
Methane emissions can offset carbon sequestration, reducing climate benefits



Higher salinity tends to reduce methane emissions

Recent PNW studies show low methane release from least-disturbed tidal wetlands, even at low salinities

Factors influencing methane emissions



Source: Williams et al. 2025

Methane emissions in PNW tidal wetlands and diked pastures

Predicted annual methane flux (g/sq m/yr) from BRT model

Wetland class	***N***	**Mean**	**SE**
Reference swamp	5	0.56 a	0.15
Reference marsh	15	4.44 b	2.18
Restored marsh	15	36.30 b	27.77
Wet pasture	3	37.25 ab	34.61
Dry pasture	5	0.21 ab	0.84

Source: Williams et al. 2025

Strikingly low methane emissions in 5 least-disturbed PNW forested tidal wetlands

Predicted annual methane flux (g/sq m/yr) from BRT model

Wetland class	***N***	**Mean**	**SE**
Reference swamp	5	0.56 a	0.15
Reference marsh	15	4.44 b	2.18
Restored marsh	15	36.30 b	27.77
Wet pasture	3	37.25 ab	34.61
Dry pasture	5	0.21 ab	0.84

Source: Williams et al. 2025

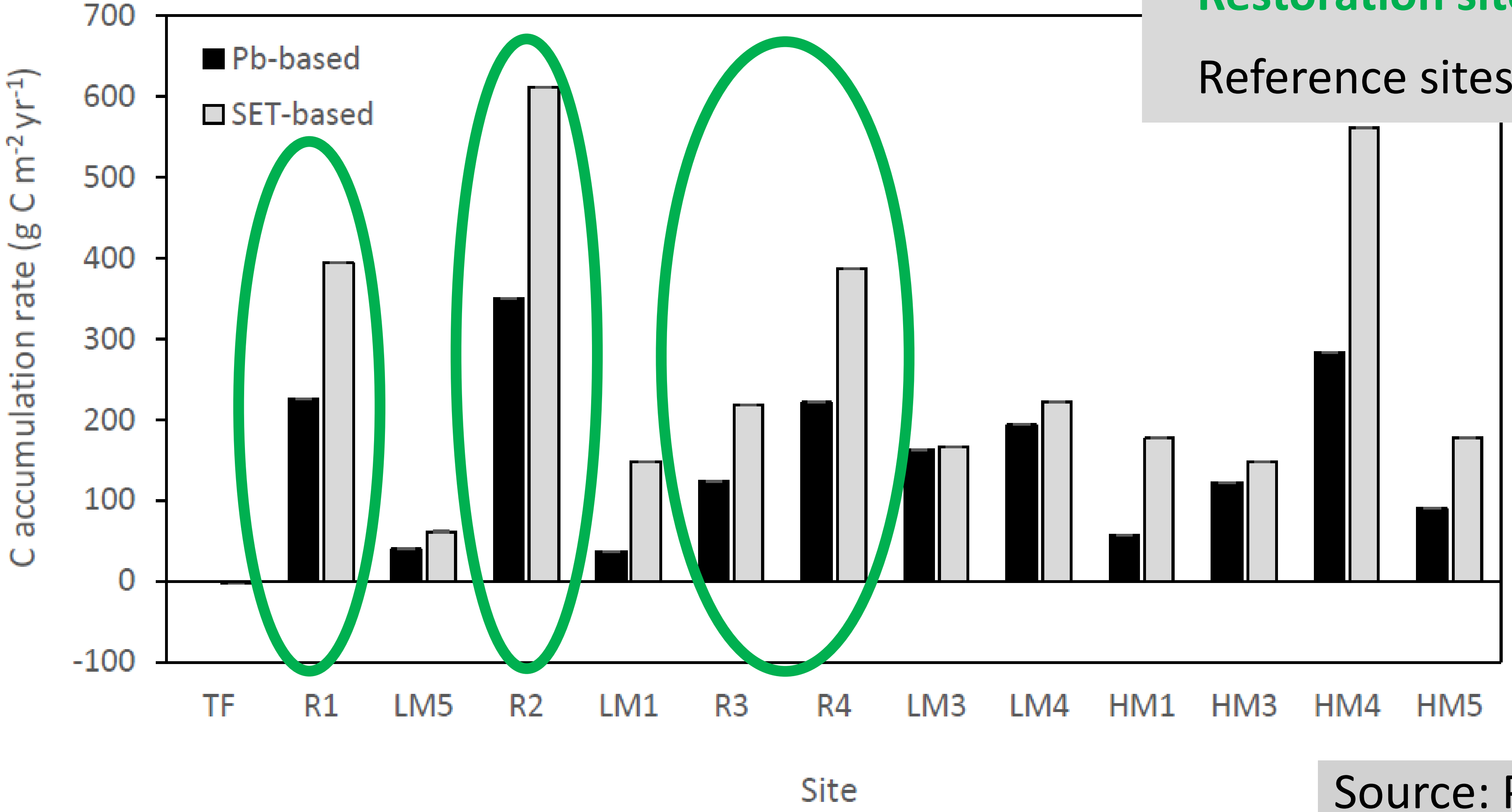
Higher methane emissions from restored tidal marsh and unrestored wet pasture

Predicted annual methane flux (g/sq m/yr) from BRT model

Wetland class	*N*	Mean	SE
Reference swamp	5	0.56 a	0.15
Reference marsh	15	4.44 b	2.18
Restored marsh	15	36.30 b	27.77
Wet pasture	3	37.25 ab	34.61
Dry pasture	5	0.21 ab	0.84

Source: Williams et al. 2025

But restored sites may recover quickly, reducing methane emissions



Accretion rate averages:

Restoration site: 27.4 mm/yr

Reference sites: 10.3 mm/yr

Source: Poppe and Rybczyk 2021

Restoration practices to enhance carbon sequestration and sea-level rise resilience

- Re-establish natural deposition/accretion processes
- Design elements: slow flood flows and capture sediment
- Be sure to monitor your results!
- These actions benefit fish as well as carbon functions

Photo: Laura S. Brophy, CC BY-NC

Restoration design elements for fish and carbon functions

First principle: re-establish natural processes

- Free flow of tides and sediment are vital for future survival of tidal wetlands
- Upgraded tide gates may improve fish access, but they impede sediment (and many other natural processes)

Photo: U.S. Fish and Wildlife Service

Restoration design elements for fish and carbon functions

- Design elements that increase sediment deposition:
  - Tidal channel restoration
  - Large woody debris
  - Topographic mounds to support trees and shrubs, where appropriate
  - Woody plantings at appropriate elevations/salinities
  - Encourage beaver
- All of the above have associated fish habitat benefits
- All of the above improve sea level rise resilience too!

Tidal channel restoration and large woody debris

Photos: U.S. Fish and Wildlife Service (L), Bill Bridgeland (R)

Topographic mounds and woody plantings

Photos: Fran Recht (L), Laura Brophy (R)

Intertidal beaver dams in tidal marsh

Intertidal beaver dams in tidal swamp

Photos: Laura S. Brophy (L and R), Greg Hood (center)

Summary: What can a restoration practitioner do to benefit both fish and carbon functions?

- Choose sites across the elevation gradient for fish population resilience and a range of carbon opportunities (e.g. rapid storage and high stocks)
- Protect existing high marsh and tidal swamp: very high carbon stocks
- Prioritize sites with landward migration space
- Incorporate design elements that capture sediment and benefit fish
- Highlight your region’s strengths, especially intact natural processes
- Monitor your results!

Links to publications

Brophy and Ewald 2017, https://doi.org/10.13140/RG.2.2.19021.79845

Brophy et al. 2017, [LMZ slideshow]

Brophy et al. 2019, https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0218558

Davis et al. 2019, https://doi.org/10.1002/tafs.10134

Endris et al. 2024, https://doi.org/10.1016/j.biocon.2024.110779

Endris et al. 2024, https://doi.org/10.1016/j.biocon.2024.110779

Ensign et al. 2023, https://www.science.org/doi/10.1126/science.adj0513

Greene et al. 2021, https://salishsearestoration.org/w/images/6/66/Greene_et_al_2021_chinook_salmon_estuary_density_dependance.pdf

Janousek et al. 2020, https://doi.org/10.1007/s12237-020-00782-5

Janousek et al. 2021, http://dx.doi.org/10.13140/RG.2.2.14514.32961

Janousek et al. 2025, in final review (Global Biogeochemical Cycles)

Kauffman et al. 2020, https://doi.org/10.1111/gcb.15248,

Peck et al. 2020, https://doi.org/10.1029/2019JG005464

Poppe and Rybczyk 2021, https://doi.org/10.1371/journal.pone.0257244

Thorne et al. 2015, http://dx.doi.org/10.3133/ofr20151204

Williams et al. 2025 (in press), https://doi.org/10.1002/eap.70011

Woo et al. 2019, https://doi.org/10.1007/s12237-019-00613-2

Discussion

Photo: Laura S. Brophy, CC BY-NC

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