Tidal Wetland Fluxes

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University of Georgia

OCB Fluxes WHOI Summer 2014

Plum Island wetlands from PIE LTER Rowley field camp

With help from many including Anne Giblin, Jim Morris, Matt Kirwan, Inke Forbrich, Hap Garritt, Nat Weston, Joe Vallino, Sergio Fagherazzi, WJ Cai, Jim Bauer, Pete Raymond

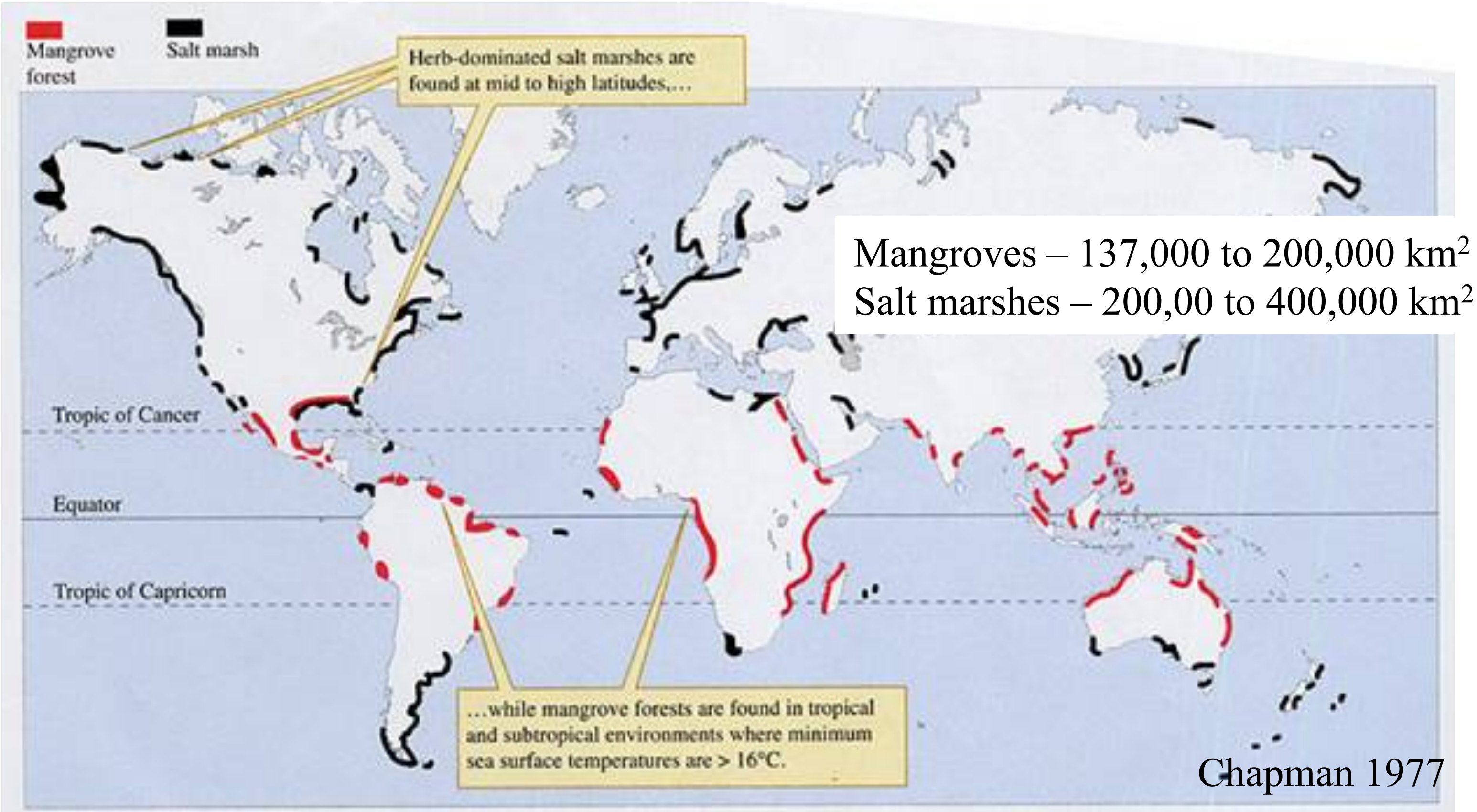
Overview

- Background – What these systems look like, where they are, what's their rate of C burial and their role in the coastal ocean C budget?
- Geomorphics – evolving systems tied to SLRR, sediment supply, climate, ecogeomorphic feedbacks. What they will look like in 100 yrs?
- Fluxes - measurement approaches: component mass balance, recipient system mass balance, newly discovered hotspots, recent direct measures of NEP and old problems re-emerging…

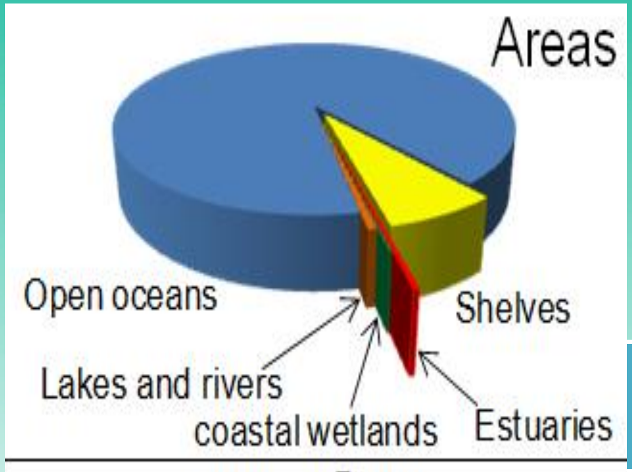

Mangroves

Salt marshes

Distribution of tidal wetlands



- Intertidal distribution from must below MSL to just above MHHW
- Ephemeral - arising only in past 4-8k yrs - peat ages to 8k yrs
- Dynamic - ability to trap sediments and accrete vertically, to prograde into open water areas, and to transgress terrestrial landscape – often in parallel with SLR
- Geological succession typically defined for building phase only. Few areas where we've seen reversals – e.g., LA and Nile deltas and New England marshes



Global Tidal Wetlands C Sequestration Budget

	Area (km^2)	C Burial Rate ($gC\ m^{-2}\ yr^{-1}$)	Global C Burial ($TgC\ y^{-1}$)
Mangroves	137,000 – 200,000	120 - 226	31 - 45
Salt Marshes	200,000 – 400,000	57 – 218	11 – 87
TOTAL			**42 - 132**

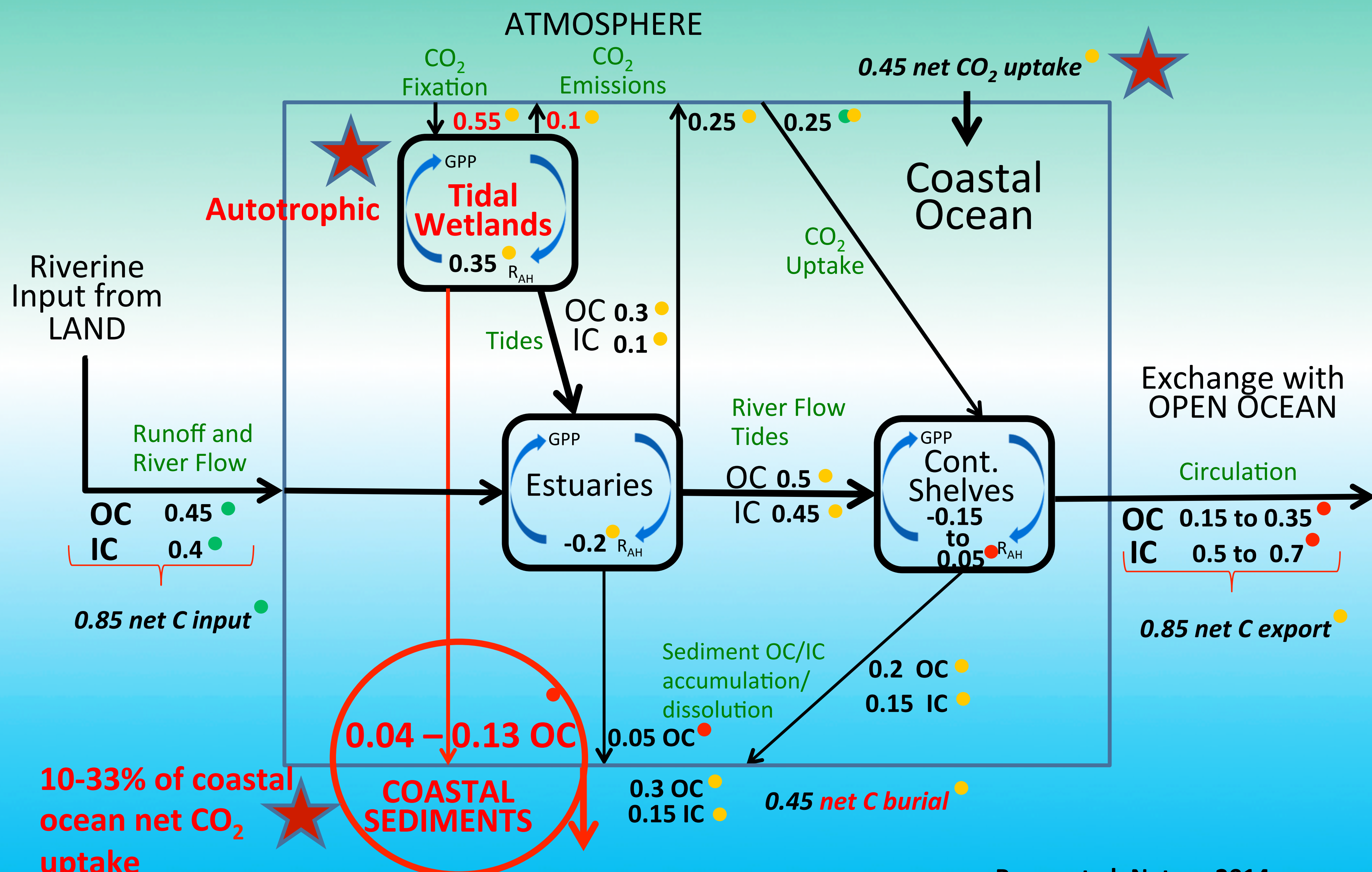
Hopkinson et al. 2012

Steps in Budget Creation

1. **Areal Extent**: Estimates from the literature (km^2) (1/2 already lost)
2. **Burial rate**: Estimates from the literature
    1. Derived from measures of **sedimentatio**n ($cm\ y^{-1}$ based on ^{14}C, ^{210}Pb, ^{137}Cs, SET, surface plates)
    2. Measures of **C density** ($g\ C\ cm^{-3}$) typically determined as product of bulk density ($g\ dry\ cm^{-3}$) and C content (%C from TC or LOI)
3. **Area * sedimentation rate * C density = C Burial**

Seldom is C sequestration the goal when any of these measures are taken
Tremendous variability at plot level, within sites, across sites and geographic regions

Coastal Ocean C Budget – PgC y^{-1}

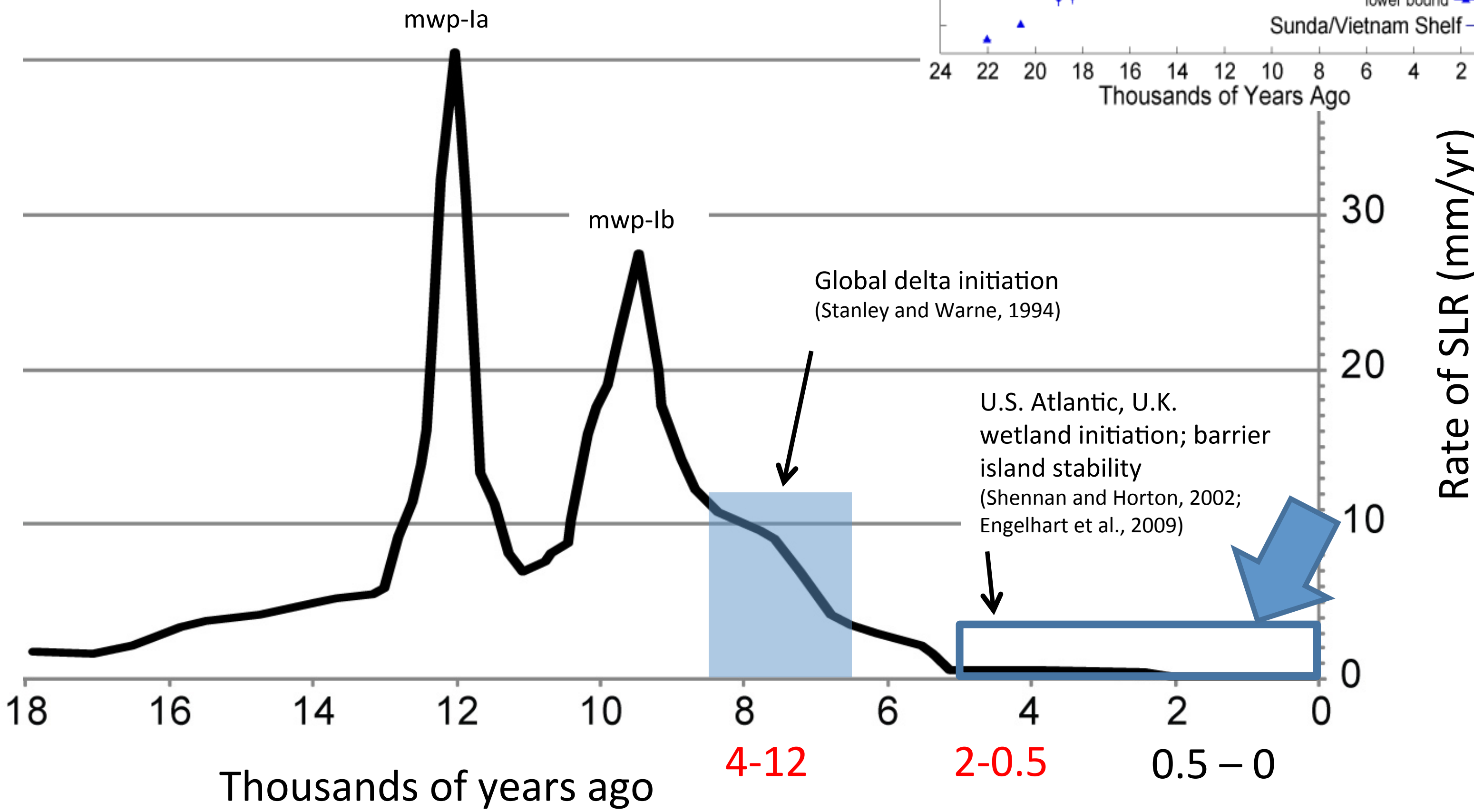


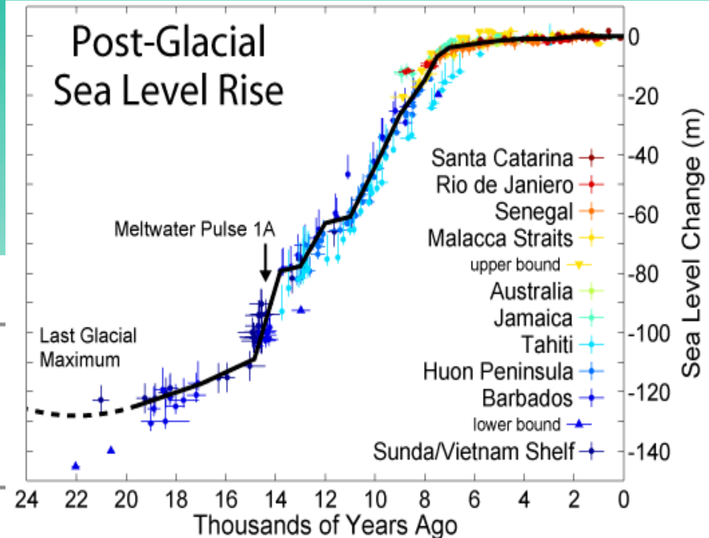
Bauer et al. Nature 2014

Geomorphic evolution

- Ontogeny of a tidal wetland since last glaciation
- Current configuration
- Future – predicting effects of SLRR, changing sediment availability, ecogeomorphic feedbacks
  - Won’t discuss relative impact of temperature on P vs R (more R, less NEP)

Wetlands are a "new" system: SLRR since last glacial maximum





(Slide courtesy of Rob Thieler, USGS)

(SLR rate based on Fairbanks, 1989)

Peat Depths in Barnstable Marsh – data used for Redfield's ontogeny model

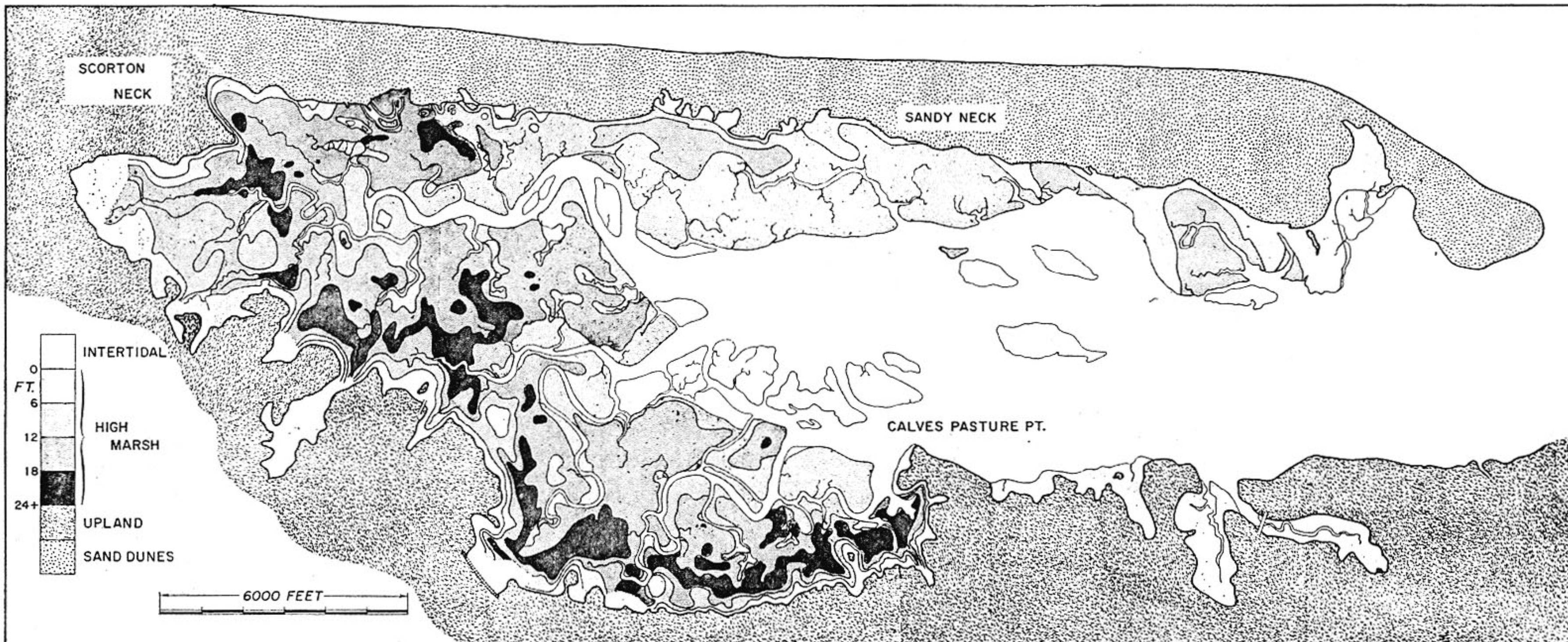


Fig. 2. The Barnstable Estuary, showing the distribution of depth of peat in the high marsh. Contour intervals, 6 feet.

Redfield 1967

Wetland evolution over past 5,000 yrs

when SLRR was 0-0.5 mm/yr

Redfield 1967

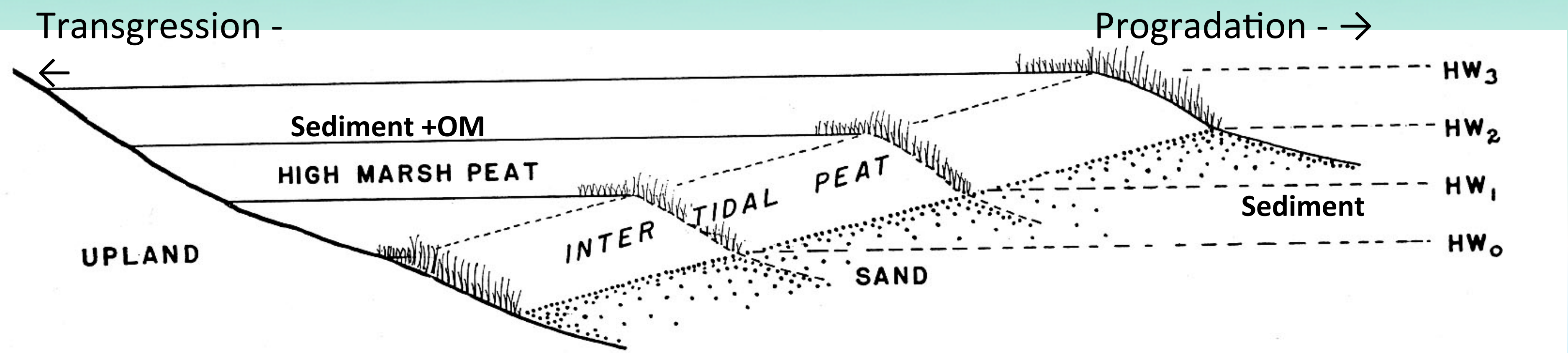
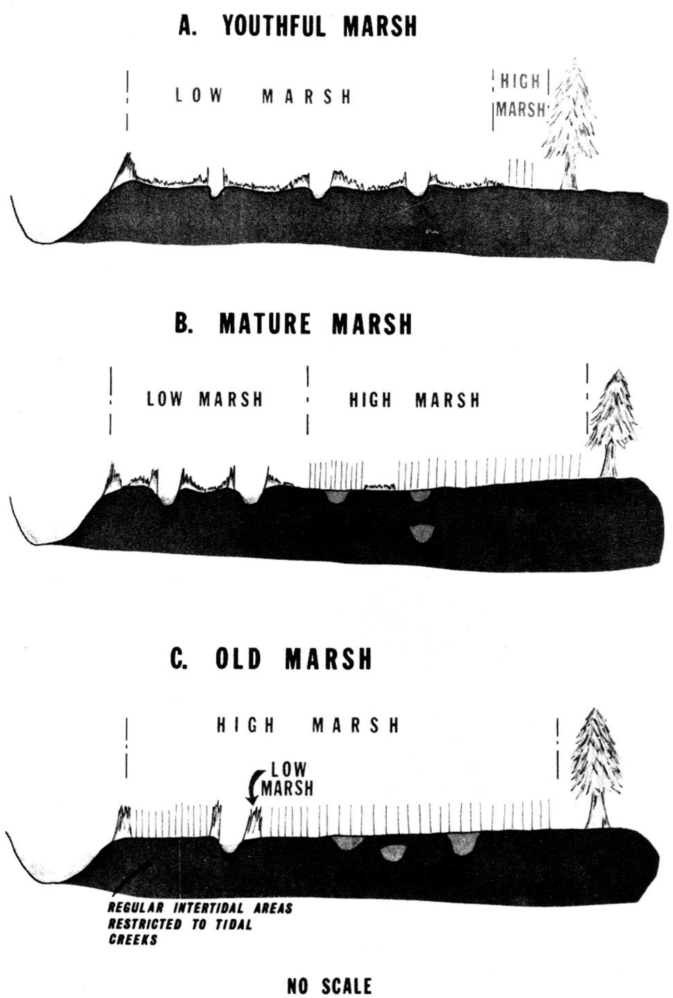


Fig. 1. Development of a typical New England salt marsh with rising sea level and continued sedimentation.

As sea level rises, elevation of the marsh surface increases as increased tidal flooding enhances plant production and allows mineral sediments to accumulate and organic matter to be buried.

- Progradation is 100% sediment-limited and reflects watershed and coastal sediment supply
- Accretion is sediment and OM-limited – e.g., autochthonous peat production
- Transgression is topographically limited, and proceeds in accordance with SLR

There is much more than just wetland presence or absence however: wetlands build in a 3D sense – "evolving" over time – flux implications
Frey Classification of Marsh Developmental Stages



Mostly low marsh, well developed, high density drainage systems, pronounced topography, rapid sedimentation rates

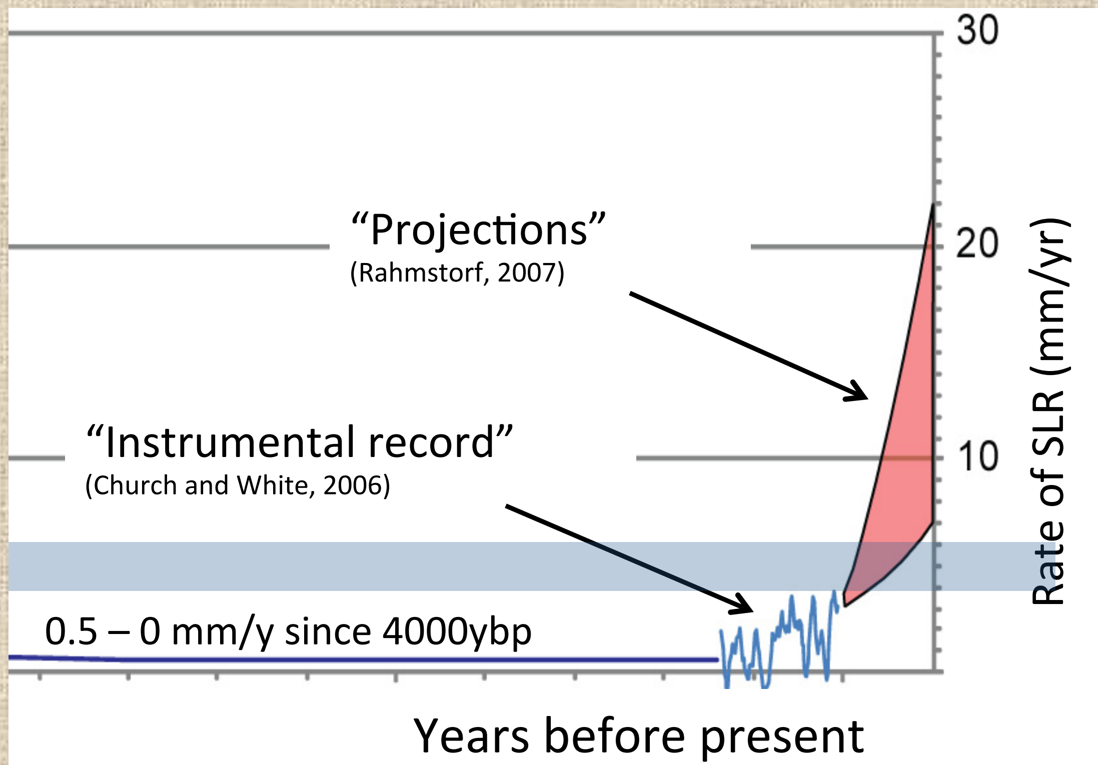
Approximately equivalent areas of high and low marsh (S. patens in NE), good drainage in low marsh, but infilling in high marsh, relatively slow rates of sedimentation, decreasing up-marsh

Mostly high marsh, drainage channels mostly filled with surface runoff important, planar surface, extremely slow rates of sedimentation,

d. Degrading marsh - needed

Increasing creek length and drainage density, shoreline erosion, increased rates of sedimentation

So what about the future?
Changes in drivers of marsh C sequestration:
SLR / sediment / temperature



mm/yr

14/y 2100

8/y 21st avg

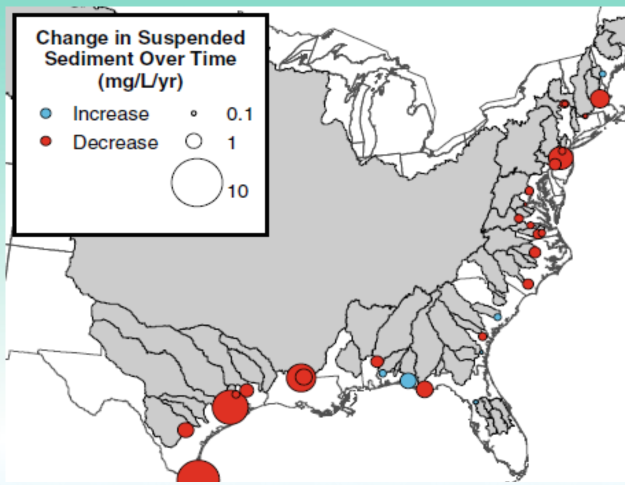
3.2/y -Satellite

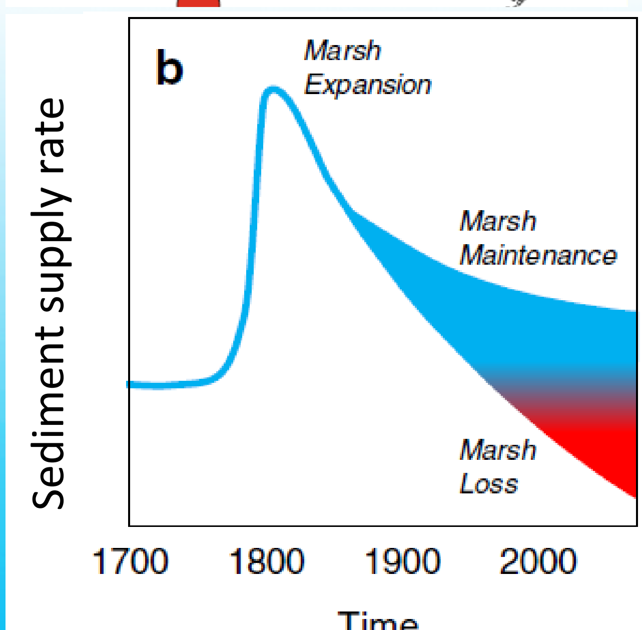
1.7/y - Tide gage

Years before present

Past, present, and potential future <u>rates</u> of sea-level rise

Changes in drivers of marsh C sequestration: SLR / **TSS** / temp





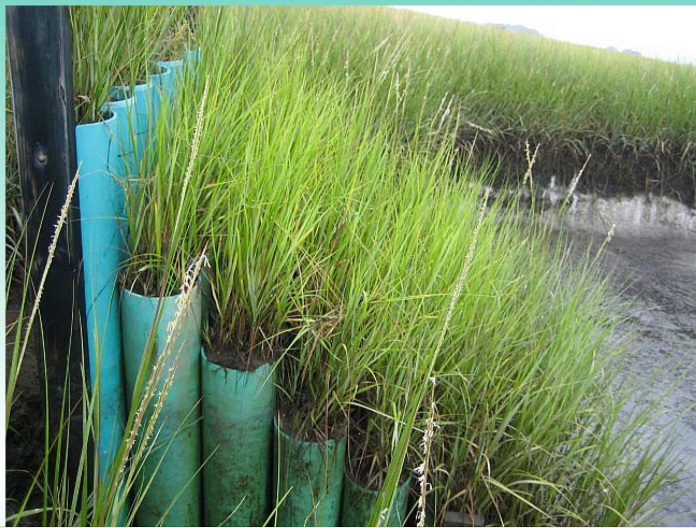
Nat Weston 2013

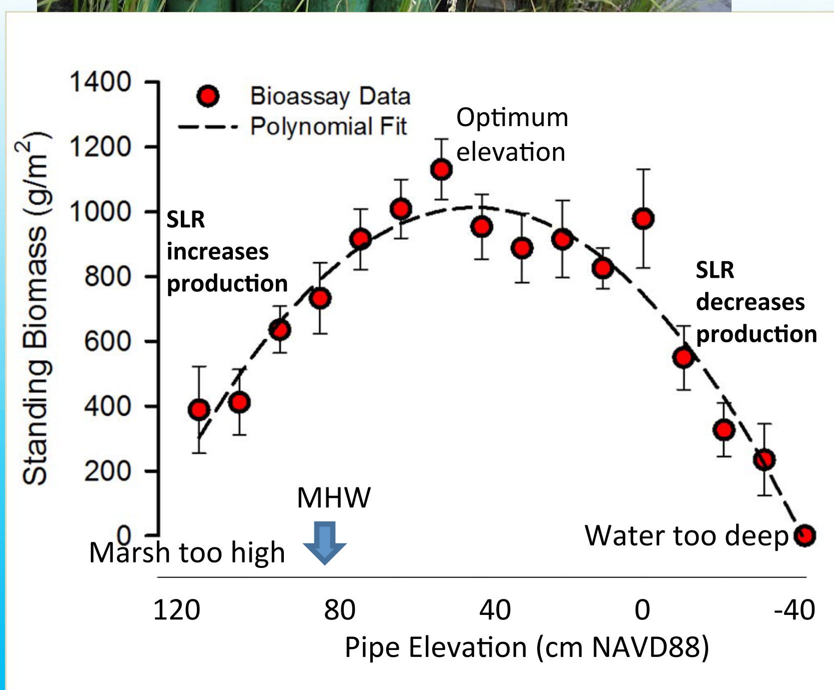
SEDIMENT INPUTS TO ESTUARIES

Variations in export of sediments from rivers to estuaries since colonial days in the U.S.

- Sediment concentration has decreased in >90% of rivers on US east coast past 30 yrs.
- But this trend has changed over time. The large increase in 1800's reflects forest clearing and conversion to agriculture.
- Decreases through 1900's reflect agricultural abandonment, better agr erosion control, dams along rivers.
- Sediment export could be increased locally through dam removal in the future

How will wetland productivity & C sequestration respond to changing SLRRs and sediment inputs?





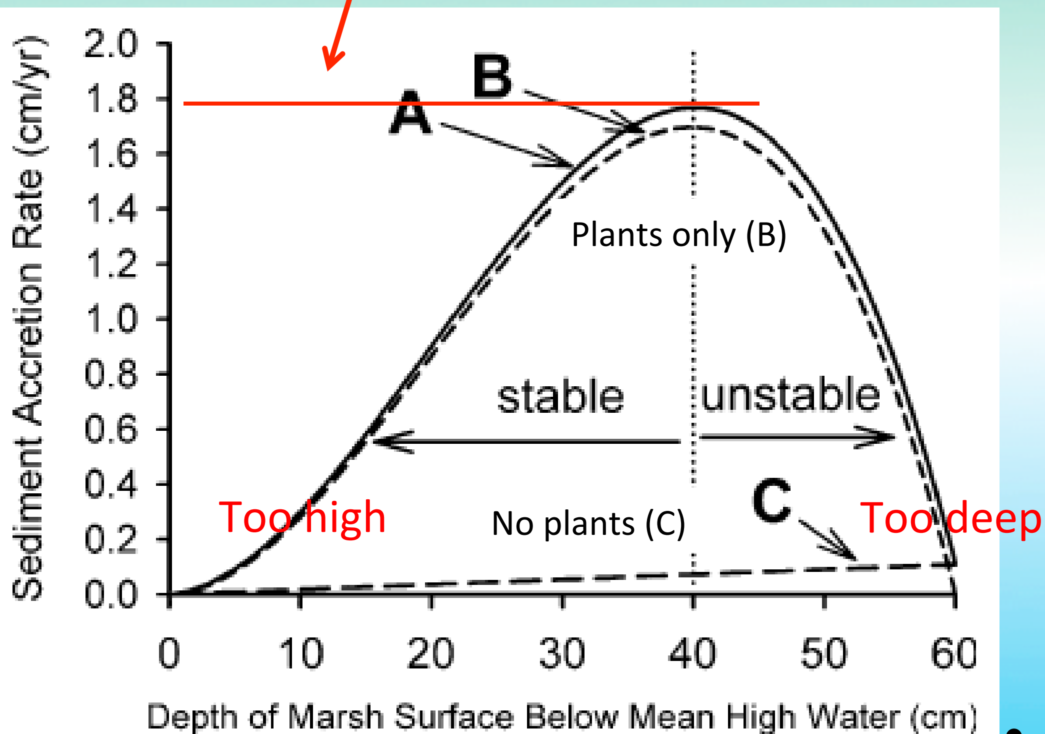
Ecogeomorphic feedbacks:

- Plants have an optimum elevation relative to flooding depth – not too much or too little
- Biomass increases with SLR when marsh is above optimum elevation
- Biomass decreases with SLR when below the optimum elevation
- e.g., biomass of high marsh will increase, while low, creekbank marsh biomass will decrease
- Optimum elevation defines the tipping point - stable/unstable

Jim Morris 2002 and 2007

Effect of plants on sediment trapping

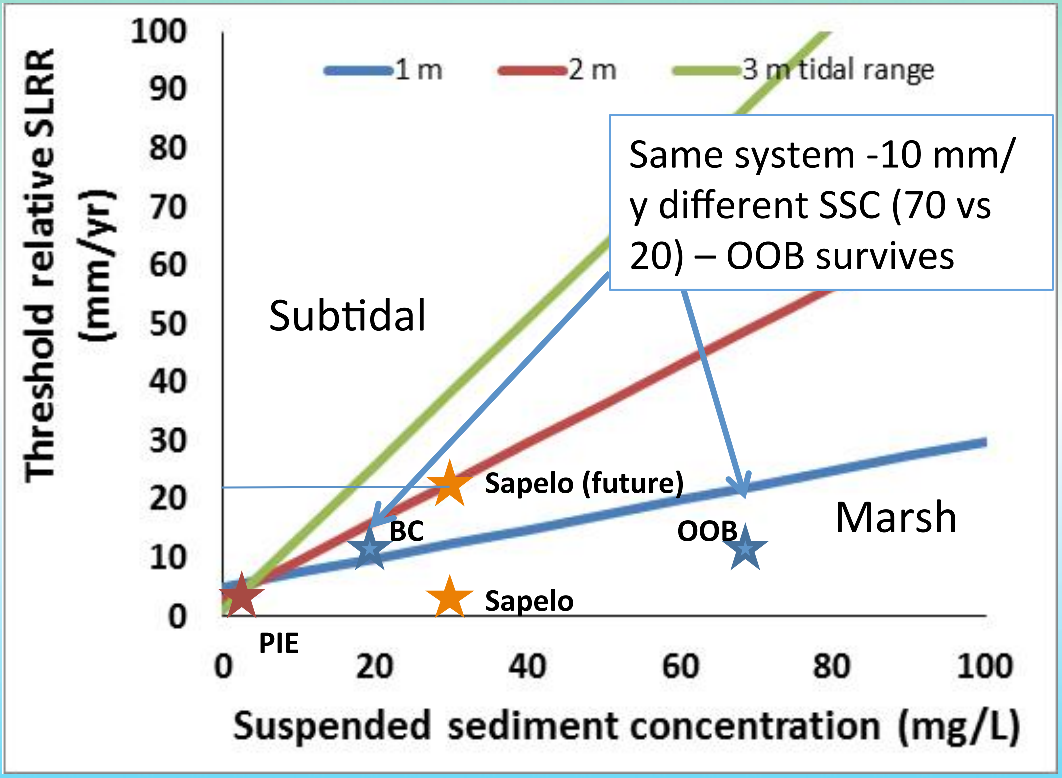
Threshold rate of SLR above which this marsh will not survive



Morris 2007

- Accretion rate is greatest at an elevation just below the elevation of maximum plant biomass.
  - Increased biomass = increased sediment trapping
    - Accretion in absence of vegetation is very low (line C)
  - Increased flooding time accounts for greatest accretion rate being just below region of maximal biomass "trapping" effect
  - At limits, plant biomass decreases to zero – hence little to no accretion
- Effect of SLR on accretion will depend on position of wetland platform relative to elevation of greatest production

Wetland accretion also controlled by sediment availability (TSS) and tidal range



Kirwan et al. 2010

Ecogeomorphic feedbacks enable marshes to persist at SLRR >> than at inception

Threshold rate of SLR -

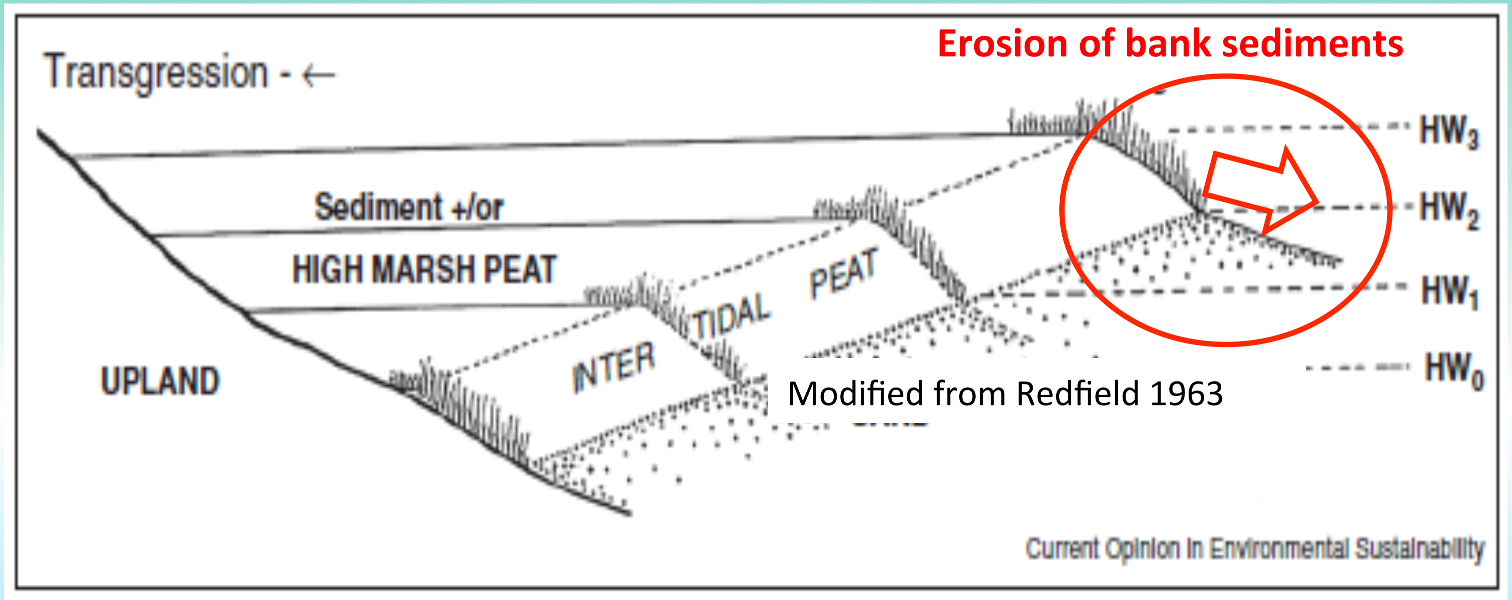
SLRR beyond which wetlands will drown

- Rate is higher in systems with more sediment availability (dam removal option?)
- Rate is higher in systems with larger tidal range

Beyond the threshold –
Initially marshes adjust to increasing SLRR by becoming "deeper" relative to SL.
When flooding depth > optimum biomass depth sediment trapping will drop off and accretion will slow to the point that SLRR > accretion rate

SLRRs in excess of bay infilling can reverse progadation

Mariotti and Fagherazzi 2013



- Shoreline erosion controlled by tidal flat width, which depends on continued sediment inputs
- SLR increases tidal prism volume and thus tidal currents and erosive forces. Tidal flats decrease is size without new sediment.
- Erosion of creek and bay creekbank marshes increases, thereby decreasing total marsh extent
- C sequestration decreases / perhaps reverses if peat is oxidized

Creekbank / Marsh Edge Erosion

- Liberated marsh sediment then available for marsh surface deposition
- Erosion of Yantze delta subtidal sediments help sustain tidal wetlands

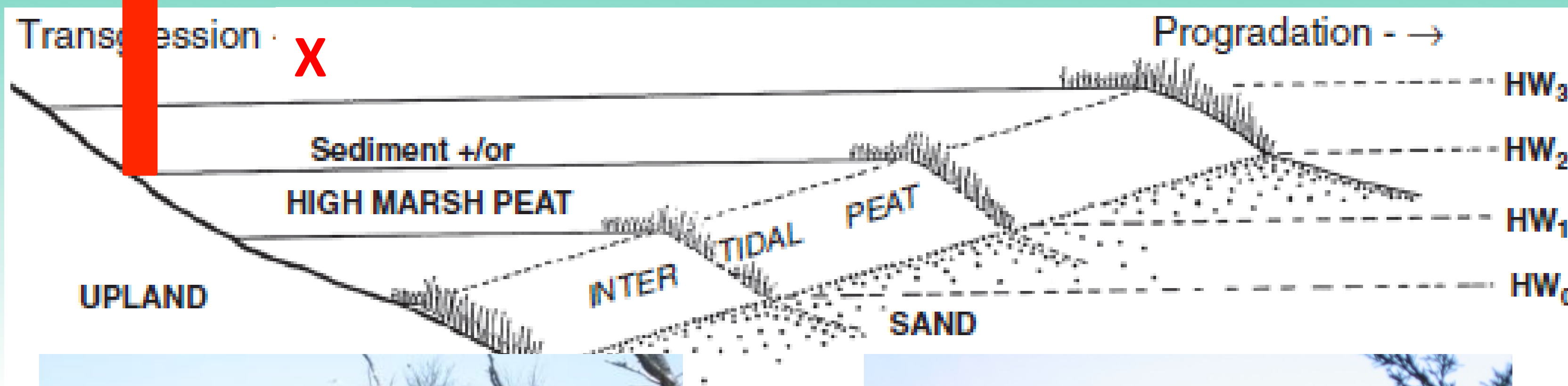
Erosion of marsh scarp

From Mariotti and Fagherazzi 2013
Plum Island Estuary

Tidal Flat ← Marsh

SLR will increase transgression, but only in absence of armoring

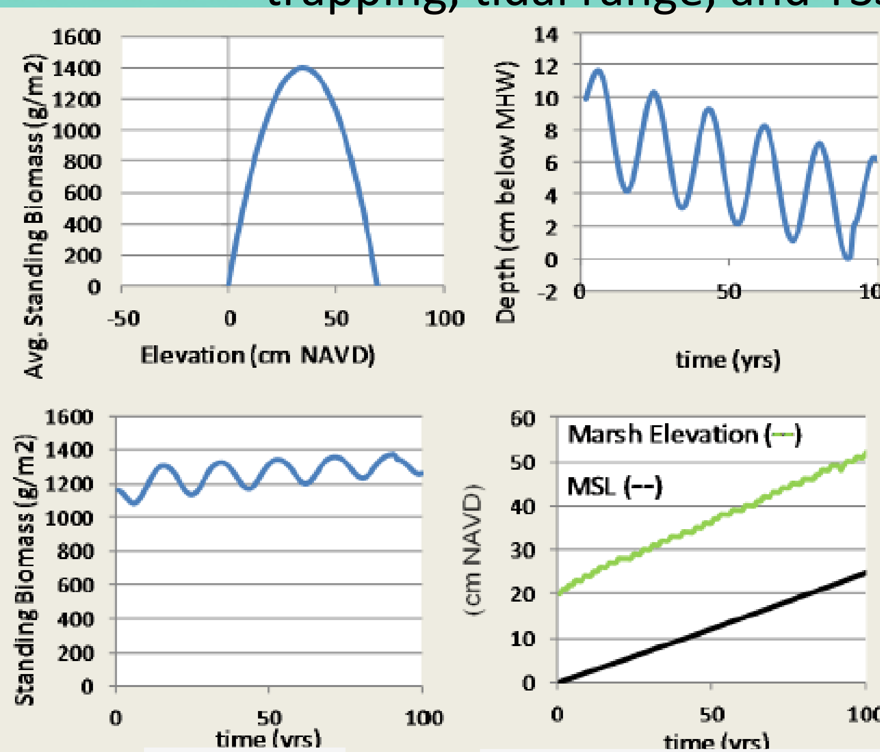
Bulkheads limit tidal penetration into uplands



- Armored shorelines prevent rising tidal waters from flooding uplands, thereby halting transgression – Sequestration potential decreases
- With such a large fraction of the human population living in the coastal zone, armoring will be an increasingly common practice

Morris Marsh Equilibrium Model

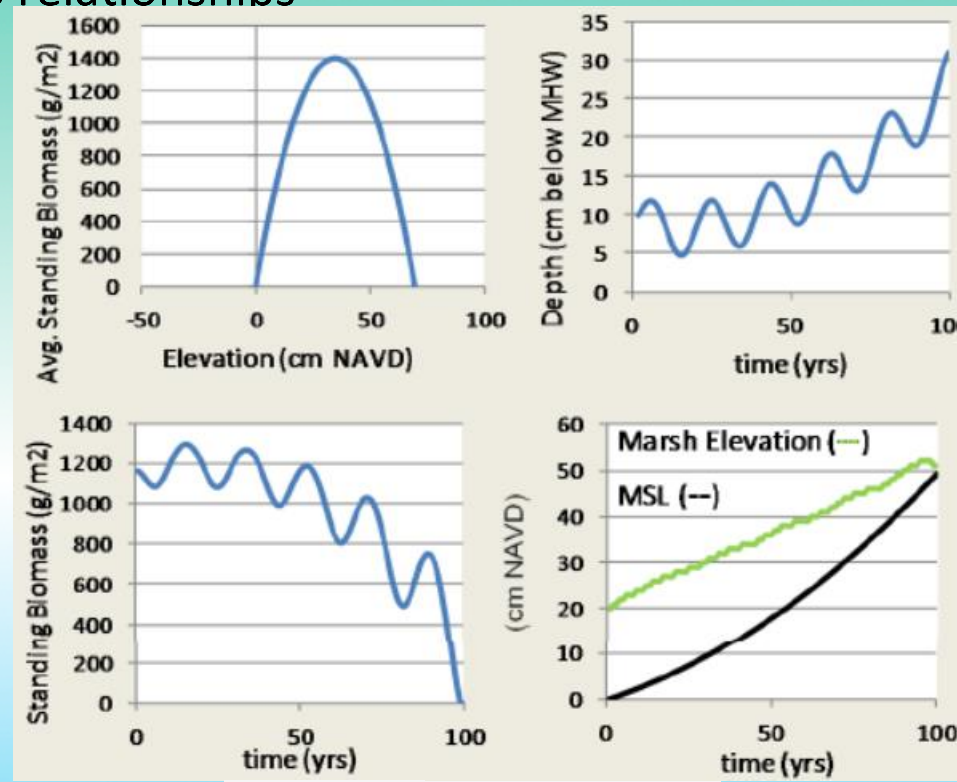
Demonstrates combined effects of flooding vs biomass, biomass vs trapping, tidal range, and TSS relationships



Biomass

Marsh Elev & MSL

Time (0 to 100 yrs



Biomass

Marsh Elev & MSL

Time (0 to 100 yrs

Microtidal, TSS 25 mg/l, 25 cm SLR by 2100

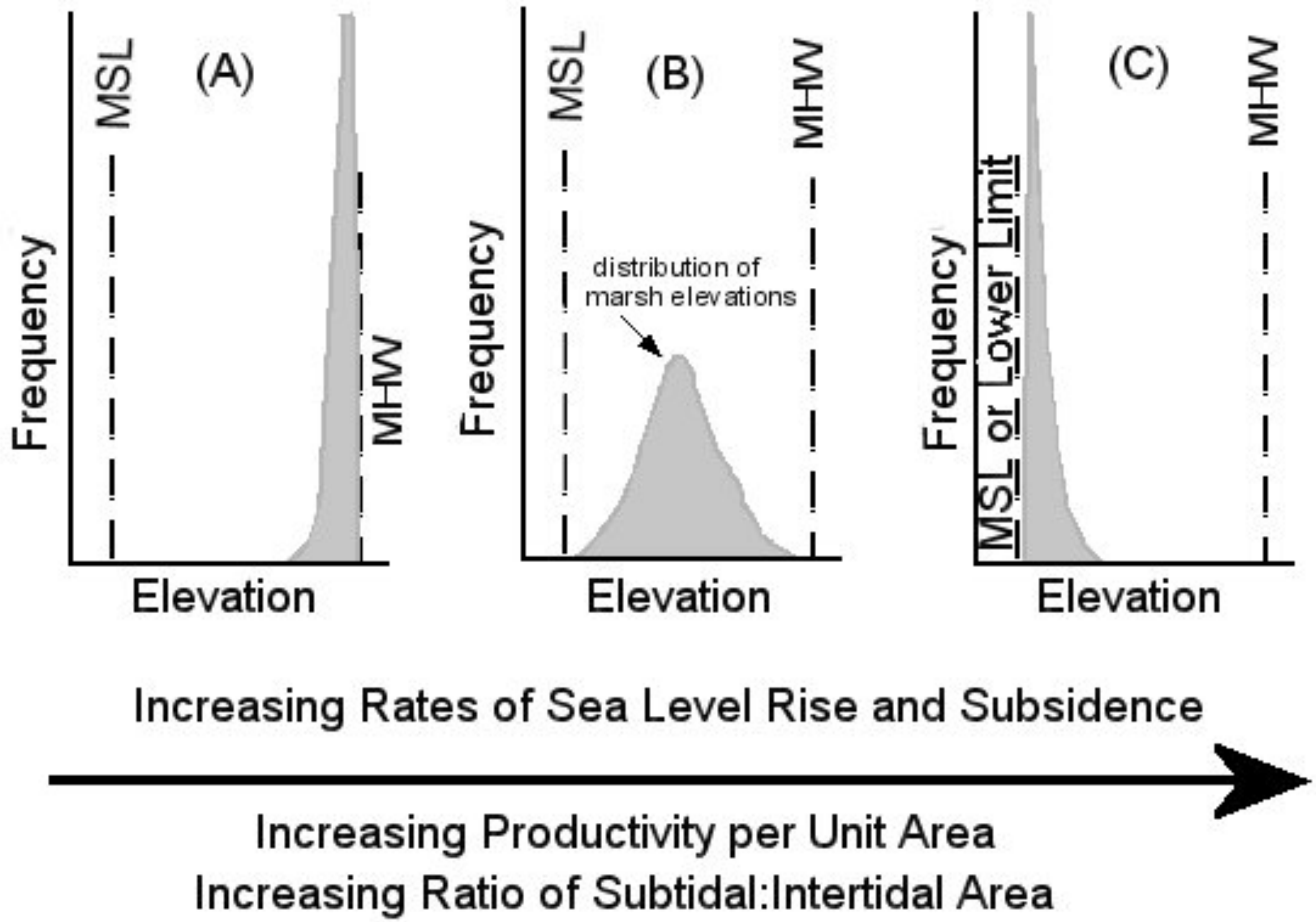
System survives and
C sequestration rate increases

Microtidal, TSS 25 mg/l, 50 cm SLR by 2100

Biomass declines, accretion declines,
C sequestration reverses, system collapses

PREDICTIONS from Morris Model

Hypothesized distribution with slow (A), moderate (B), and rapid (C) sea-level rise.

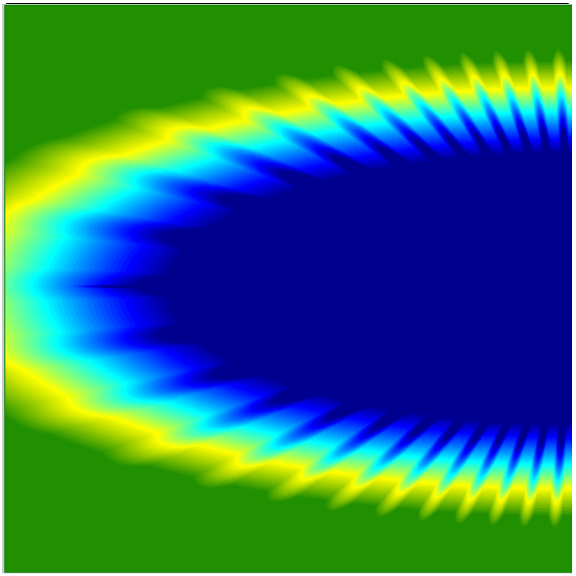


Translation to 3D landscape perspective
Kirwan Model experiment (constant SLRR):

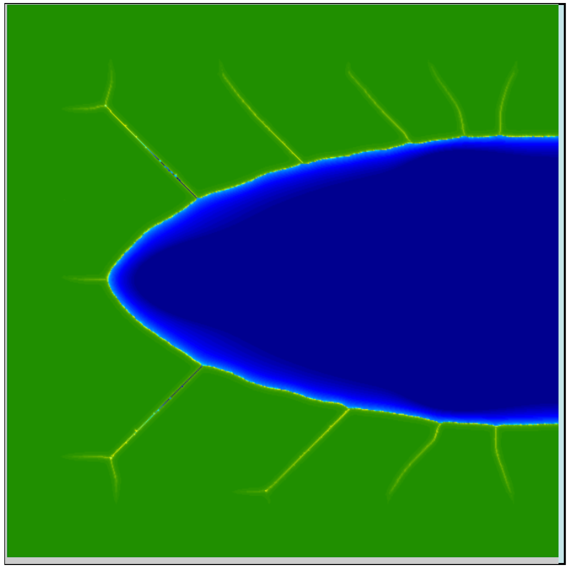
- Accretion rate a function of: inundation depth, vegetation growth, and sediment concentration.
- Channel evolution a function of: discharge, vegetation growth

Low sediment concentration (1000s of years)

High Sediment Concentration (develops in ~100 yrs)

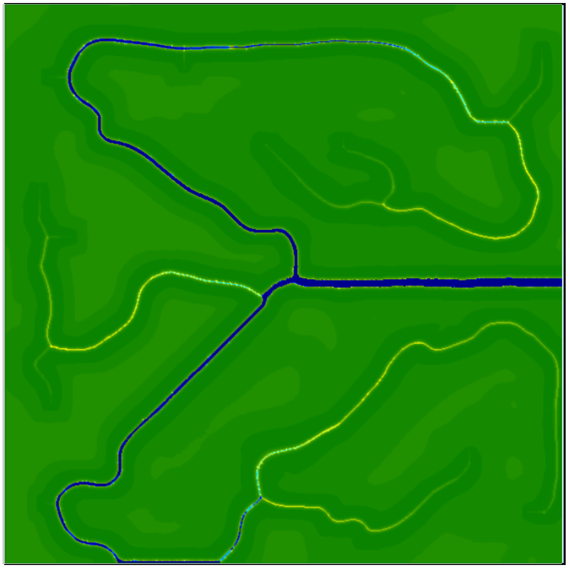


Initial condition: Subtidal basin with Marsh fringe



Platform and channel network develop.

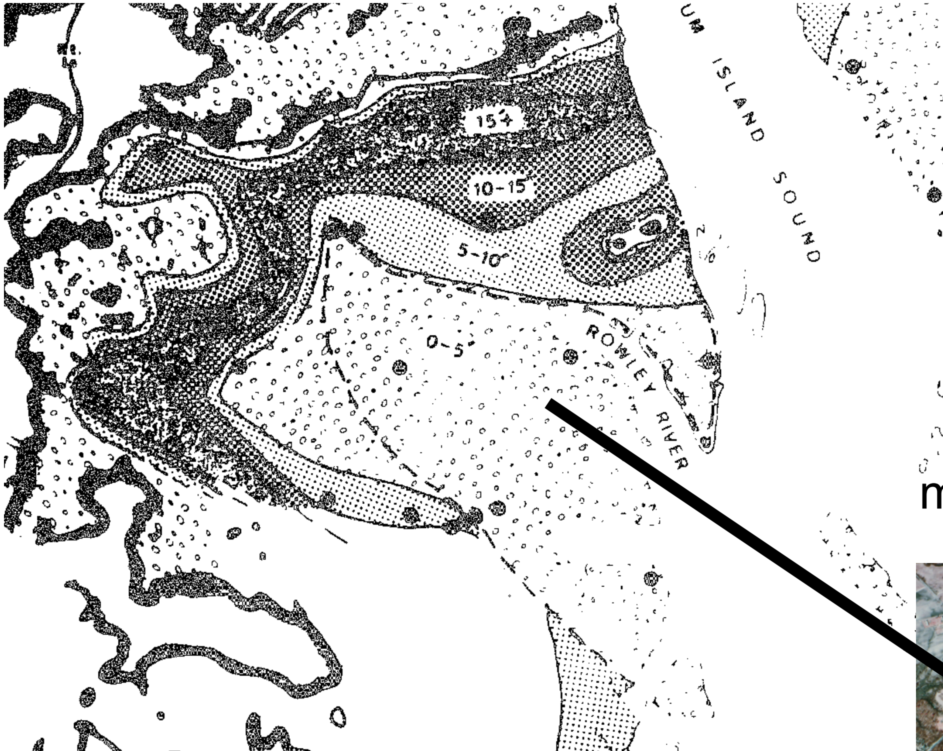
Some marsh progradation, Remains dominated by open water



Sediment supply increase

Rapid expansion

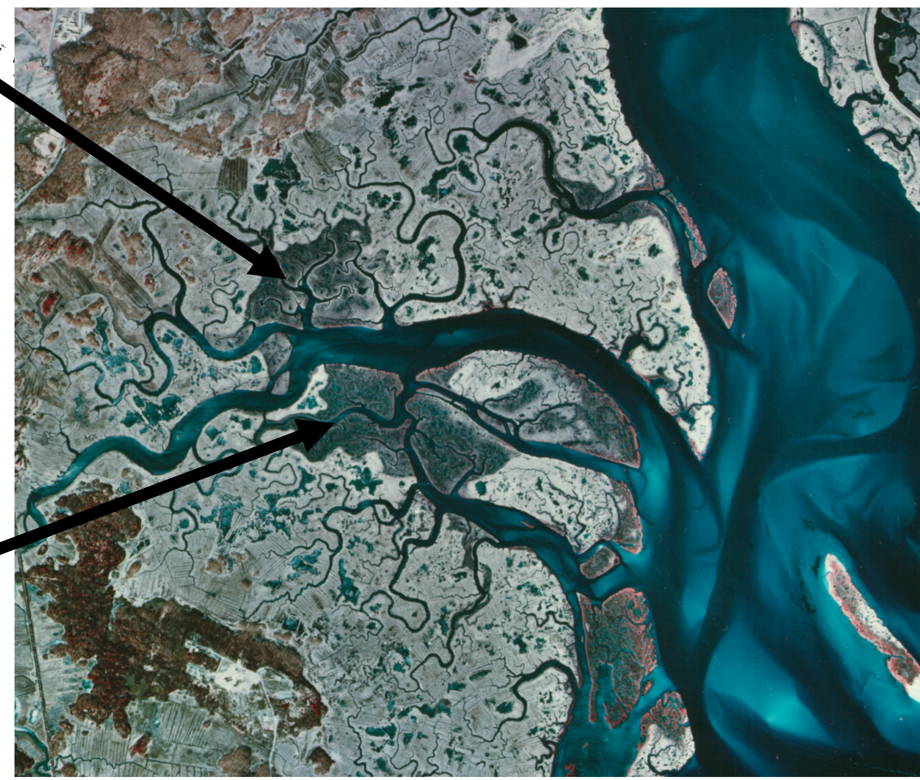
System dominated by Expansive platform



Example of Kirwan model predictions: effect of watershed erosion on marsh expansion

Peat Isopachs from McCormick 1969

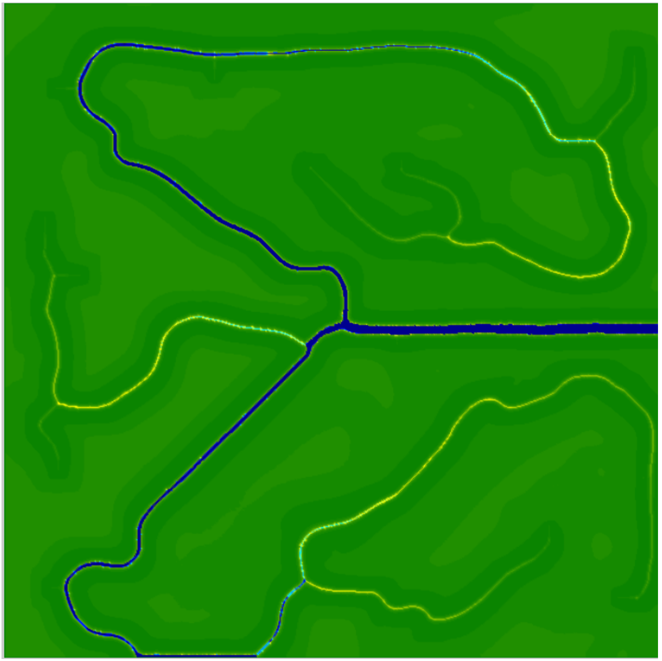
mid-March 1992 Color Infrared photograph



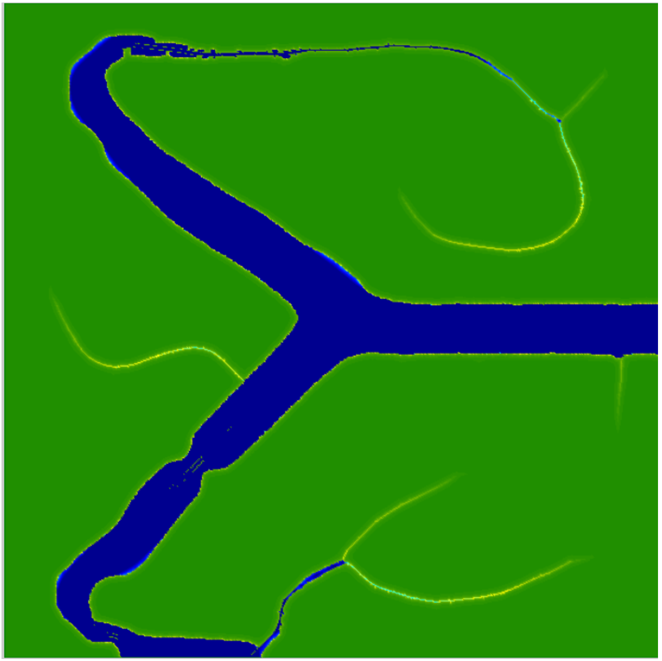
Dark marsh regions highlight low elevation marshes that formed as a result of massive erosion during New England agricultural period

Sediment reduction (still constant SLRR):

high sediment concentration (during land clearance)



low sediment concentration (“pre-settlement” or modern levels)

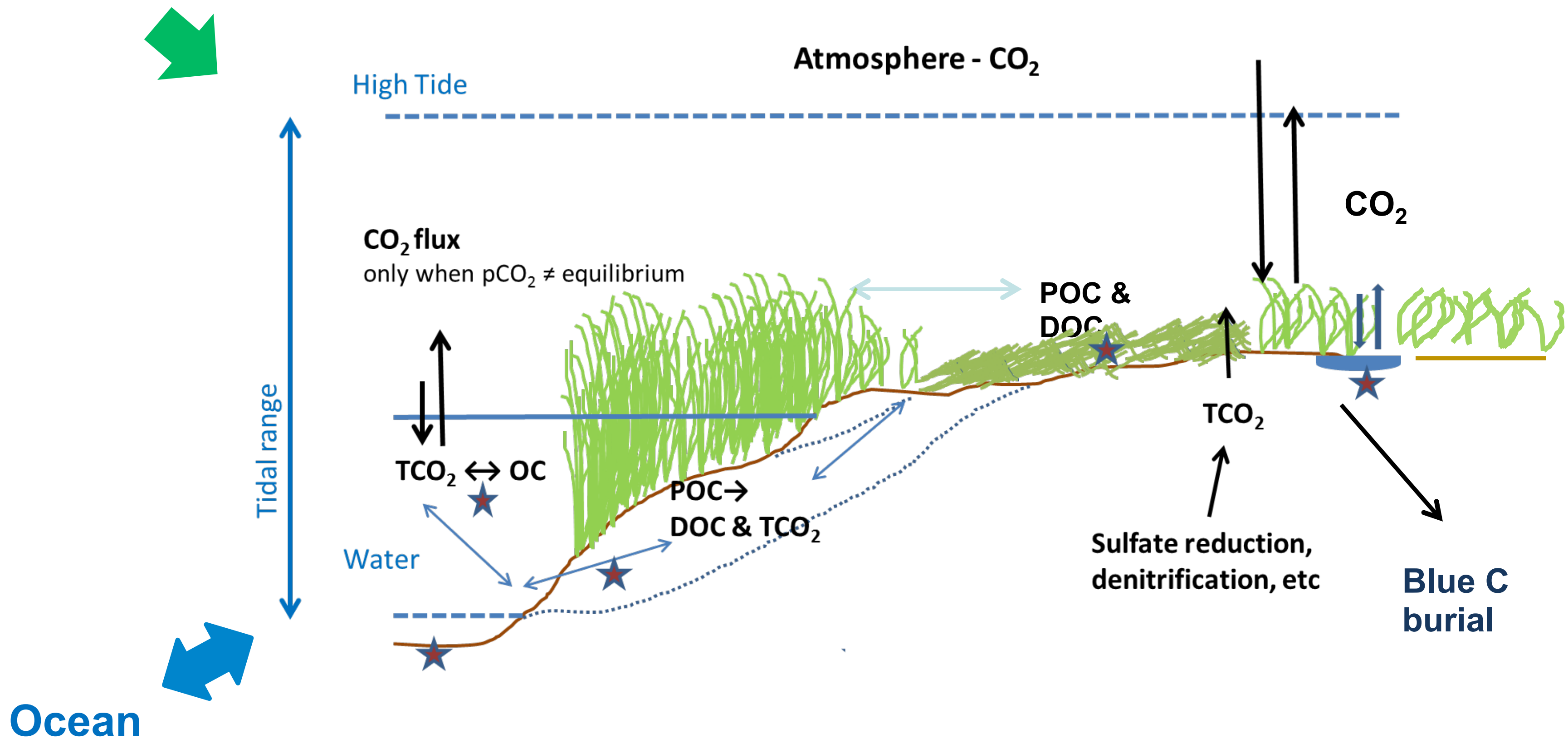


Channels expand, but system remains dominated by expansive platform

Ecogeomorphic feedbacks allow marsh to survive under conditions in which it could not develop!

Massive sediment reduction in estuaries worldwide (reforestation, dams).
Ecogeomorphic feedbacks allow marsh to persist in metastable equilibrium.

Tidal wetland fluxes



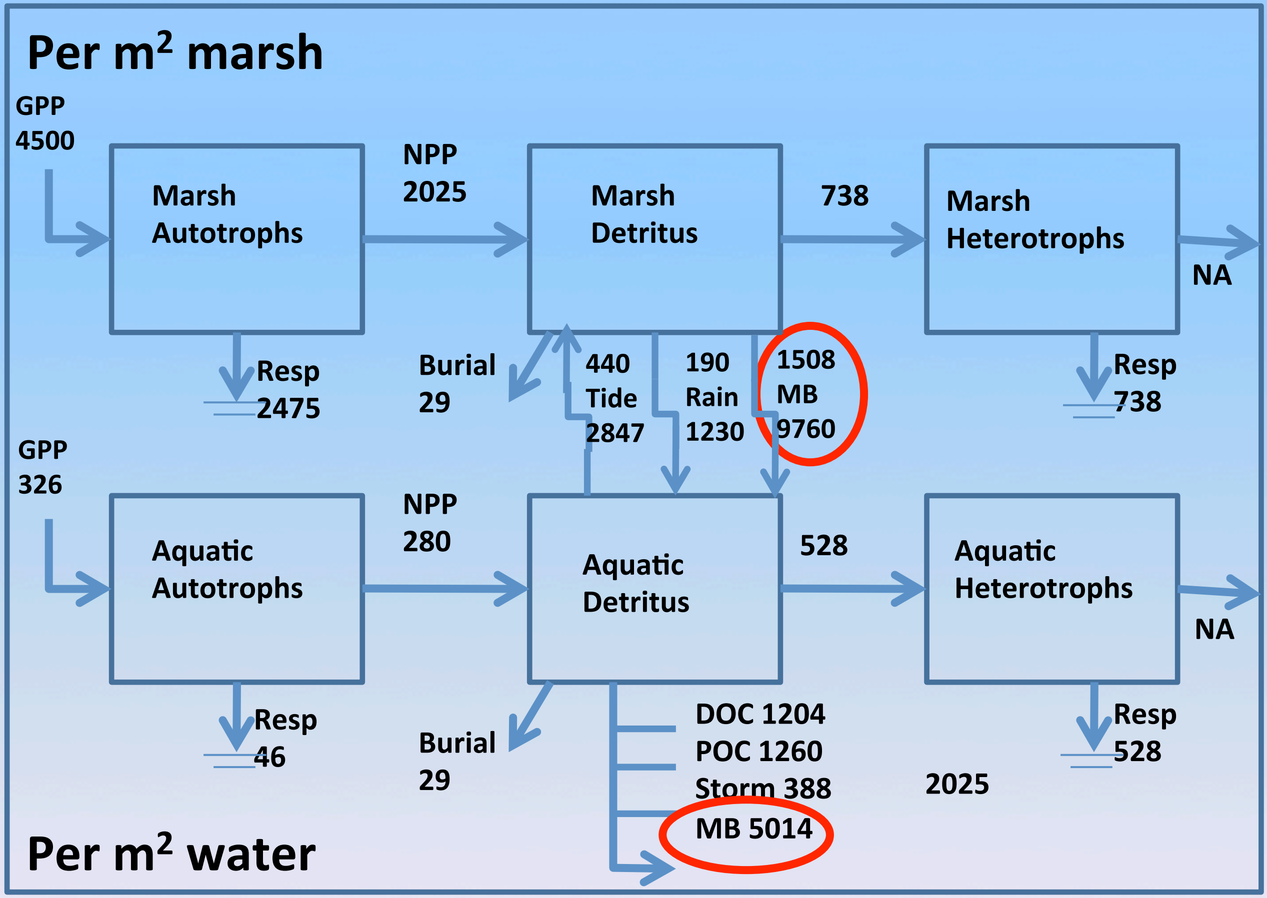
Estuarine creeks and bays

Tidal wetland showing vegetation zones, pannes, and ponds

Salt Marsh C Budget – adding all the pieces, using mass balance for some huge difficult to measures fluxes

Budget based on Sapelo Island, GA – similar for other salt marshes

Units – gC per unit area per yr



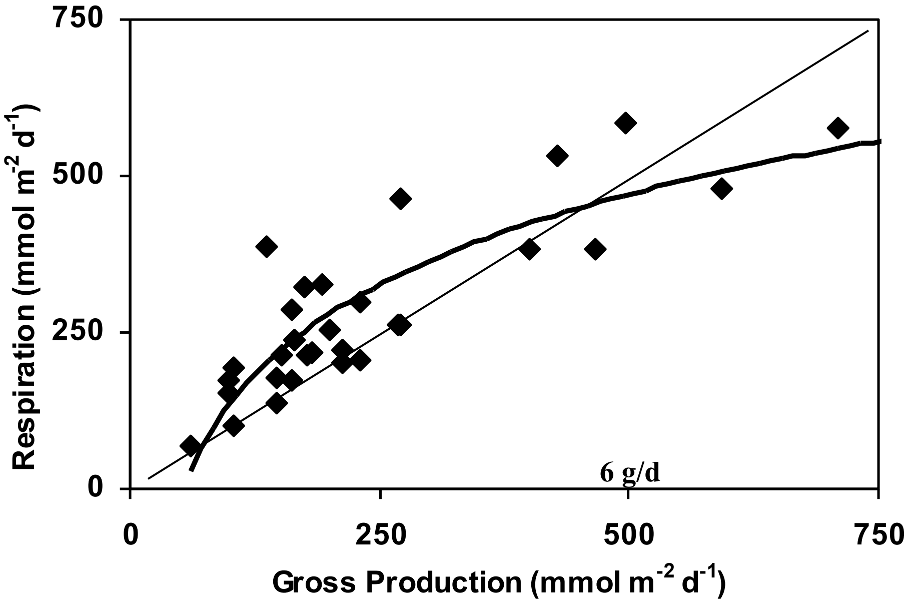
Based on hodgepodge of geomorphic states, large uncertainties and high variabilities in fluxes

Hopkinson 1988

Look at it from the recipient system point of view

Rather than calculate flux from system to system directly or by mass balance, examine metabolism of receiving system and calculate allochthonous inputs by difference

Relation between respiration and GPP for estuarine waters



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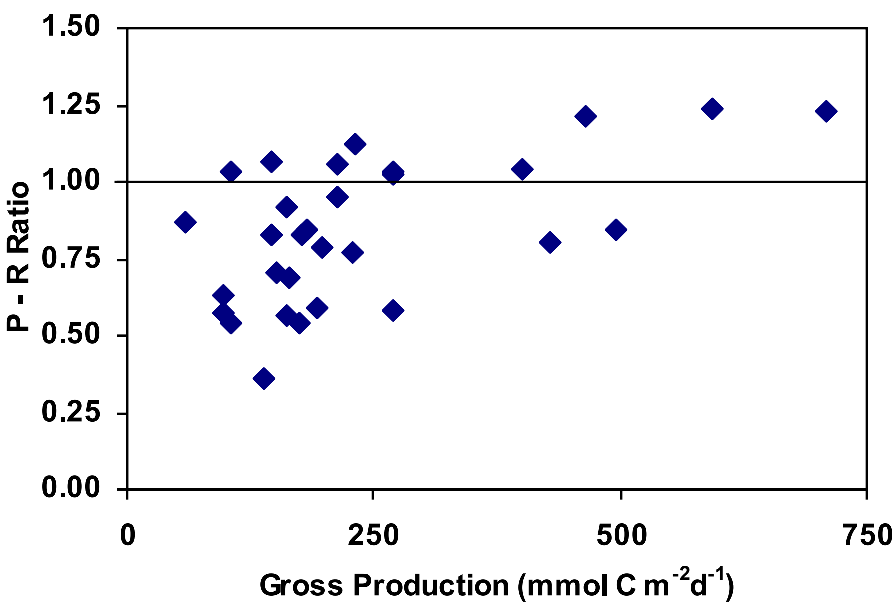


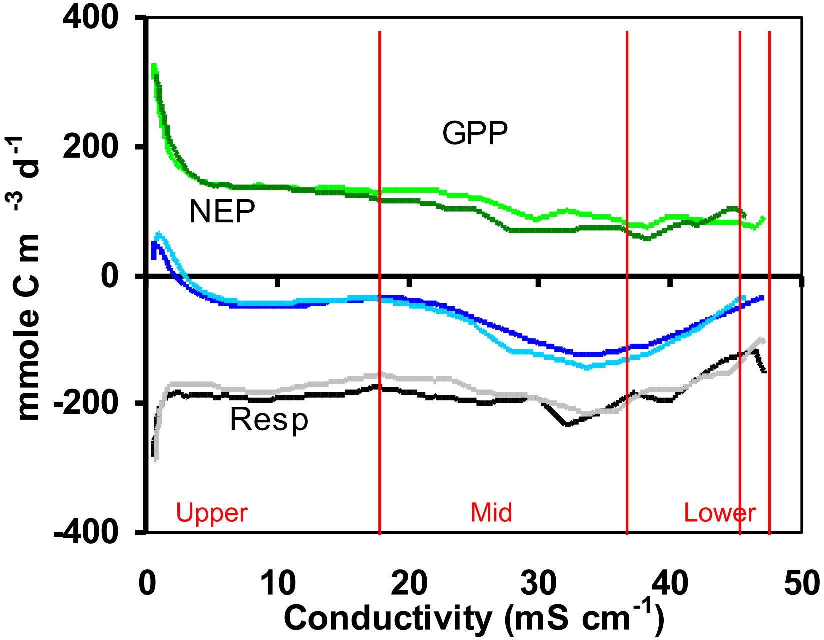
- Respiration closely related to primary production, but at rates common to wetland dominated systems, respiration typically greater than production
- P/R ranges from 0.36 – 1.38, with an average of 0.86. Thus estuaries are typically heterotrophic and dependent on allochthonous inputs

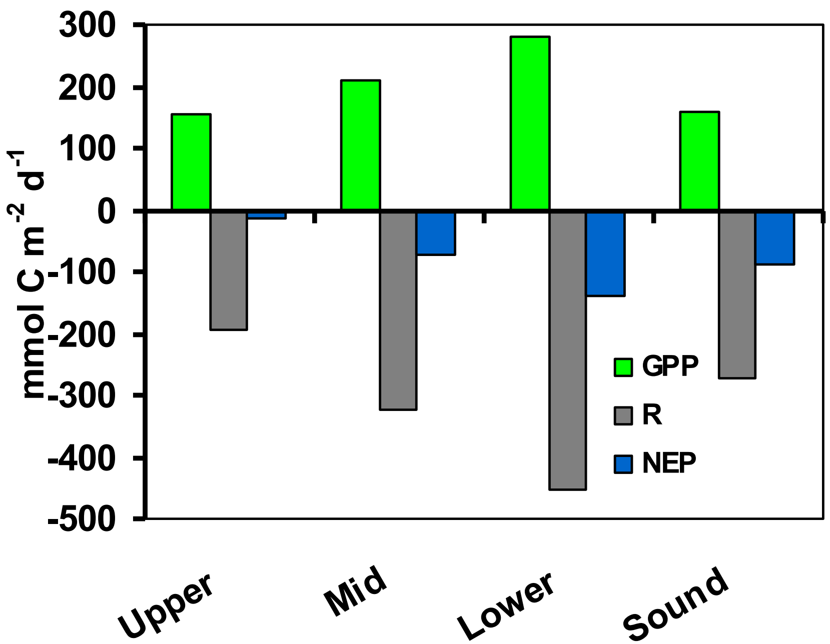
Data J. Caffrey,
synthesis Hopkinson and Smith 2004

Recipient system mass balance

- Total Annual Estuarine Resp: 76-150 x 10^{12} mol C y^{-1}
  - Based on area of 1.4 x 10^{12} m^{-2} (Gattuso et al. 1998)
- Measured inputs:
  - Riverine allochthonous inputs: 34 Tmol C y^{-1}
  - Estuarine autochthonous GPP: 35 T mol C y^{-1} GPP
    - Benthic and pelagic (Smith and Hollibaugh 1993)
- Mass balance for other allochthonous inputs:
  - 7-81 x 10^{12} mol C y^{-1}
  - Presumably tidal wetlands and seagrass beds

Hopkinson and Smith 2004





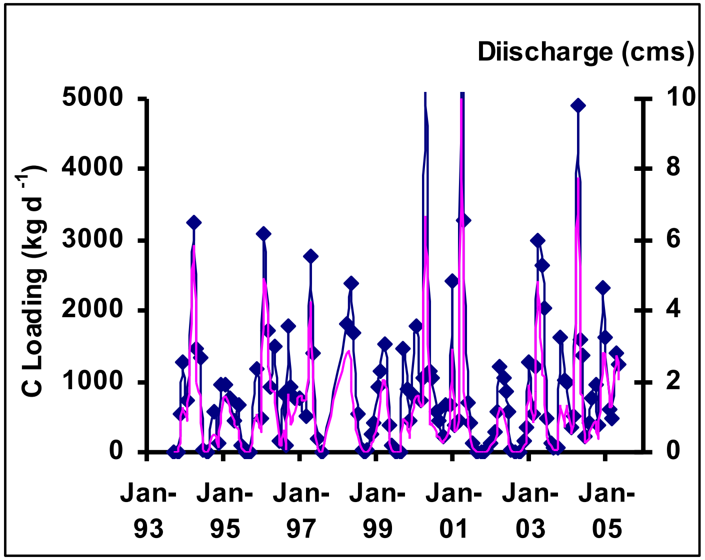
Recipient System Case Study – Plum Island Estuary

Measure aquatic NEP to estimate allochthonous inputs

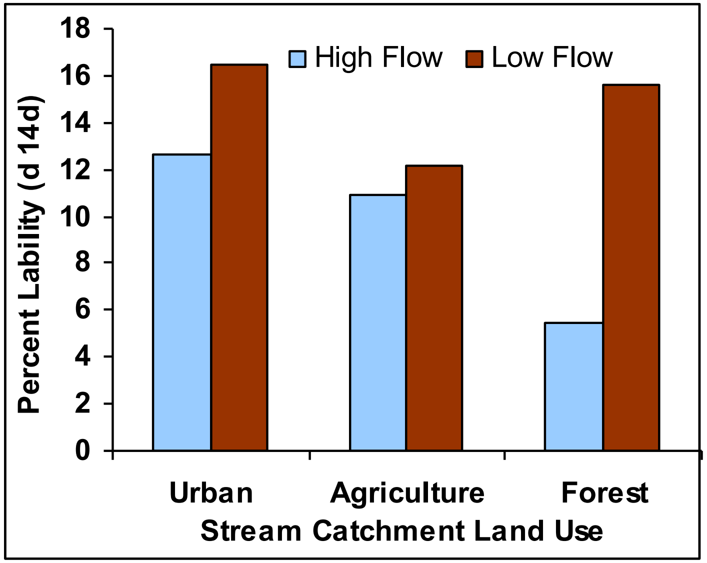
- Balance net heterotrophy with:
  - Measures of labile riverine C uptake
  - C isotope distribution which define other allochthonous inputs
- Final balance must be from marsh

- Here – June example showing general pattern of estuarine metabolism evaluated for 4 zones

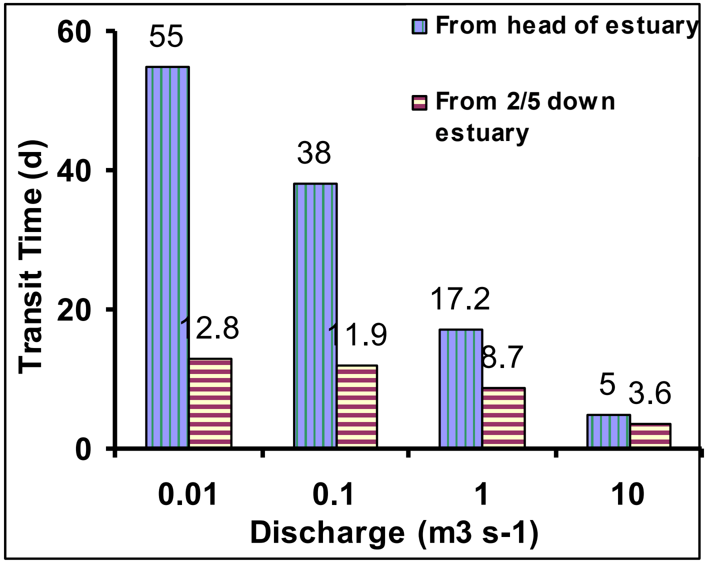
Bioassay Approach to Estimate Watershed C Utilization in the Estuary



- Establish LU – C and H_2O yield relation
- Quantify C and H_2O export
- Establish LU – C lability relation
- Establish runoff – transit time relation
- Calculate potential C utilization (plus account for C flocculation and sedimentation)
- Compare to NEP to evaluate importance

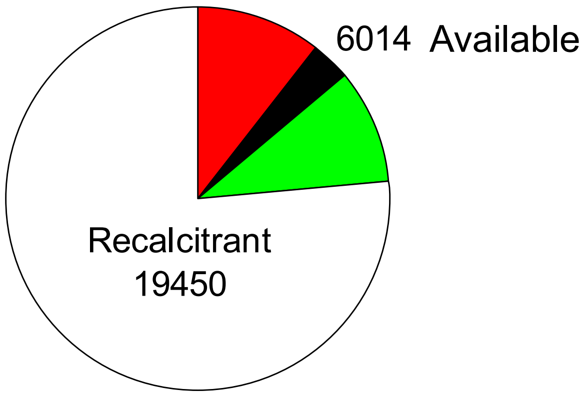


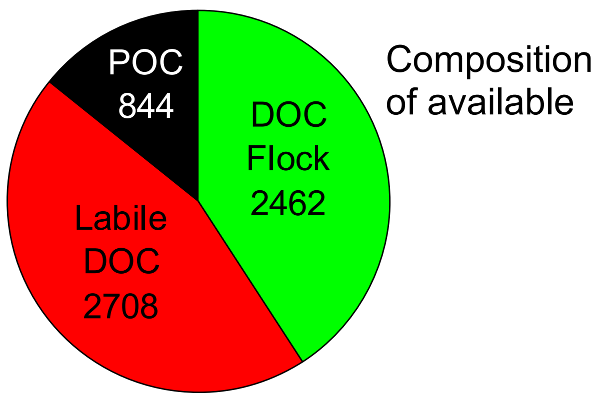
Uhlenhopp et al. 1996

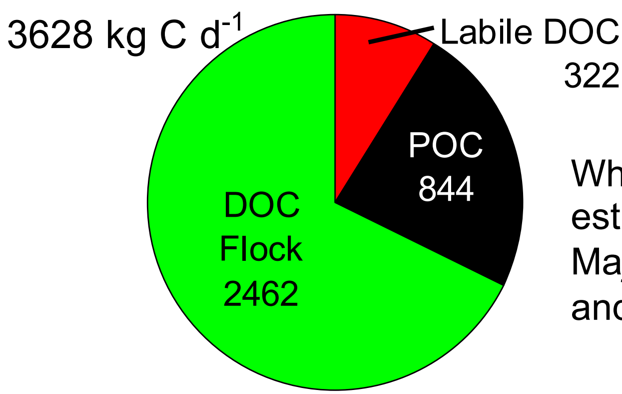


Vallino and Hopkinson 1998

Sources and Fate of Riverine DOC







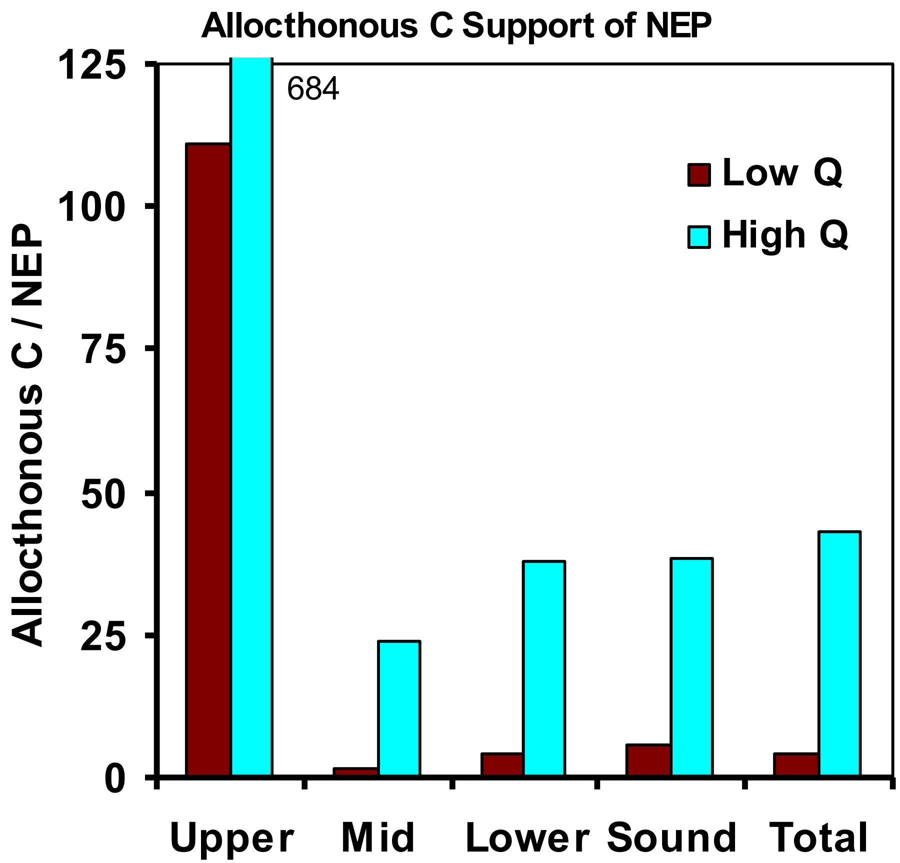
What's actually used during estuarine passage
Major assumption about POC and floc use

25,464 kg/d: Total watershed inputs of C

6,014 kg/d: potentially available (23% of total), assuming floc (10% DOC) and POC settle and labile DOC decomposed

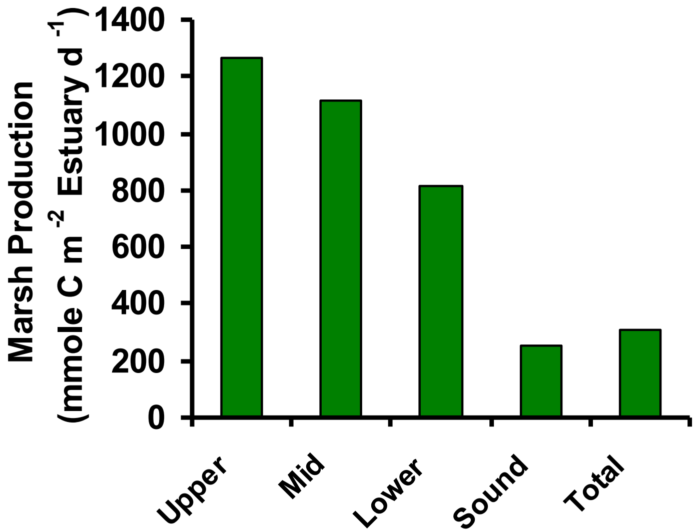
3,628 kgC/d Utilized: based on decomp rate and transit time of labile DOC (12% of labile DOC used)

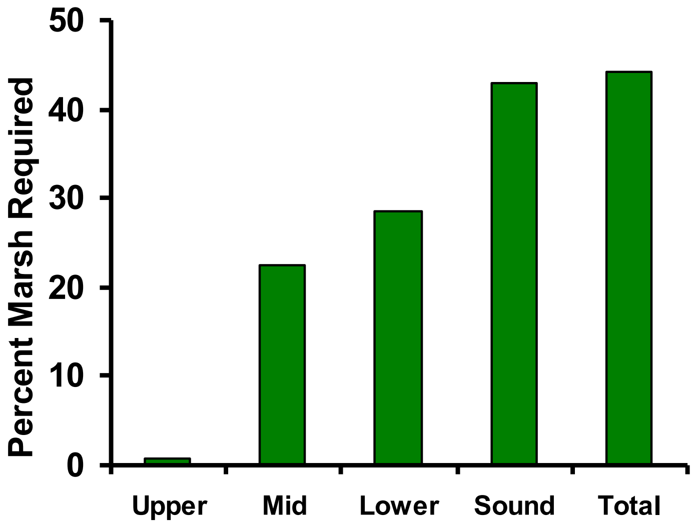
Comparing Bioassay Results to Metabolism - an additional NEP deficit



- Allochthonous watershed inputs meet NEP demand only in upper 5 km
- In remaining estuary, watershed C meets only 1 to 40% of demand.
- The deficit is extreme in summer, during time of minimal discharge (but floc and POC utilization probably spread over year)

What Other OM Sources Fuel the NEP Deficit?





- δ^{13}C and Δ^{14}-DOC, POC and CO_2 isotope distribution indicates role of fringing marshes
  - NPP >300 gCm^{-2}yr^{-1}
  - Marsh area >> water area
- From 1-45% of marsh NPP required
- Mechanisms?
  - Drainage of tidal creek bank DOC and DIC at low tide
    - Drainage DOC>riverine DOC (but unknown lability)
  - A portion of respiration occurs on marsh during high tide

Inconsistency between classical bottle/plot level measures and whole system measures – the importance of hotspots

OBSERVATION 1: $\sum$(benthic + pelagic components) $\neq$ free-water / whole system measures of P and R

- Benthic and pelagic respiration is ½ respiration of free-water respiration

OBSERVATION 2: Benthic and marsh platform denitrification is ½ denitrification of entire system

OBSERVATION 3: Volume and constituent concentrations of creekbank drainage >>> riverine inputs

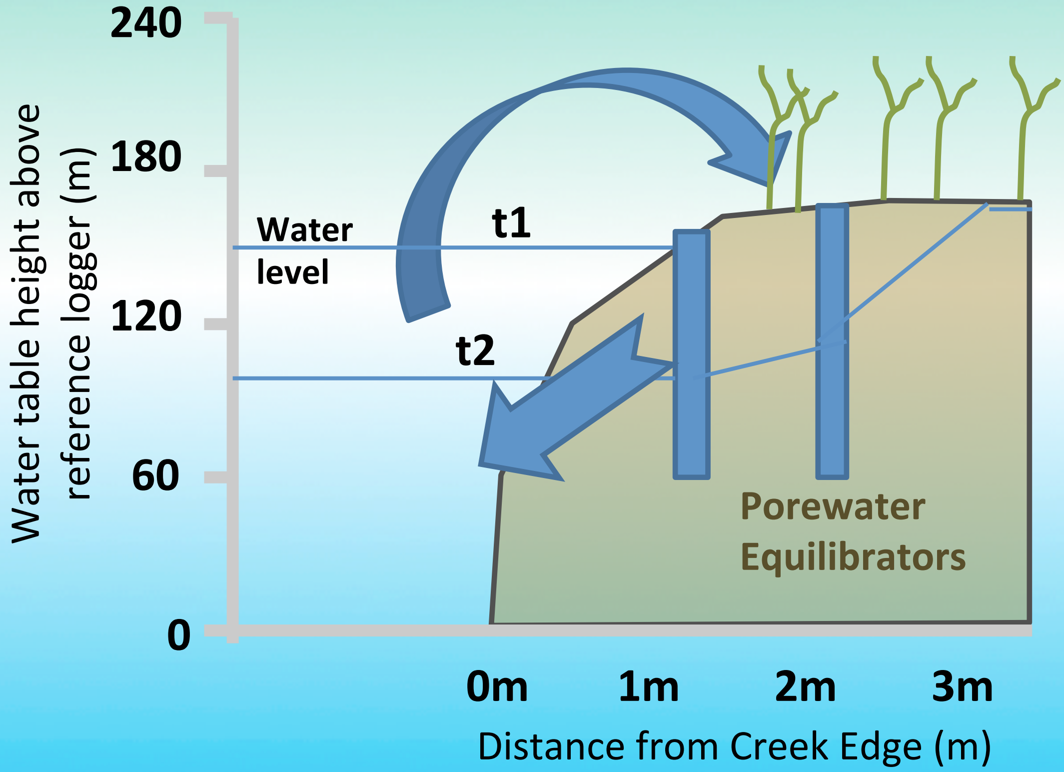
Creekbank edge is an apparent hotspot

Comparison of component and open-water measures of respiration

Based on a synthesis of estuarine respiration worldwide (Hopkinson and Smith 2004)

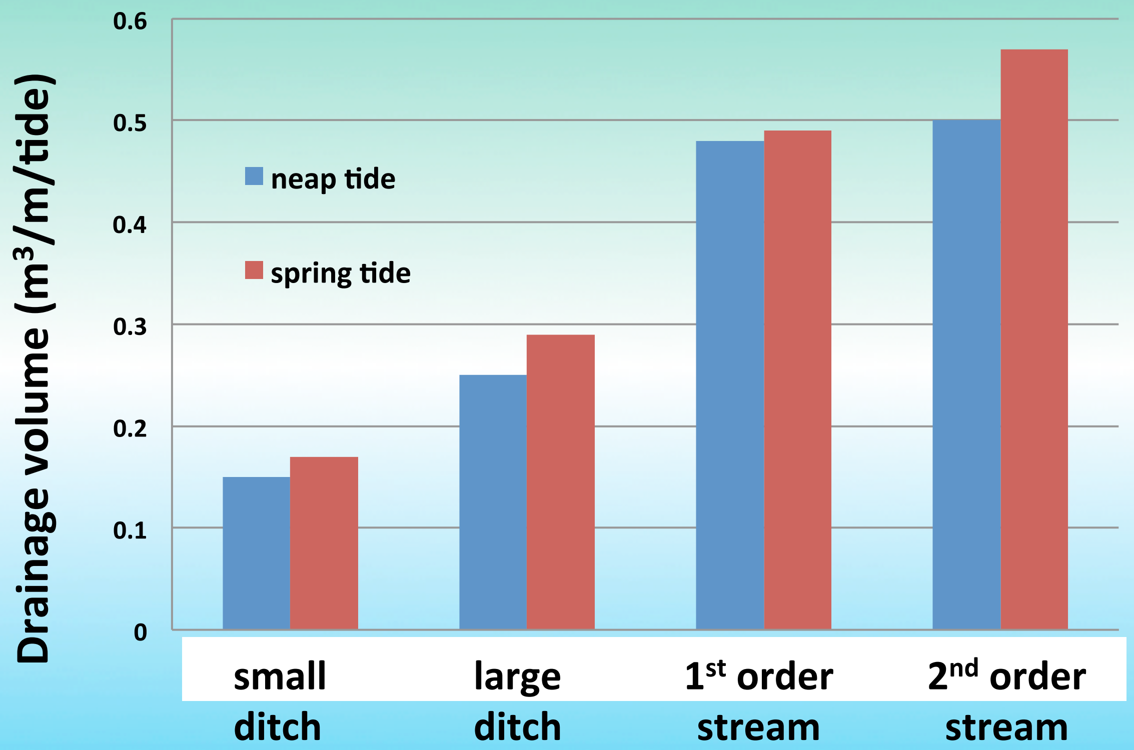
- **Pelagic resp: 114 mmol C $m^{-2}d^{-1}$**
- **Benthic resp: 34 mmol C $m^{-2}d^{-1}$**
  - **Pelagic 4X benthic (consistent with most syntheses showing that 24% of total system production is respired on bottom)**
- **Benthic and Pelagic = 148 mmol C $m^{-2}d^{-1}$**
- **Whole system resp = 294 mmol C $m^{-2}d^{-1}$**
- **Why the disparity?**
  - **Container effects (removal from fresh supplies, stirring, etc), but hard to imagine such a great effect**
  - **Influence of hotspots - adjacent systems not included in containers (e.g., creekbank edge - marsh drainage)**

Creekbank Edge – a link between the marsh platform and tidal creeks



- Tidal water fills / saturates marsh sediment during inundation
- Sediment water above field capacity drains during falling tides
- What is the drainage magnitude, its composition and how does it influence C & N biogeochemistry?

Creekbank drainage volume dependent on stream order



Depth from creek bottom to marsh surface increases with ditch / creek size

- Drainage greater on spring tides than neap tides
  - presumably a "head" issue
- Increasing drainage with increasing stream order, but plateaus at highest orders
  - again a "head" issue

Importance of drainage in a macrotidal system in agreement with Childers' observations of flume fluxes

Creekbank Drainage vs. Parker River Discharge

Annual drainage

163 $m^3\ y^{-1}$ (per m shoreline)

Scaled to ditch and creek length and order

660,000 $m^3\ d^{-1}$

Average annual discharge

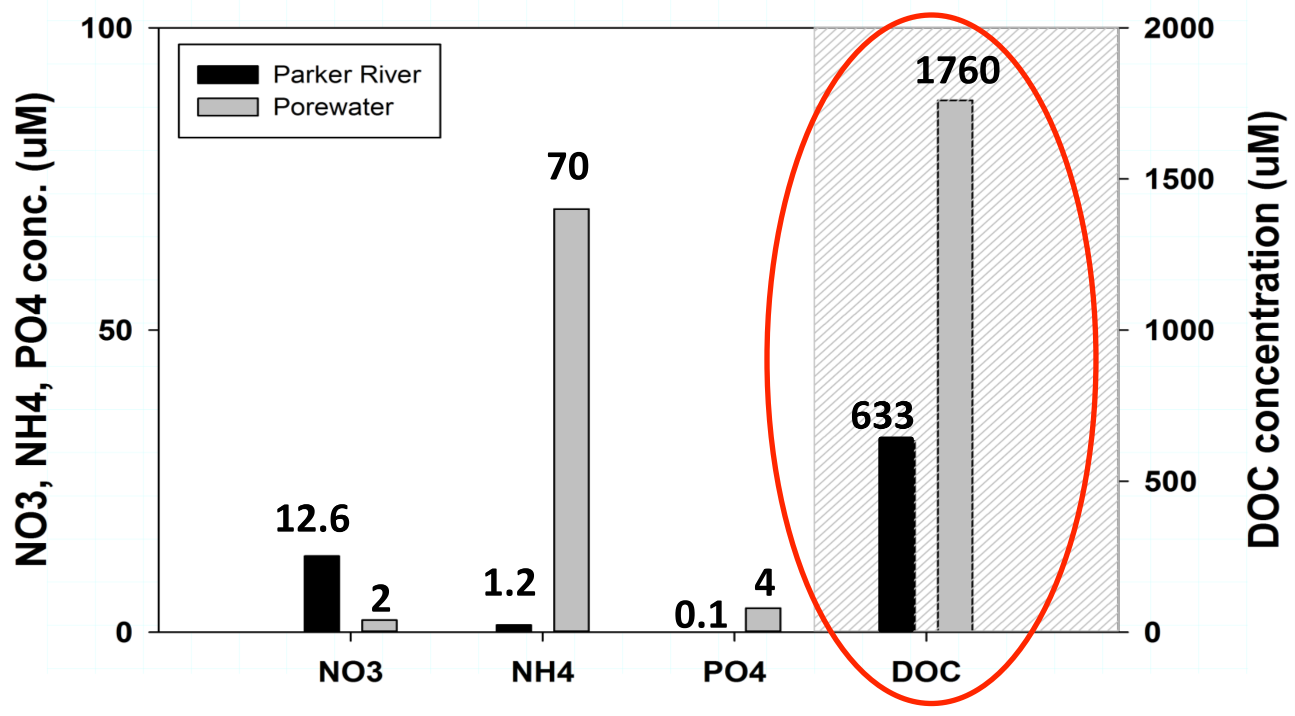
1 $m^3\ sec^{-1}$

86,000 $m^3\ d^{-1}$

Drainage : Discharge = 8 : 1

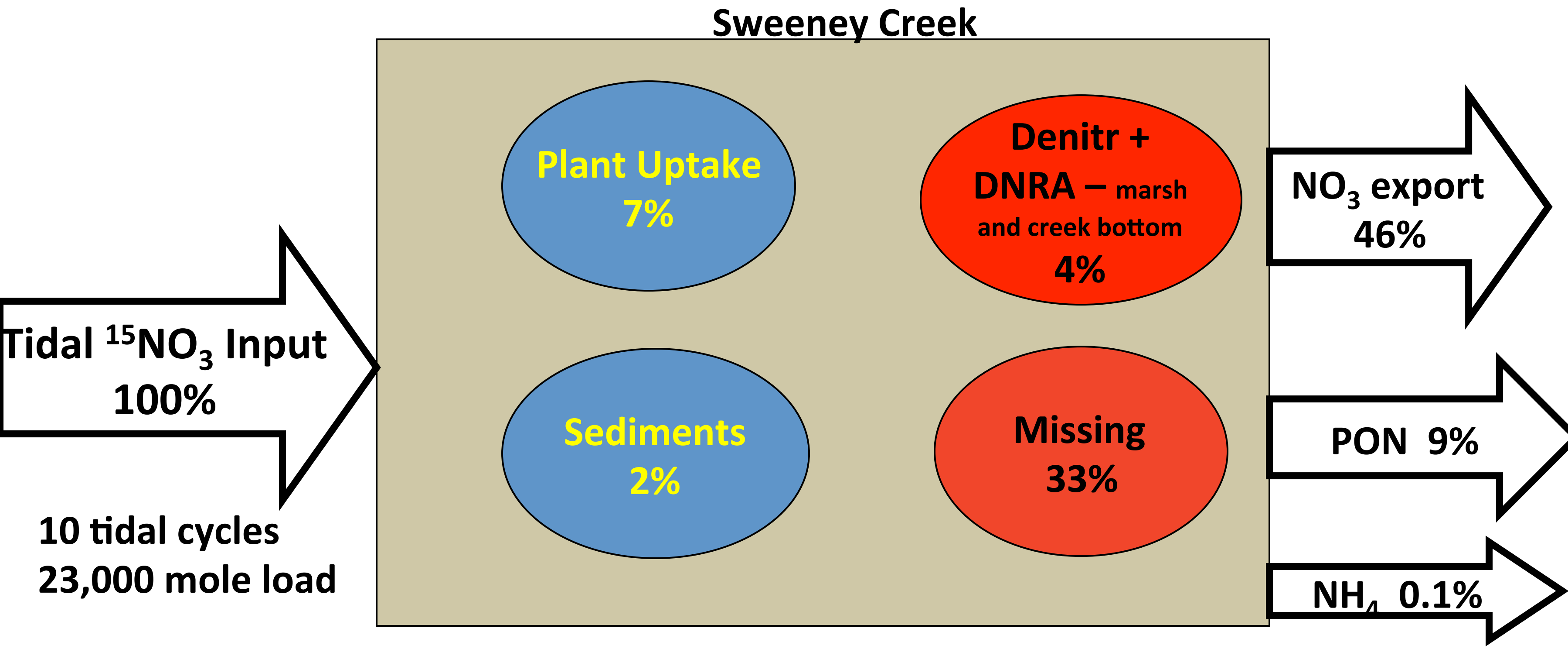
The ratio of drainage to discharge ranges over several orders of magnitude, depending on river discharge: e.g. up to 800:1 at 0.01 $m^3\ sec^{-1}$.

Potential Impact: comparison of river and drainage water chemical concentrations



- DOC drainage sufficient to fuel majority of mid-estuary aquatic heterotrophy
- $^{13\&14}$C-isotopic signature of DOC sources very different, indicating that flood tide input of DOC is metabolized and marsh DOC exported

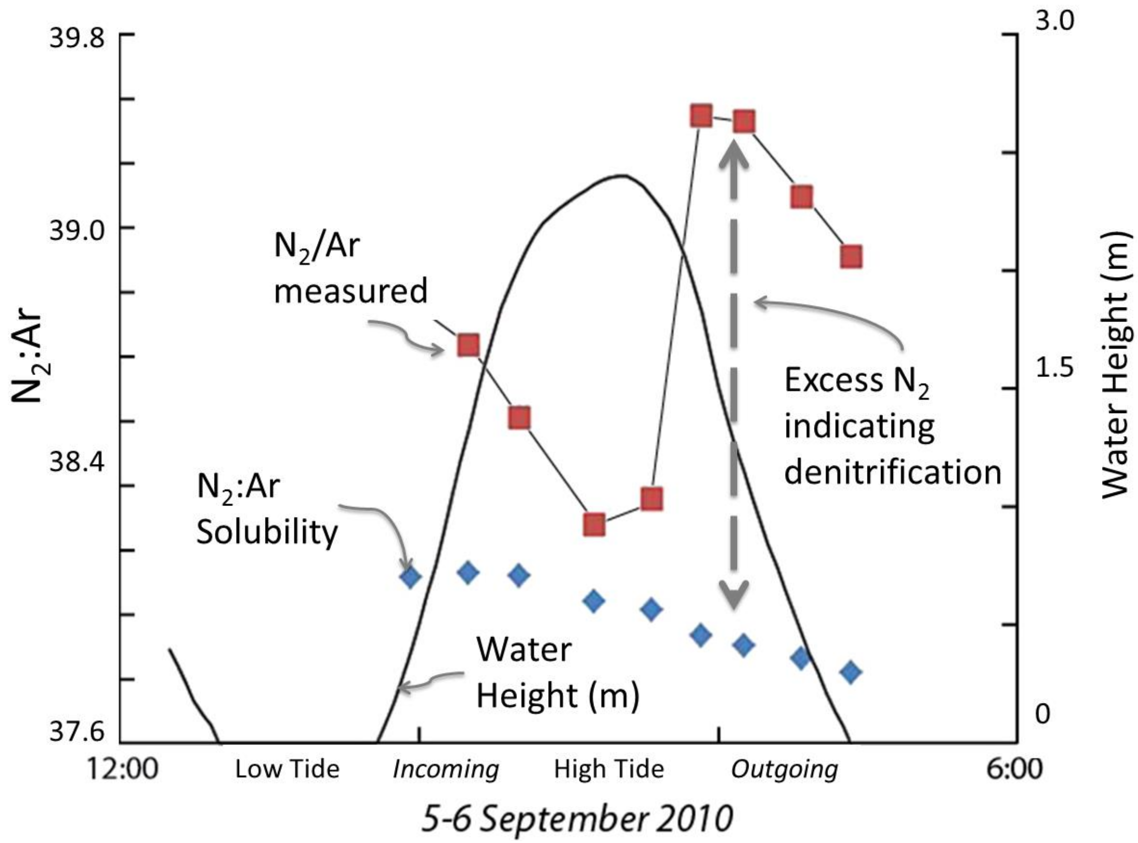
Another hotspot example – from a whole tidal creek/marsh N fertilization experiment



Drake et al 2009

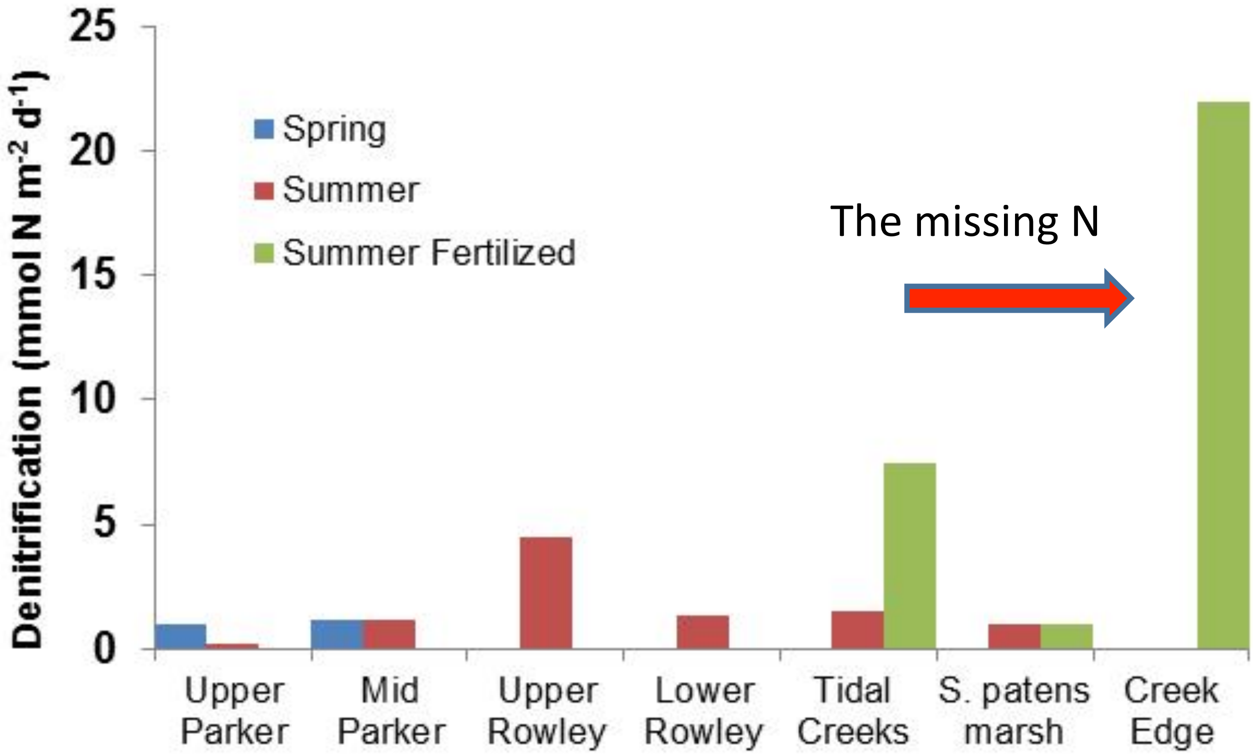
- **33% of N could not be accounted for**
- **3% of missing N could have been immobilized on detritus.**

Whole system approach "finds" the missing N: N_2:Ar ratio changes over a tidal cycle:



- Excess equivalent to ~ 30µM N higher concentration on ebb tide
- Conclusion: most denitrification is occurring in **creekbank edge** where there is active drainage and NO_3 advection - **HOTSPOT**

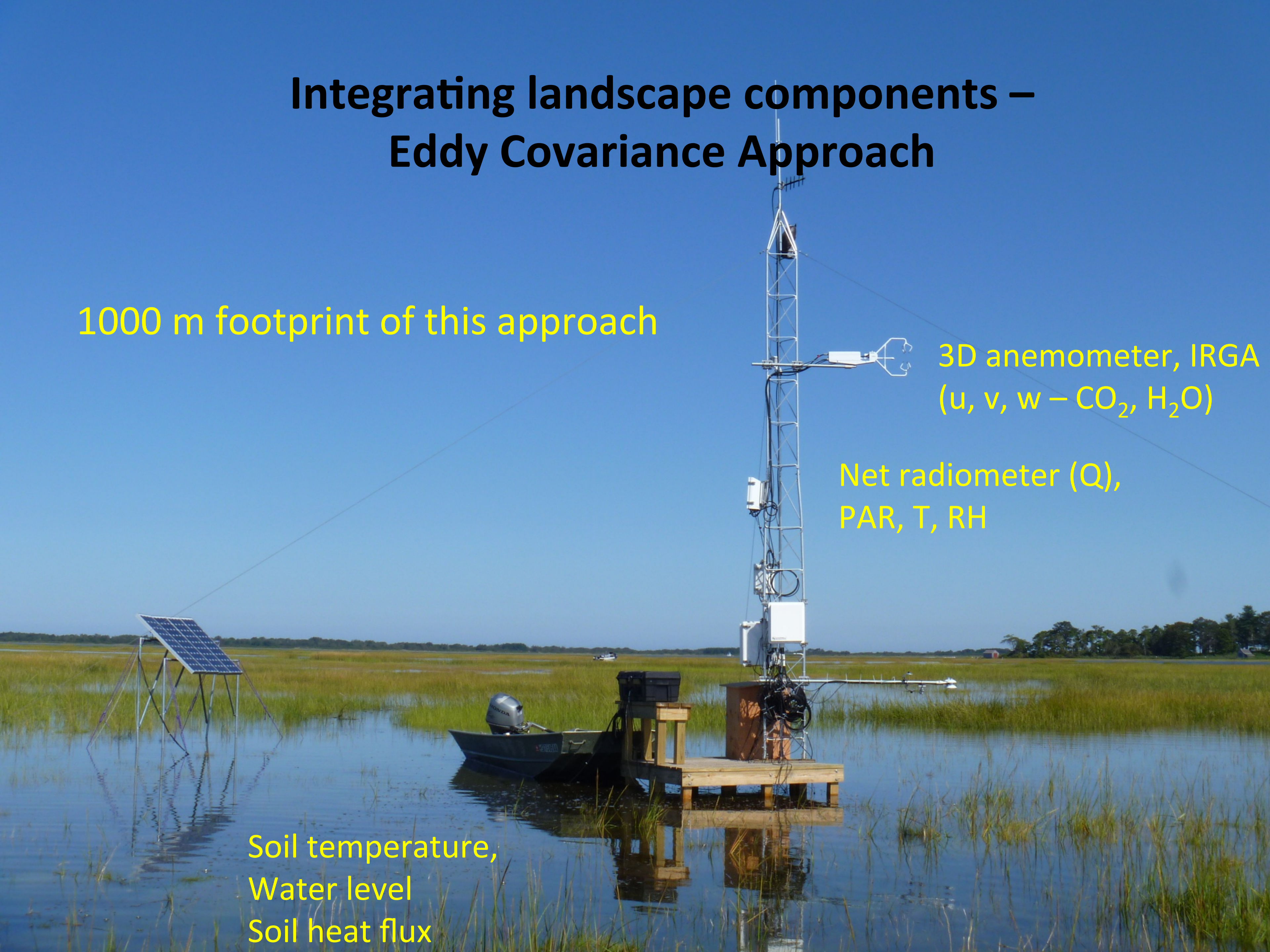
Denitrification in creekbank edge compared to other sites



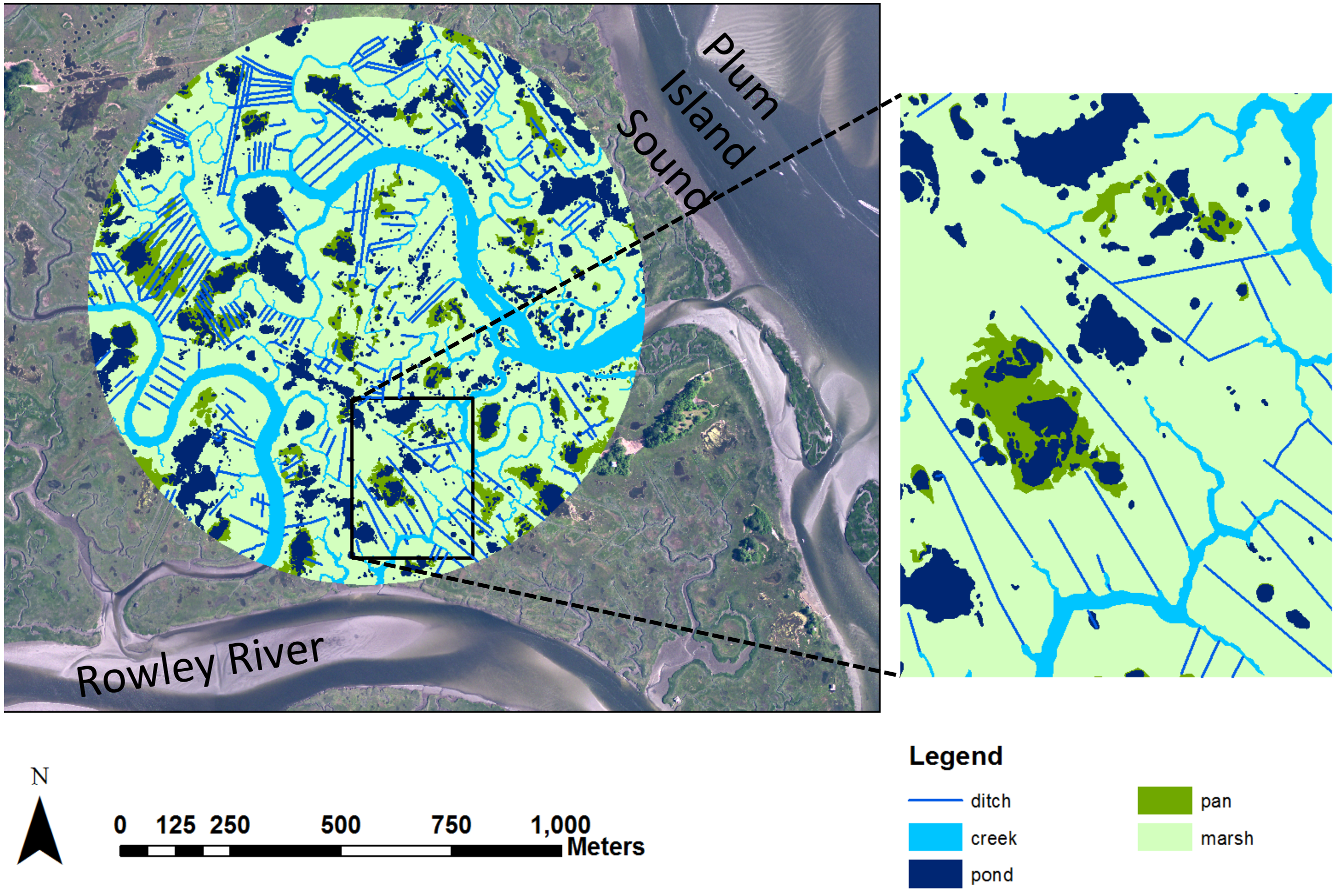
Calculated denitrification rates from N_2:Ar agree well with potential rates

- High rates in "edge" should have been expected as diffusional limitations are overcome with porewater advection
- **Our understanding of whole system N budgeting would be grossly in error if we relied solely on scaled up plot level measures.**

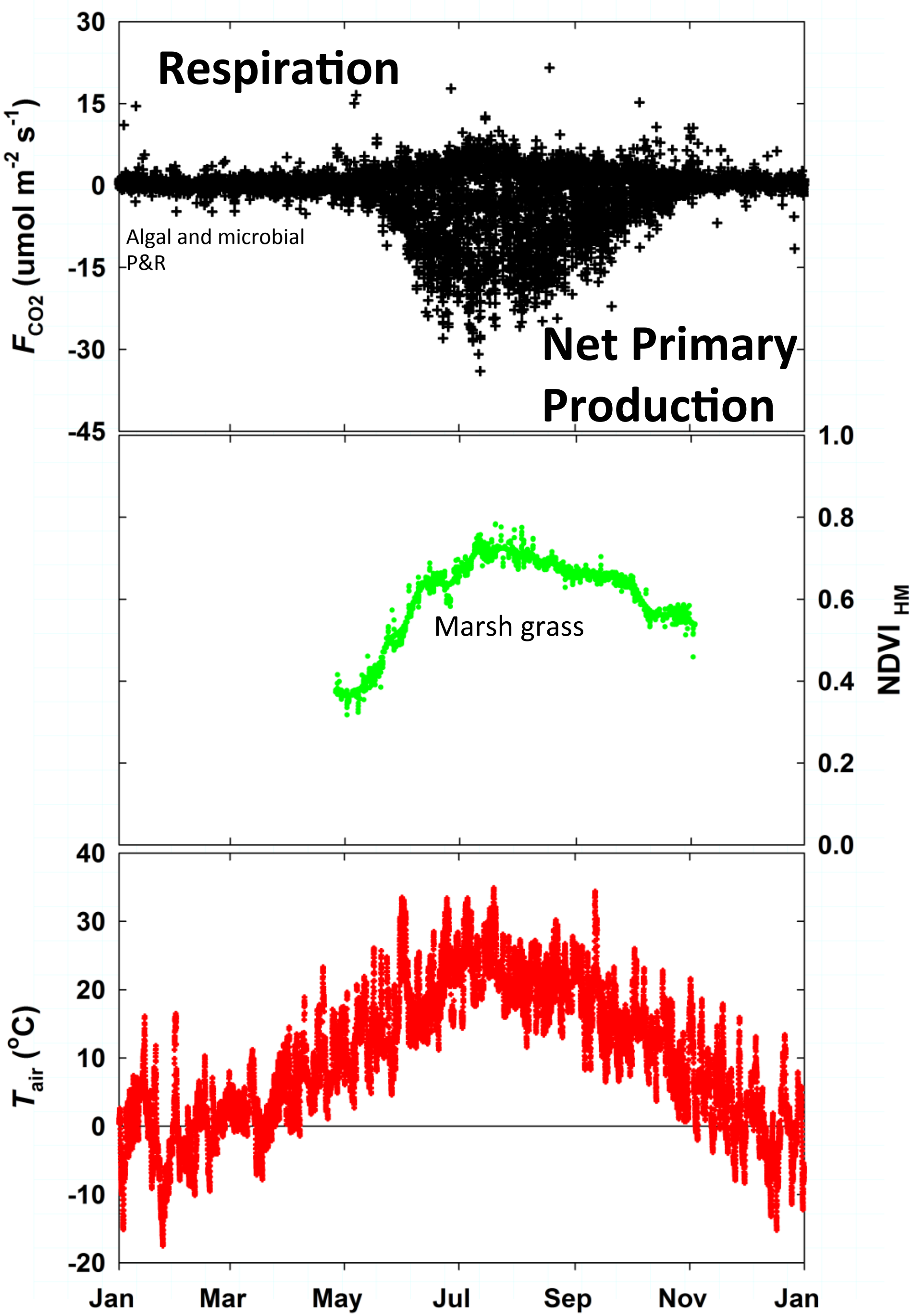
Integrating landscape components – Eddy Covariance Approach



Location of the >1km diameter tower "footprint"



- True integration of landscape elements
- Initial focus on a site with extensive ponding



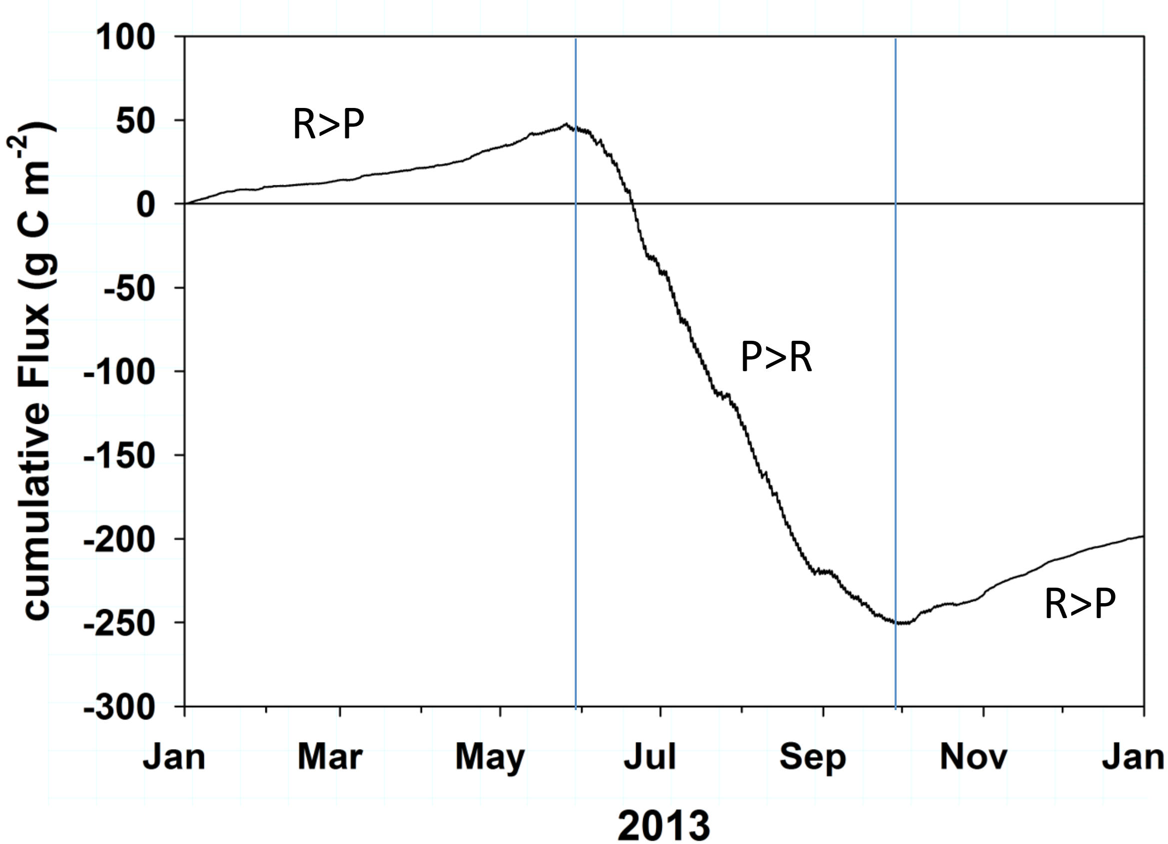
Seasonality of atmospheric fluxes

- CO_2 flux to and from atmosphere is very low UNTIL live marsh vegetation is growing

- Respiration (flux to atmosphere) related to temperature primarily

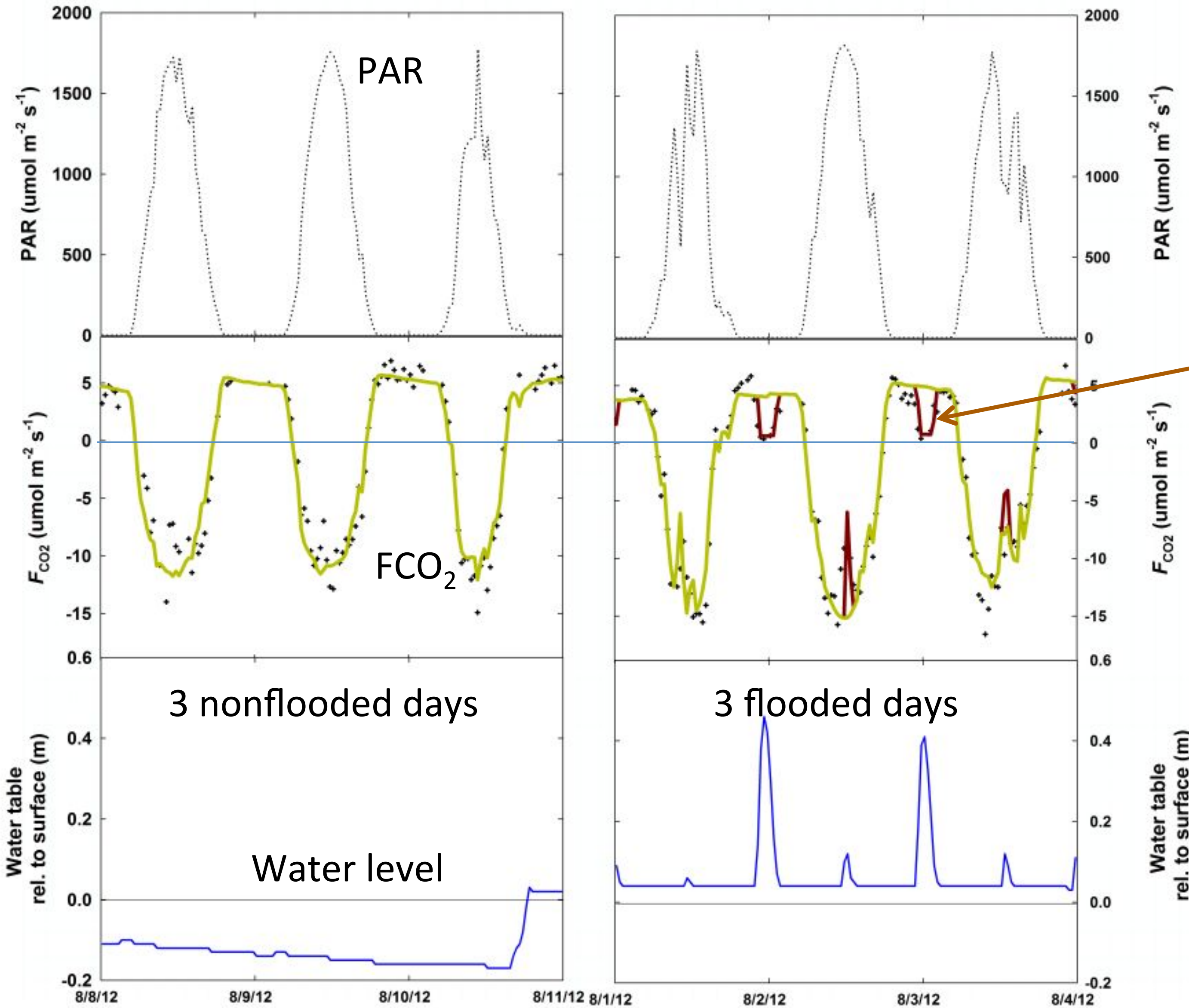
- Once marsh grass is growing, NVEE correlated strongly with biomass (NDVI), temperature and PAR (not shown).

Cumulative C flux to the atmosphere



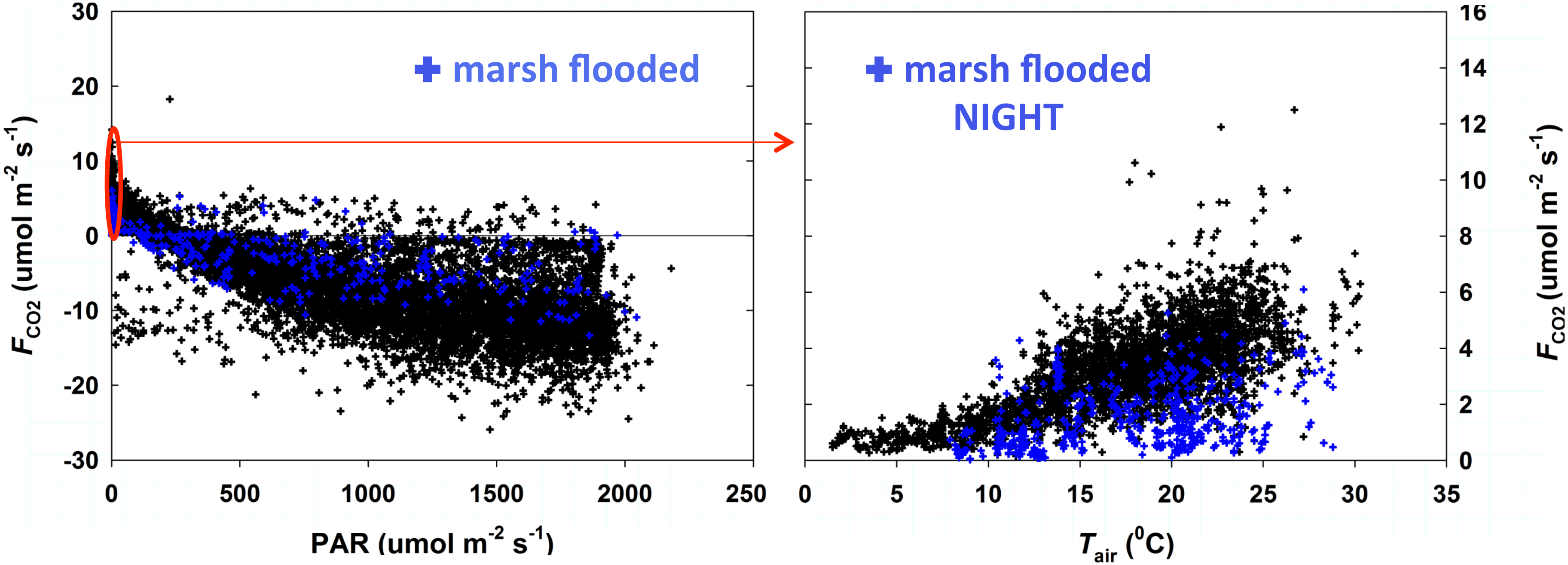
- Over a year, system transitions from being heterotrophic to autotrophic
- On an annual basis net system production ~200 gC m-2
- Possible fate:
  - Burial
    - Measured with SETs and dated cores (75)
  - OC export with tides
    - e.g., prior microbial, isotopic, metabolic studies

Special considerations in tidal wetlands: Tides!
Effect of marsh flooding on CO_2 flux



Most likely CO_2 produced during respiration is added to the water column, increasing TCO_2, and exported during ebb tide

Effect of marsh flooding on CO_2 flux



- CO_2 flux is consistently reduced during flooding – day and night
- No reason to expect GPP or R to decrease unless CO_2 or PAR becomes limiting to plants
- CO_2 produced during respiration is added to the water column, increasing TCO_2, and exported during ebb tide
    - We know TCO_2 export from creekbank drainage is high
- NVEE must be corrected for ΔDIC in flood waters (P and R)

Conclusions

- Tidal wetlands will change substantially over the 21st century as a result of changing management, sediment availability, SLR, and temperature
- Current role in coastal ocean C budget will change accordingly
  - Possible that micro and meso tidal systems will become C sources
- Must develop predictive understanding of the controls on tidal wetland C fluxes in order to model changes- **can't rely on serendipitous approach. C focused, long term, process-based, comparative ecosystem approach, integrated modeling, etc**
- Standard approaches to measuring critical C and N fluxes in tidal wetlands need to be modified to capture hotspot dynamics
- Use of flux towers a promising new approach to more accurately measure net C flux of tidal wetlands
  - Same old challenge of quantifying horizontal, waterflow-mediated DIC and OC fluxes
- Scaling results to the globe remains an extreme challenge. It's a challenge even from within single well-studied systems.

Could land use change drive marsh expansion in other areas?

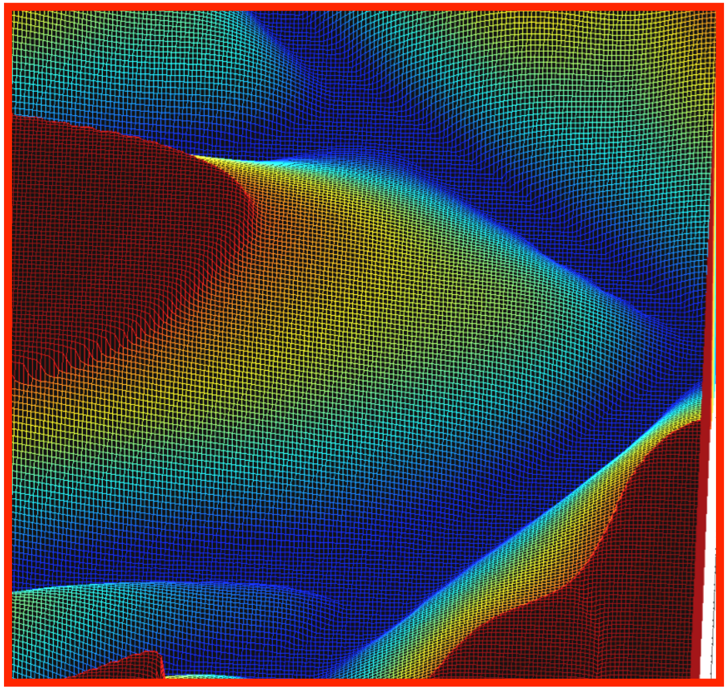
•Small subtidal delta converted to marsh in Chesapeake tributary **(Pasternack et al., 2001)**

•Mangroves expanded over sandflats in New Zealand **(Swales and Bentley, 2008)**

To illustrate general tendencies, use a numerical model:

•Accretion rate a function of: inundation depth, vegetation growth, and sediment concentration.

•Channel evolution a function of: discharge, vegetation growth



Processes affecting wetland elevation

Drivers

Sea-level rise

Sediment supply

climate

Erosion

Sedimentation

Decomposition - R

Organic Accumulation – NEP**

Flooding Frequency and Duration

&

Sediment Supply

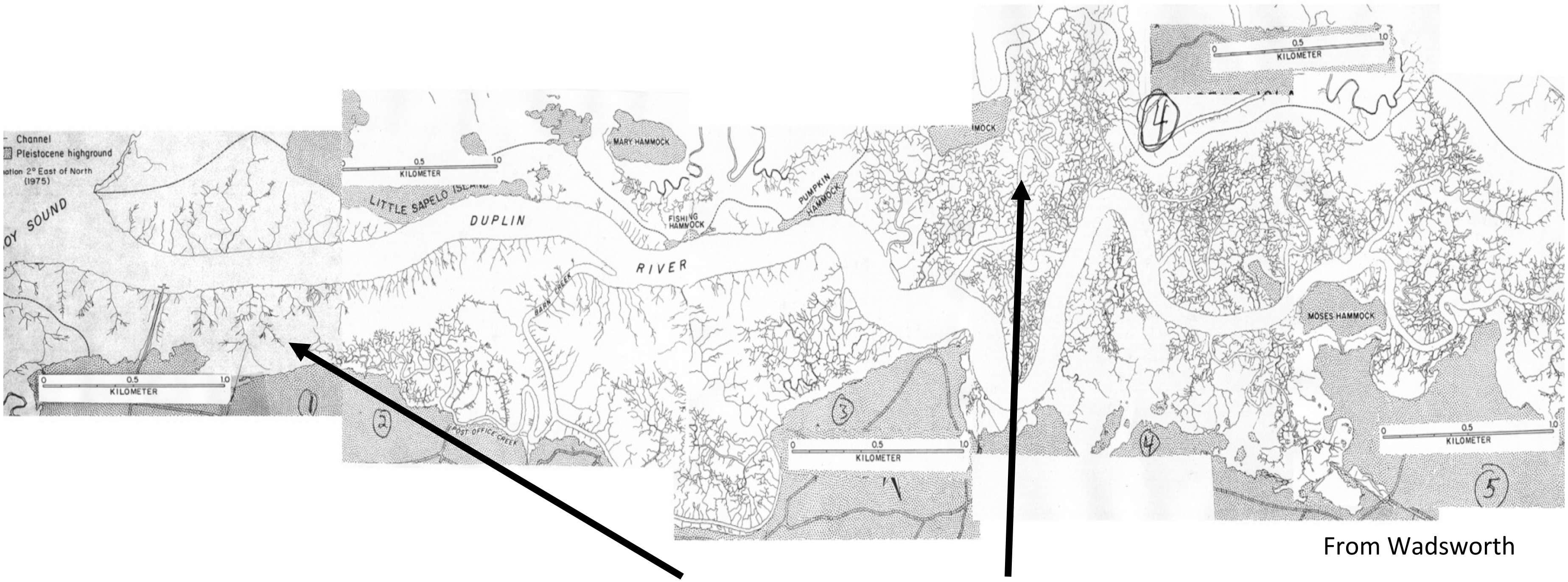
Root Zone

Subsidence & Compaction

Marsh Sediment

From Cahoon

Proof in the pudding
Drainage Network – Duplin River marshes Sapelo Island



From Wadsworth

Two drainage types of interest: discrete and reticulated

Discrete represents the "old" marsh, high elevation, creeks infilled, flooding only on spring tides, typically low primary production, Δelevation by OM and sediment

Reticulated represents "youthful" marsh, low elevation, high drainage density, flooding with all tides, high rates of production and sedimentation