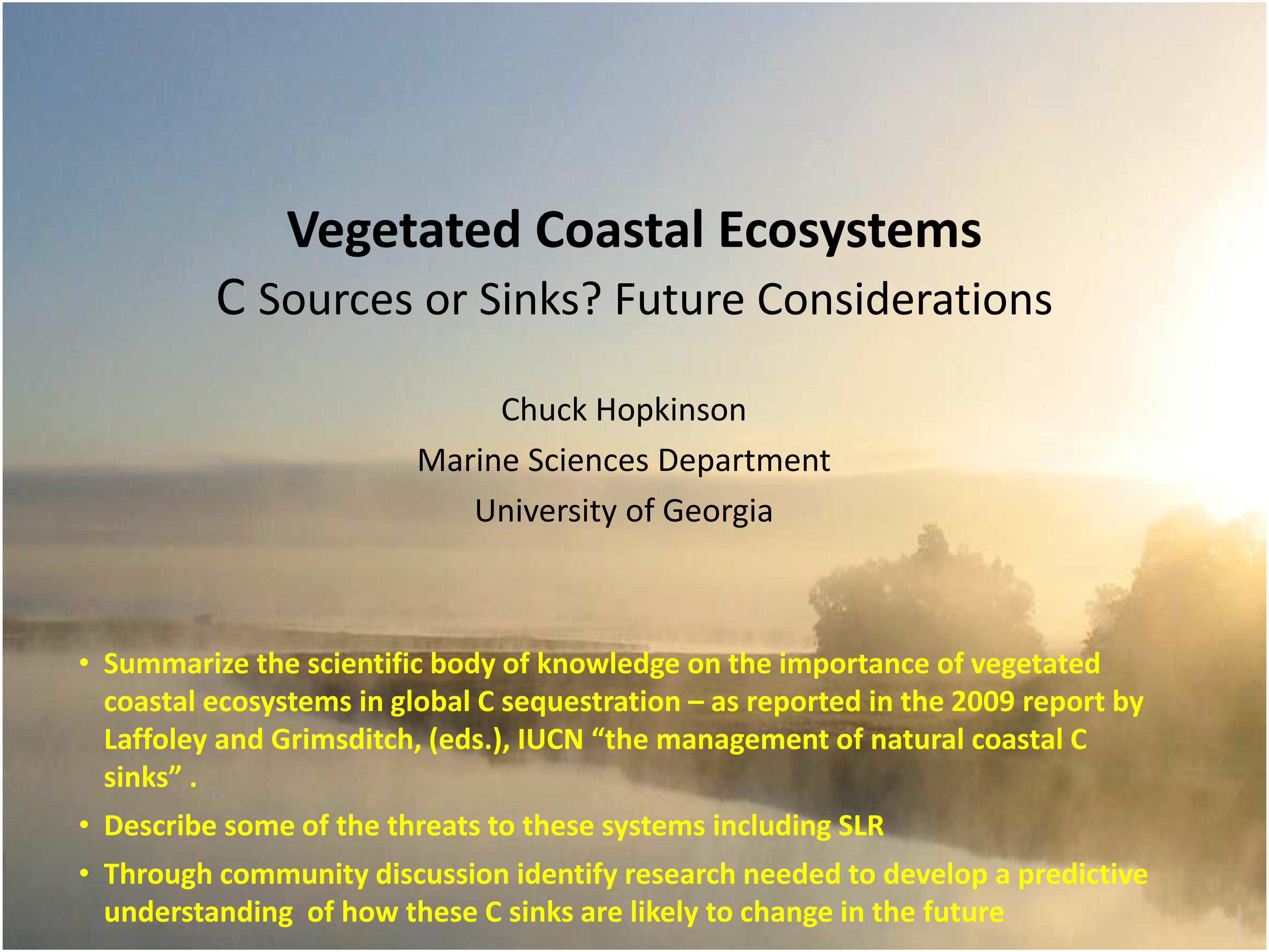
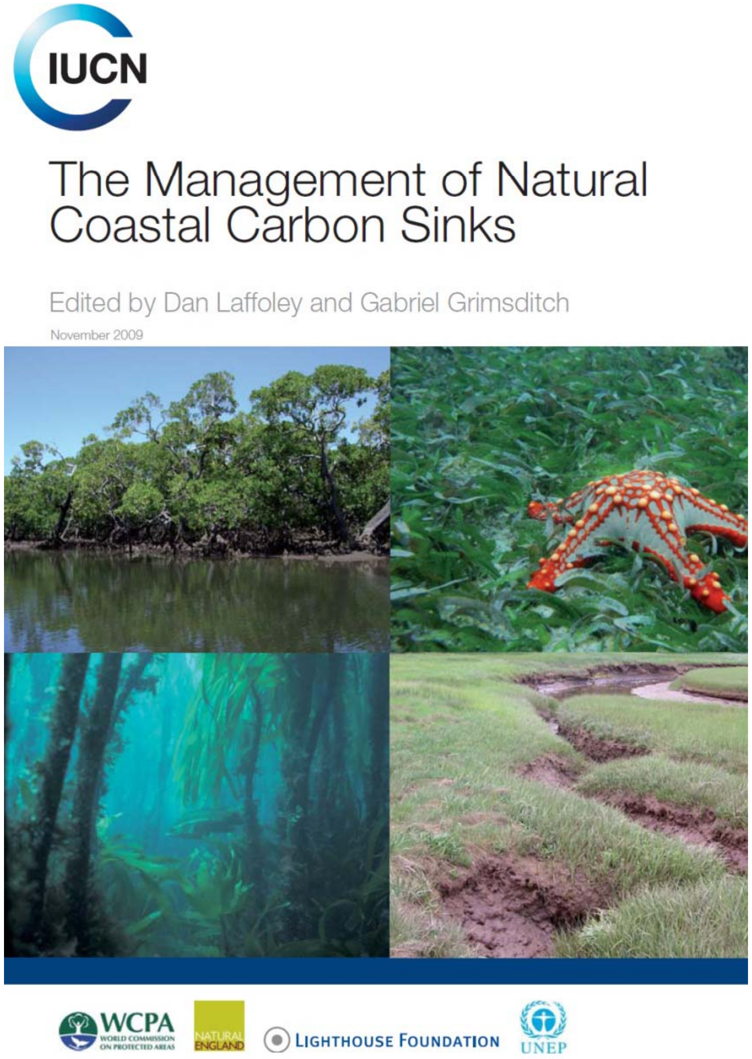


Vegetated Coastal Ecosystems

C Sources or Sinks? Future Considerations

Chuck Hopkinson
Marine Sciences Department
University of Georgia

- Summarize the scientific body of knowledge on the importance of vegetated coastal ecosystems in global C sequestration – as reported in the 2009 report by Laffoley and Grimsditch, (eds.), IUCN "the management of natural coastal C sinks" .
- Describe some of the threats to these systems including SLR
- Through community discussion identify research needed to develop a predictive understanding of how these C sinks are likely to change in the future


IUCN

The Management of Natural Coastal Carbon Sinks

Edited by Dan Laffoley and Gabriel Grimsditch

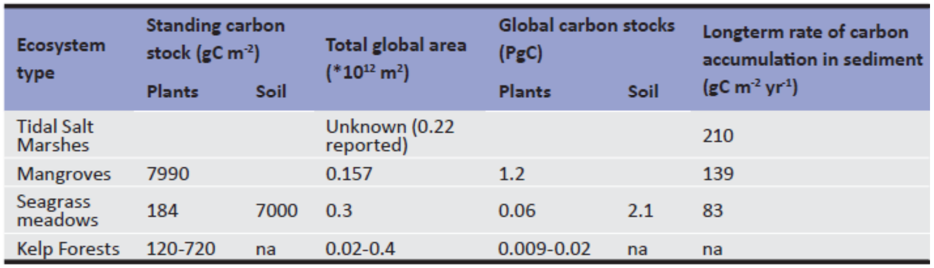
November 2009

WCPA World Commission on Protected Areas

Natural England

Lighthouse Foundation

UNEP



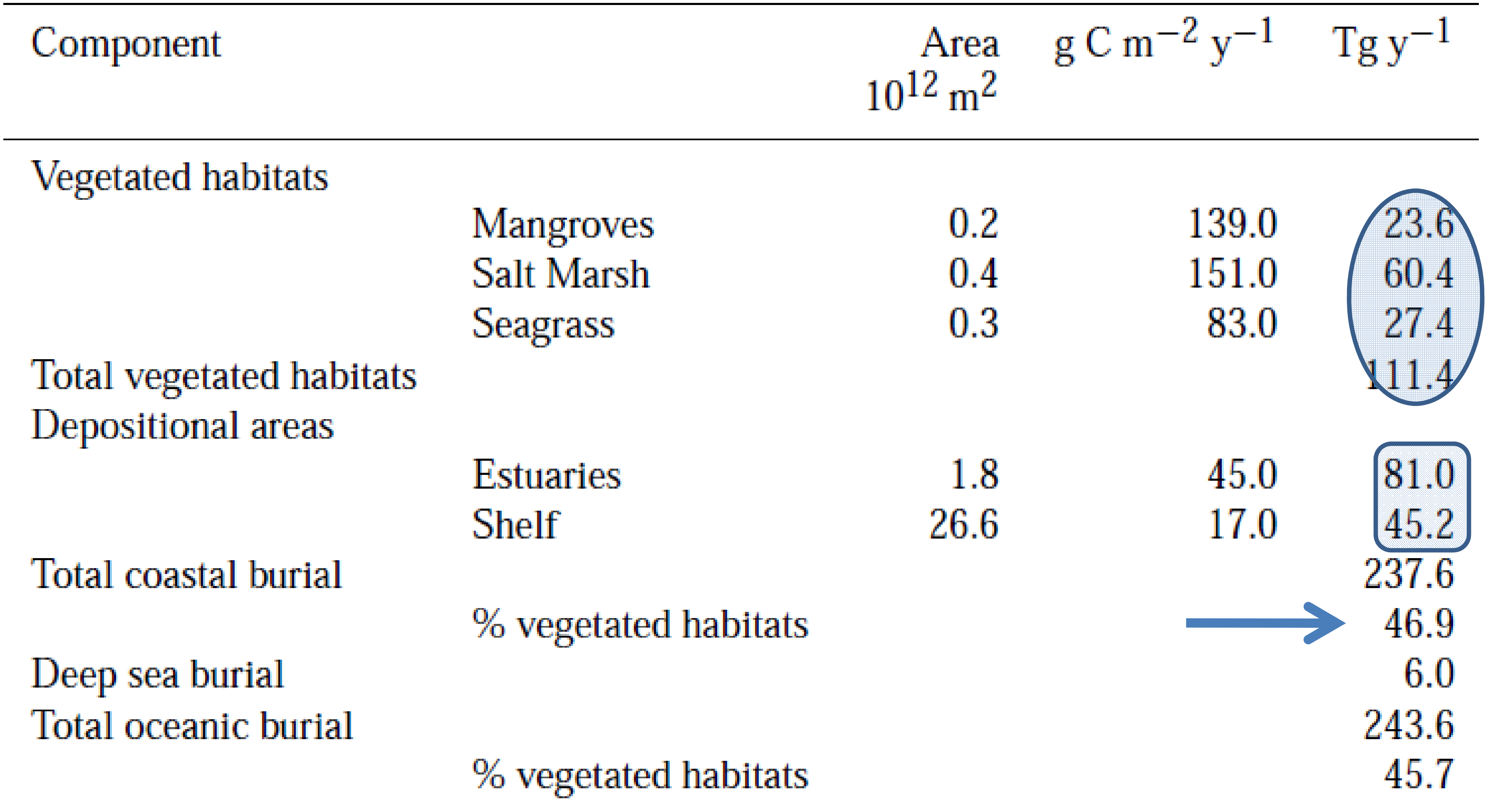
Ecosystem type	Standing carbon stock (gC m^{-2})		Total global area (*10^{12} m^{2})	Global carbon stocks (PgC)		Longterm rate of carbon accumulation in sediment (gC m^{-2} yr^{-1})
	Plants	Soil		Plants	Soil	
Tidal Salt Marshes			Unknown (0.22 reported)			210
Mangroves	7990		0.157	1.2		139
Seagrass meadows	184	7000	0.3	0.06	2.1	83
Kelp Forests	120-720	na	0.02-0.4	0.009-0.02	na	na

Summary

	Long-term C Accumulation Rate gC m^{-2} yr^{-1}
Tidal Salt Marshes	**210**
Mangroves	**139**
Seagrass Meadows	**83**
Kelp Forests	**na**

- While areal extent limited ($<1 * 10^{12}$ m^{2}), areal accumulation rate >> than for most terrestrial and oceanic ecosystems
- Vegetated coastal ecosystem C storage equivalent to all other oceanic OC stores - >100 Tg y^{-1}
- Tremendous ecosystem services
- Human impacts severe and likely to increase
- Management and restoration strongly encouraged

Punch line- Comparison of C Burial Rates

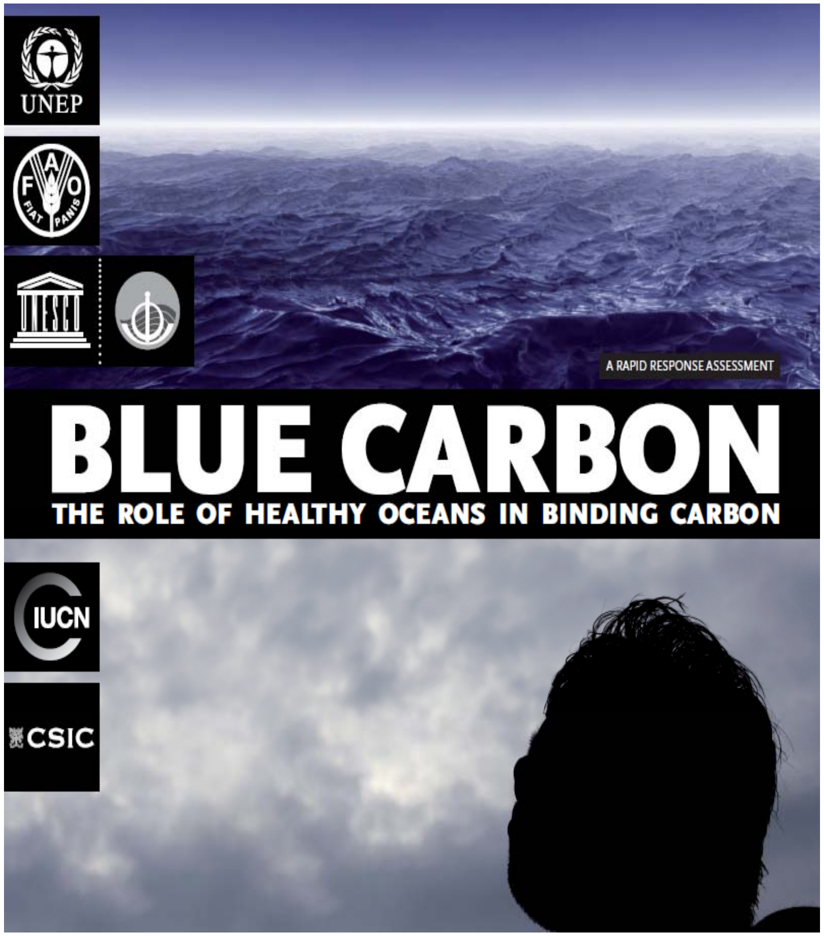


Component		Area 10^{12} m^2	g C m^{-2} y^{-1}	Tg y^{-1}
Vegetated habitats				
	Mangroves	0.2	139.0	23.6
	Salt Marsh	0.4	151.0	60.4
	Seagrass	0.3	83.0	27.4
Total vegetated habitats				111.4
Depositional areas				
	Estuaries	1.8	45.0	81.0
	Shelf	26.6	17.0	45.2
Total coastal burial				237.6
	% vegetated habitats			46.9
Deep sea burial				6.0
Total oceanic burial				243.6
	% vegetated habitats			45.7

Duarte et al. 2005

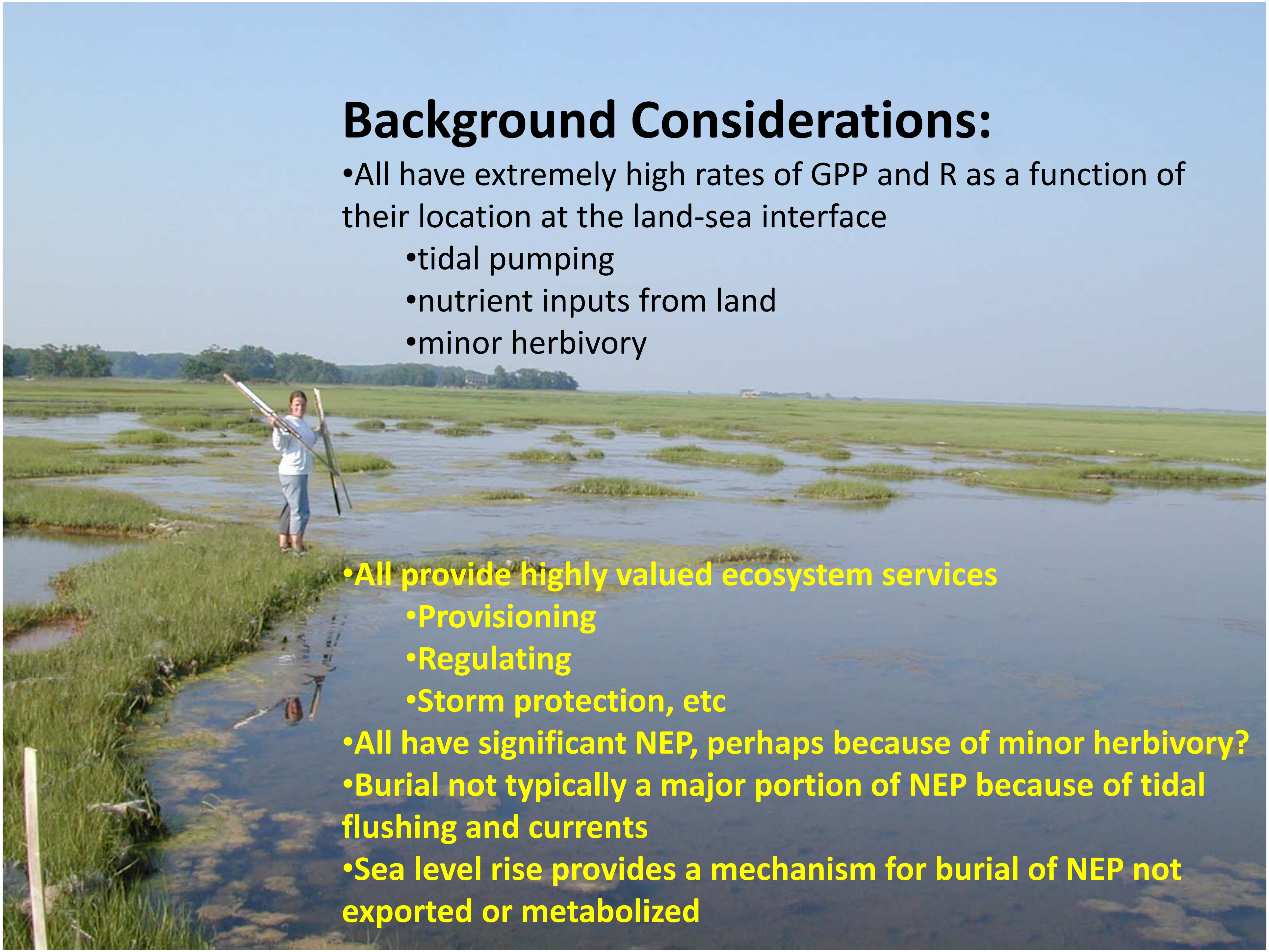
- Most budgets (Berner – 130 Tg for deltaic/shelf seds or Hedges and Keil – 160 Tg for coastal ocean) exclude vegetated habitats.
- Including vegetated habitats @ 111 Tg – total oceanic C burial is 2X previous estimates

C burial in coastal systems has almost always been of secondary interest, let alone the role of these systems in atmospheric CO_2 sequestration.



Until recently the interest in C in coastal systems has been to better understand:

- Rates and mechanistic controls on estuarine primary production, including subsystems: seagrasses, salt marshes, mangrove swamps, and kelp forests
- The NEP of these systems and their importance in subsidizing adjacent systems
- How these systems influence the nature and magnitude of terrestrial C export to the ocean
- Burial was often crudely estimated or solved by mass balance



Background Considerations:

- All have extremely high rates of GPP and R as a function of their location at the land-sea interface
  - tidal pumping
  - nutrient inputs from land
  - minor herbivory

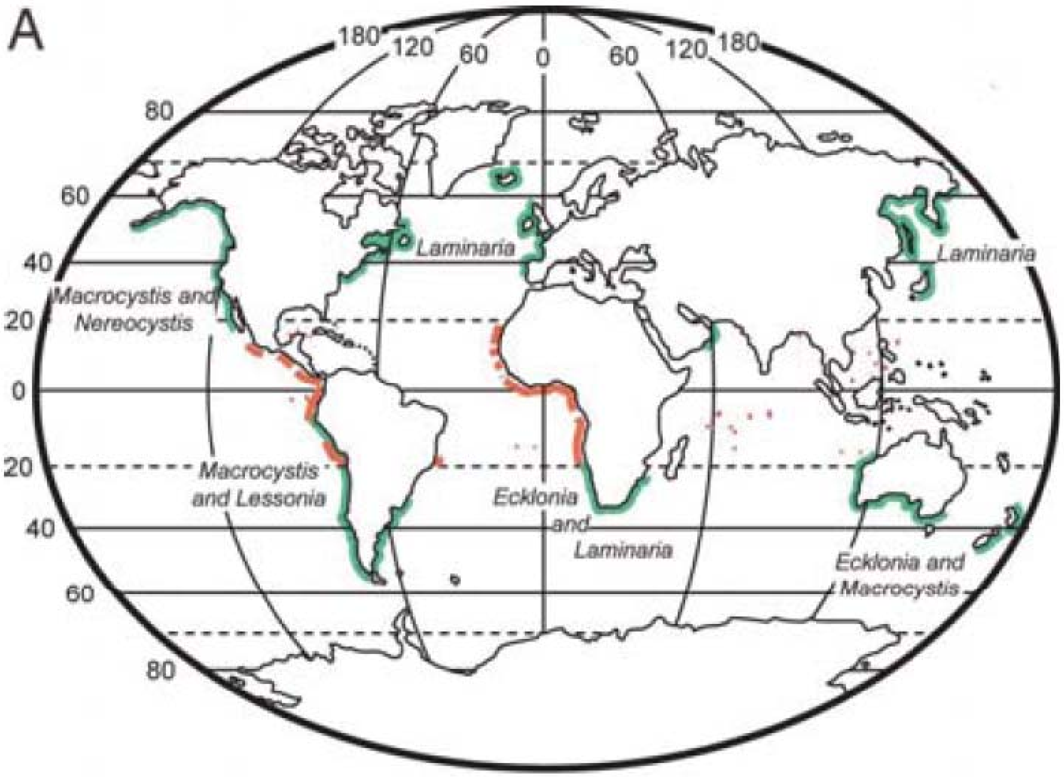
- **All provide highly valued ecosystem services**
  - **Provisioning**
  - **Regulating**
  - **Storm protection, etc**
- **All have significant NEP, perhaps because of minor herbivory?**
- **Burial not typically a major portion of NEP because of tidal flushing and currents**
- **Sea level rise provides a mechanism for burial of NEP not exported or metabolized**

Standard Approach

- **Sediment C density (g/cc) X sedimentation rate (cc/yr) = C storage or burial rate (g / yr)**
- **Account for global areal coverage to get global sequestration**
- But often times calculated from estimates of system NEP or NEP corrected for estimates of export (which we know are fraught with errors and uncertainty)
- OR from short-term estimates of surface deposition

- Need to account for compaction, surface roots, decomposition.
- Also need to scale to whole systems – show the balance between erosion and sedimentation
- And need to account for deviations from steady-state

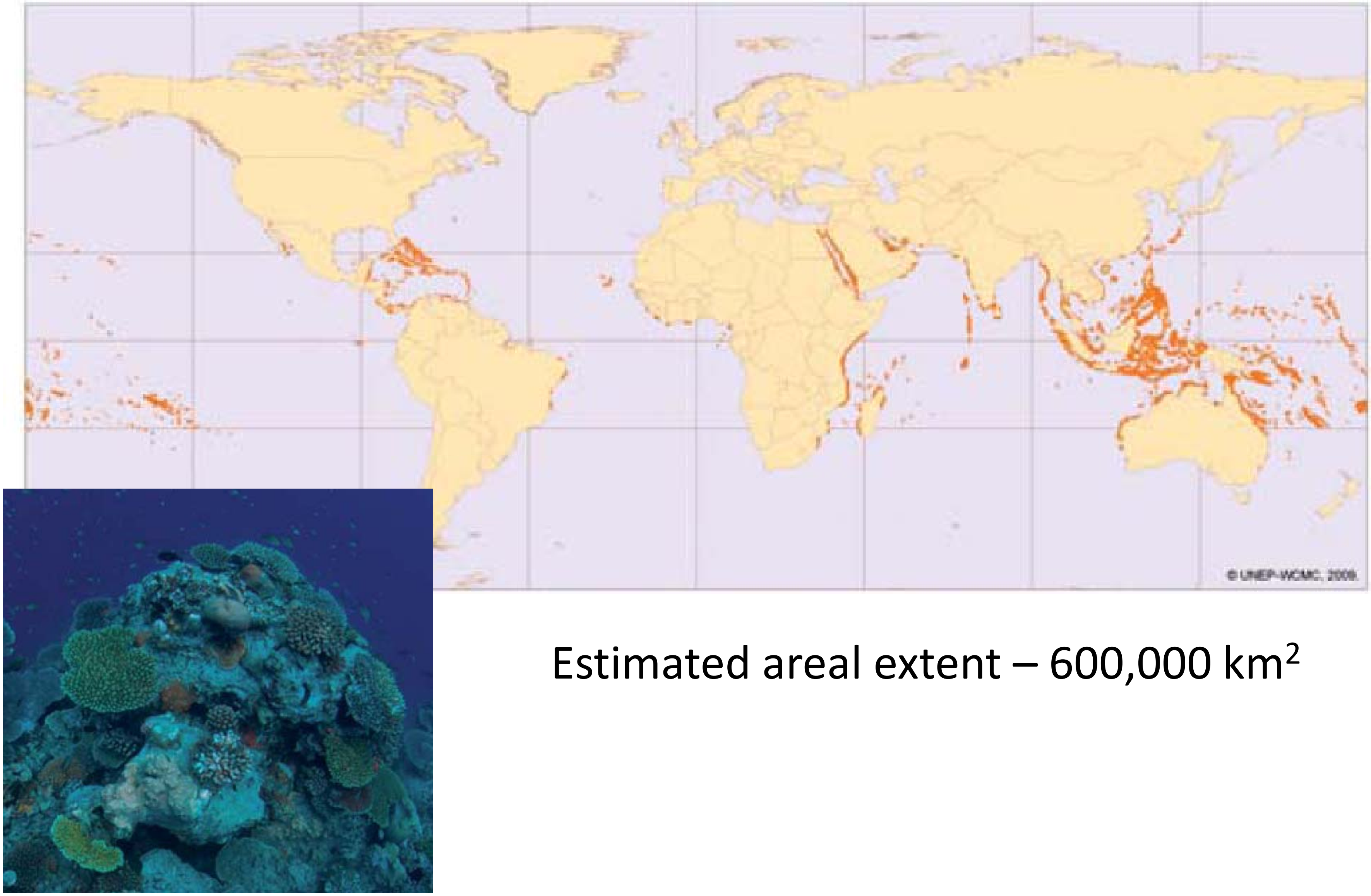
Kelp Forests – large brown algae in the order Laminariales



- Temperate and arctic systems most studied. No worldwide survey, but 30,000 – 60,000 km shoreline expected to have kelp (avg width – 500 m)
- Recently discovered deep-water tropical forests
- NEP thought to be mainly exported and not buried in forest sediments – **hence not further discussed in the context of this talk**

Coral Reefs

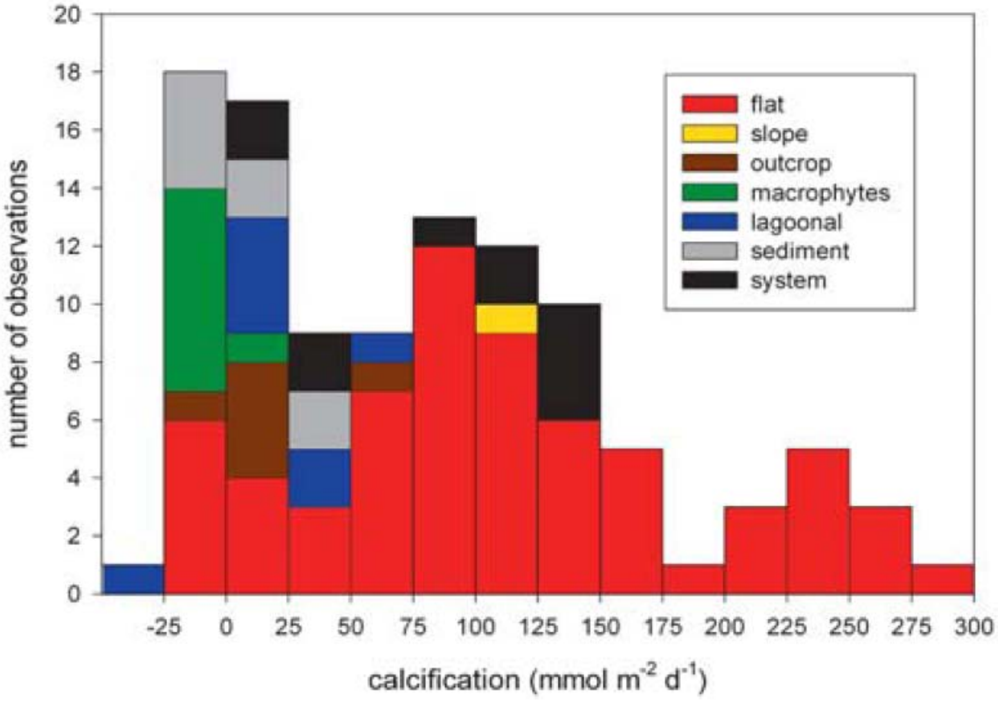
Global distribution of Coral Reefs



© UNEP-WCMC, 2009.

Estimated areal extent – 600,000 km^2

Coral Reefs



- Known for their tremendous productivity and species diversity
- BUT P/R ~ 1.04 with 0 NEP
- Reef C mass, all inorganic.: < 0.5% organic C
- Mean reef calcification rate about 1,200 g $CaCO_3$ m^{-2} y^{-1}, or 144 gC m^{-2} y^{-1}, mostly on reef flats
- Tri-modal distribution – sedimentary areas, reef flats, and other reef areas
- $Ca^{2+} + 2HCO_3^- = CaCO_3 + CO_2\uparrow + H_2O$
- Hence – reefs are net sources of CO_2 to atmosphere
- 80 Tg precipitated inorganic C and 50 Tg CO_2 -C y^{-1} **released**

Future uncertainty – UV, T, bleaching, acidification, eutrophication – what will be the effects on current stocks?

Seagrass Beds

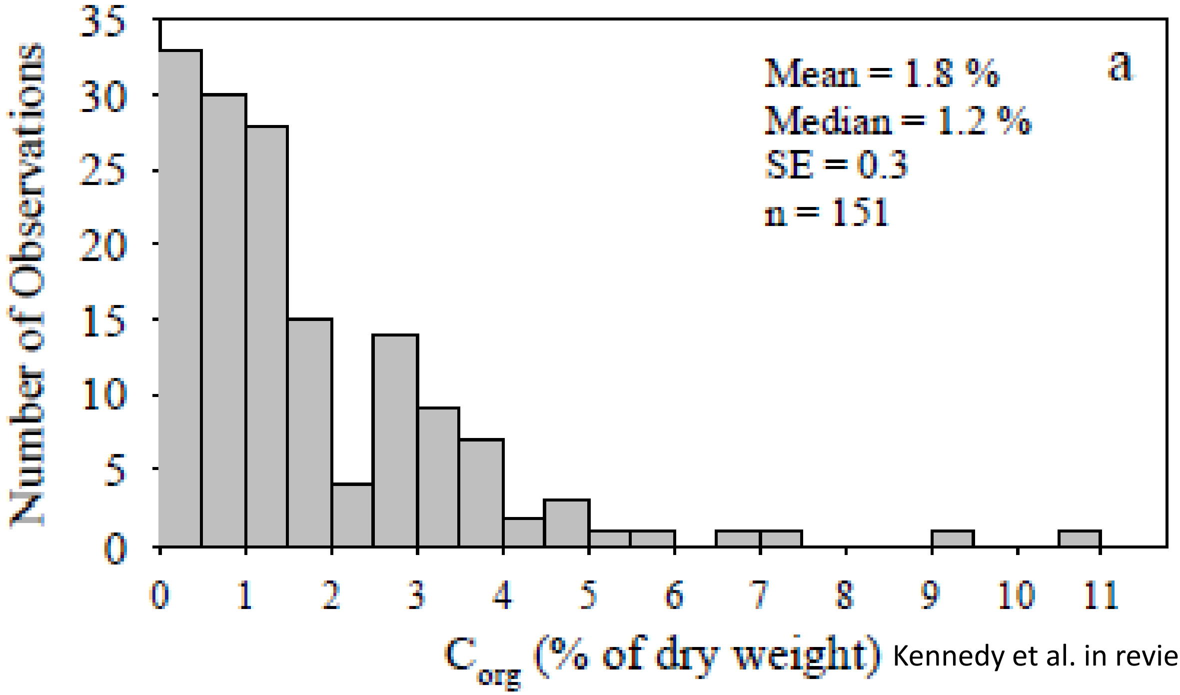
Seagrasses

Source: UNEP-WCMC, 2009; Waycott *et al.*, 2009.

Area:

- 330,000 km^2 - Nellemann et al. 2009
- 600,000 km^2 –Charpy-Roubaud and Sournia, 1990
- Very sketchy database
- Must always be submerged but above 1-2% surface light levels
- Remote sensing challenge to quantify areal extent
- Eutrophication and sediment runoff have reduced areal extent

Sediment C content in Seagrass Systems



Kennedy et al. in review

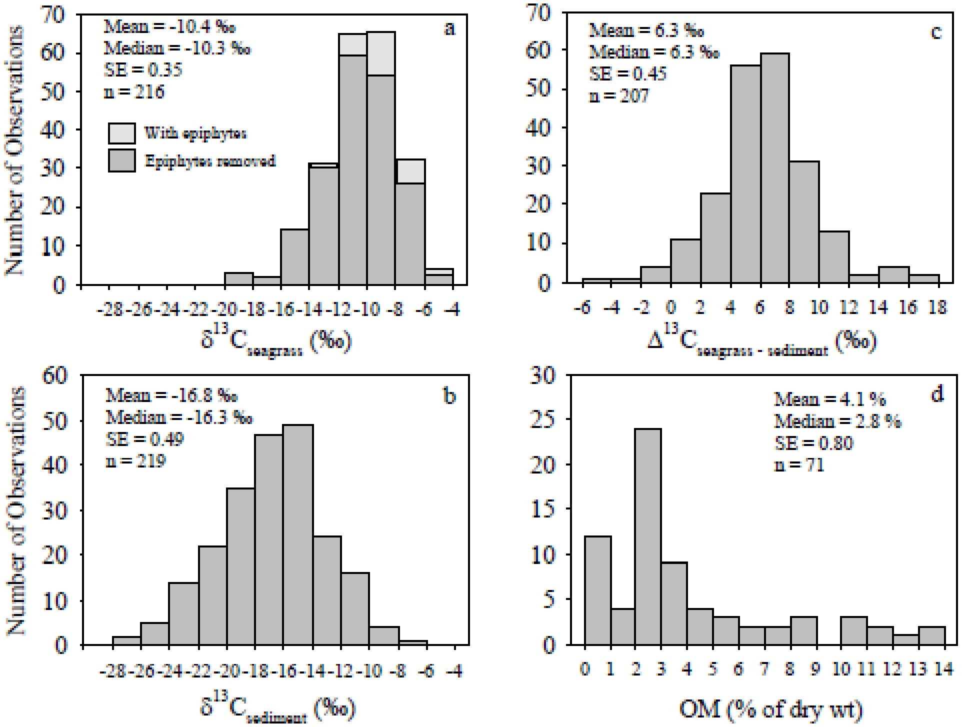
Based on 207 meadows at a limited number of sites, mostly from tropical W. Atl, Europe, SE Asia

Median C content – 1.2%

Range – 0.4% to 13% C

Bimodal distribution may reflect sandy vs organic-rich muddy sediments

C Burial – Mixture of Allochthonous and Autochthonous Sources



Stable isotopes and 3 end-member mixing analysis shows that **50% of seagrass sediment C allochthonous**, i.e., phytoplankton / epiphytes, intertidal wetlands, terrestrial systems)

C Burial – Mixture of Allochthonous and Autochthonous Sources

Areal Burial Rate – 80-130 gC m^{-2} y^{-1}

- Combination of approaches, but *few direct measures of accretion and almost all based on surface C content*
- If 50% is seagrass C and avg NEP = 120 gC m^{-2} y^{-1}, then 30-50% of net production is exported

Global Burial - 26-78 Tg y^{-1}

@300,000 – 600,000 km^2

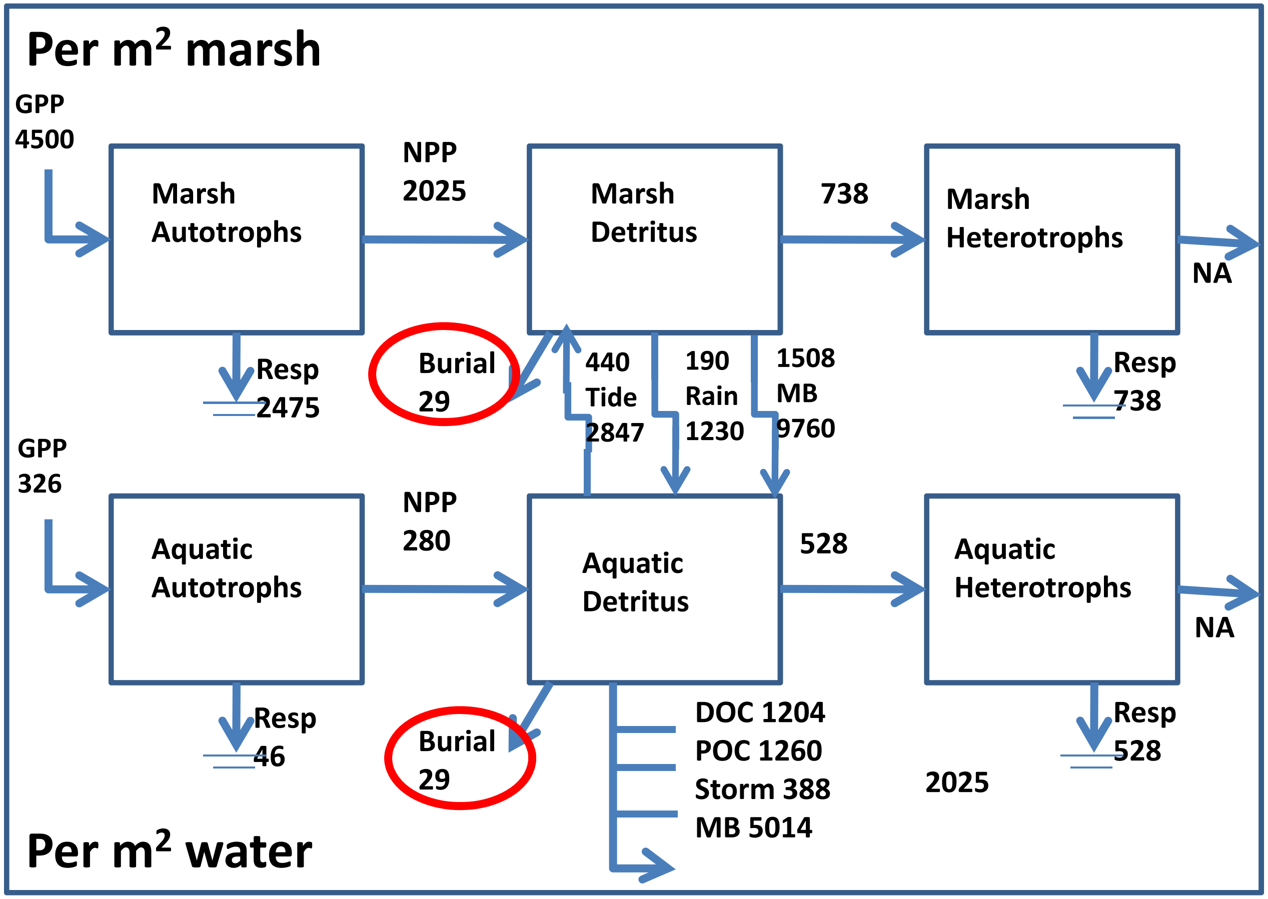
Long-term sedimentation –

- *Posidonia* meadows (Mediterranean) - 3 m over 2000 yrs
- Shark Bay (Australia) - 1m over 2000 yrs
- Florida Bay – 2m over 5000 yrs
- **=7-27 gC m^{-2} y^{-1} or 2 to 16 Tg y^{-1}**
  - Using 1.2 %C and 1.5 g/cc BD

Salt marshes

Salt Marsh C Budget –

Budget based on Sapelo Island, GA – similar for other salt marshes
Units – gC per unit area per yr



Carbon burial – only 29 gC m^{-2} y^{-1} or 1.4% of NPP
Based on profiles of ^{137}Cs and 0-50 cm soil C content

Hopkinson 1988

Source: UNEP-WCMC, 2009; Duarte *et al.*, 2008.

Tidal marshes

Area:

22,000 km^2 – Chmura et al. (19k – U.S. alone)

400- 800,000 km^2 – Nellemann et al.

Few countries have detailed remote sensing stats on total estuarine area, let alone on salt, brackish, fresh tidal marshes

- Found in temperate zones of the world in both N and S. hemisphere. Extend into boreal and arctic biogeographic provinces
- Intertidal habitat between near MSL and MHHW
- Successional development described first by Redfield for Barnstable Marsh and reconsidered by Frey for Sapelo Island
- Ability to trap sediments and accrete vertically, to prograde into open water areas, and to transgress terrestrial landscape – often in parallel with SLR
- Cores in New England marshes show organic C over 1000 yrs in age
- Succession typically defined for building phase only. Few areas where we've seen reversals – especially LA delta and more recently in New England marshes

Idealized cross-section of a marsh following continuous rise in sea level

Redfield 1967

Transgression - ← Progradation - →

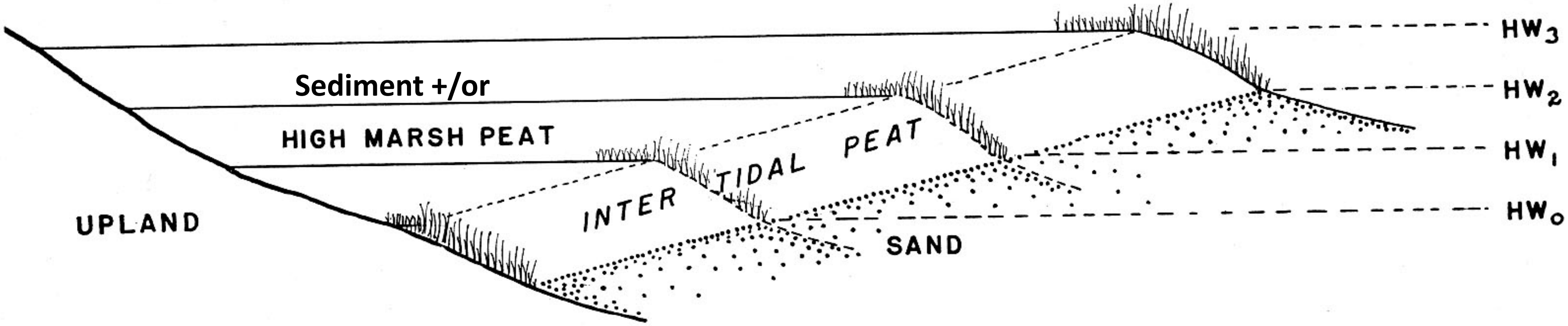
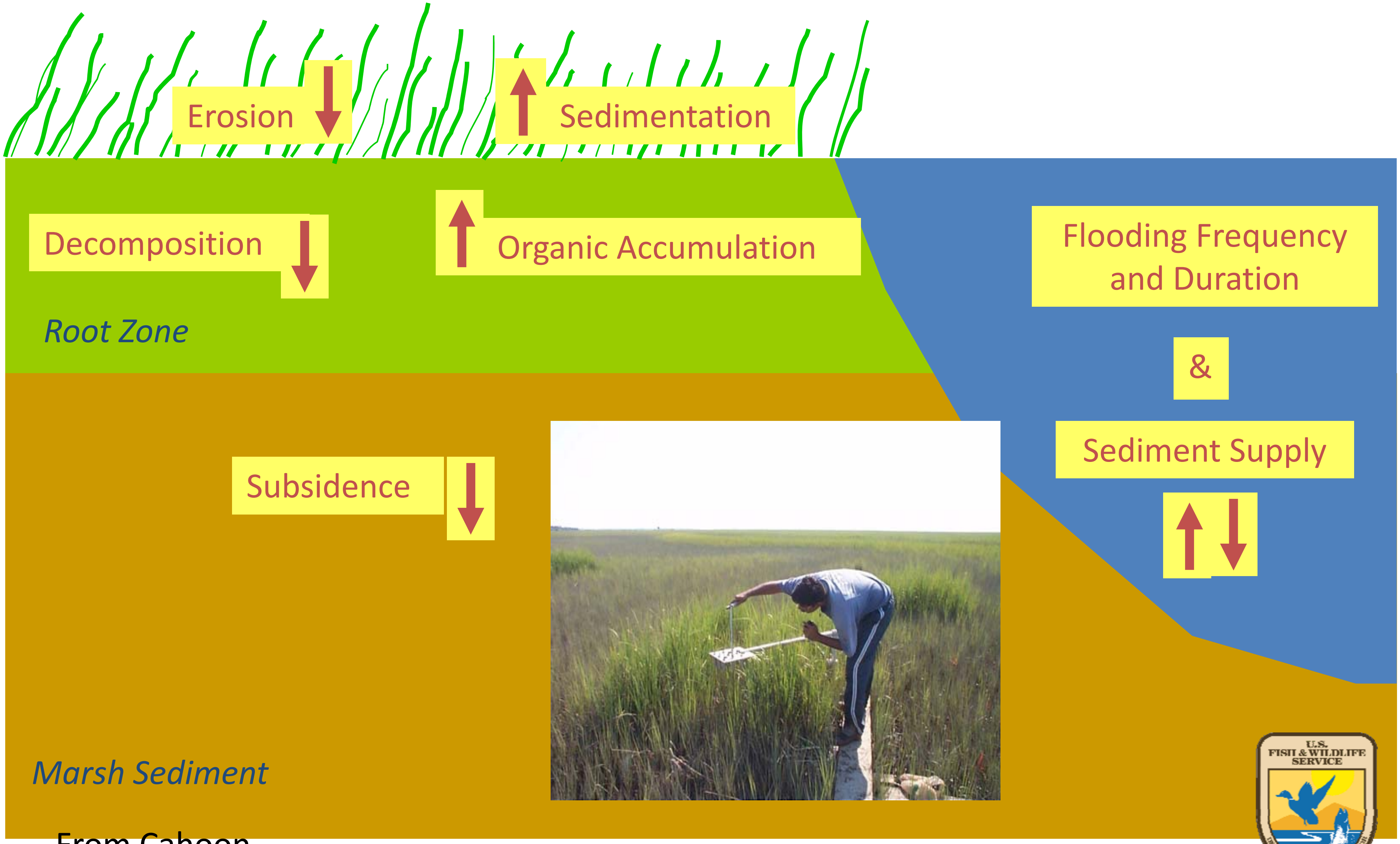


Fig. 1. Development of a typical New England salt marsh with rising sea level and continued sedimentation.

As sea level rises, elevation of the marsh surface increases as increased tidal flooding promotes 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

Processes Affecting Salt Marsh Accretion



Erosion ↓

↑ Sedimentation

Decomposition ↓

↑ Organic Accumulation

Root Zone

Flooding Frequency and Duration

&

Sediment Supply

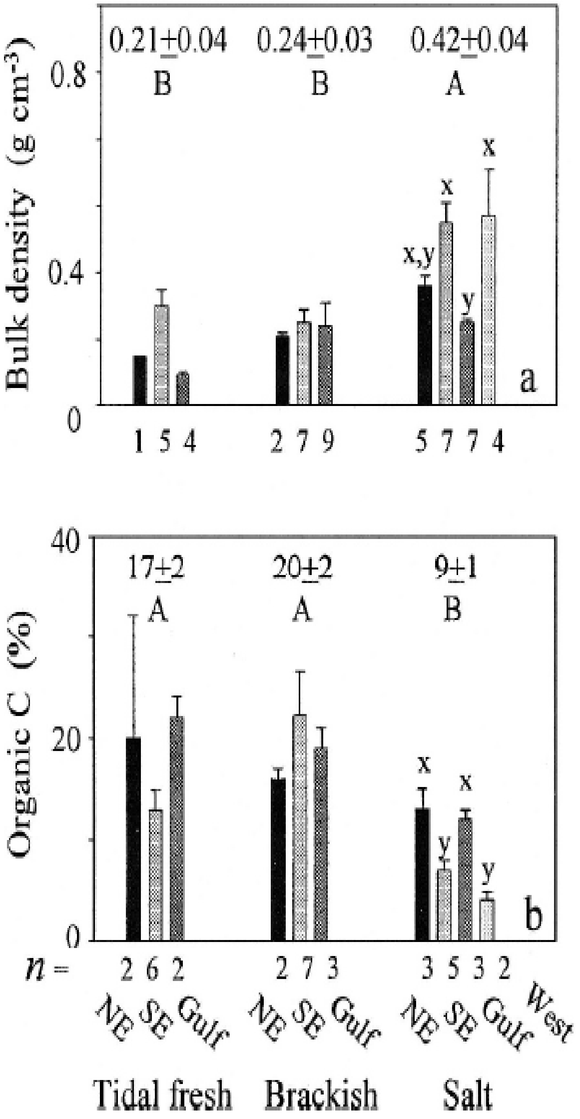
↑↓

Subsidence ↓

Marsh Sediment

From Cahoon

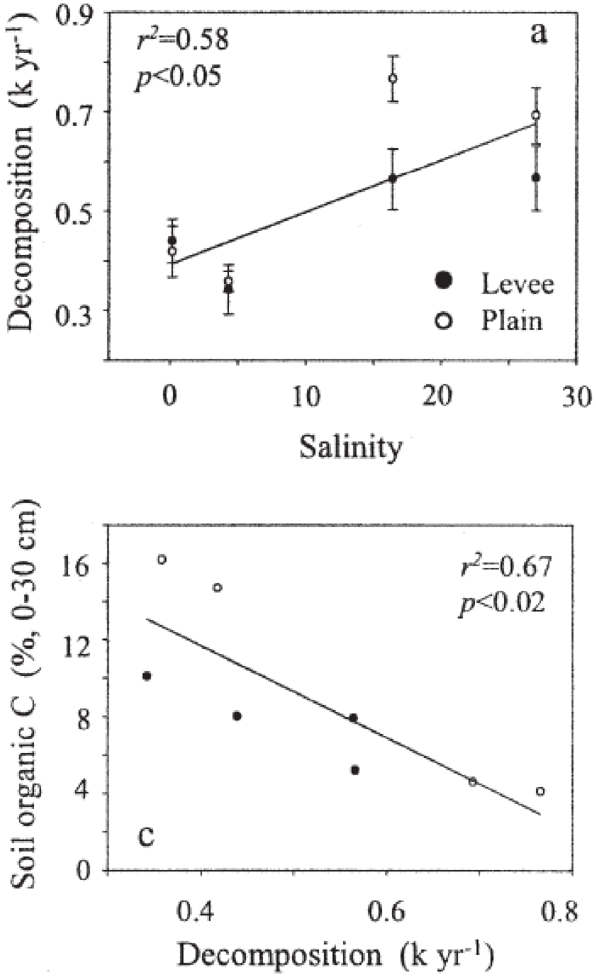
C properties of sediments



- Bulk density typically highest in salt marsh, reflects higher sediment content
  - but not TSS pattern
- BD shows no geographic pattern

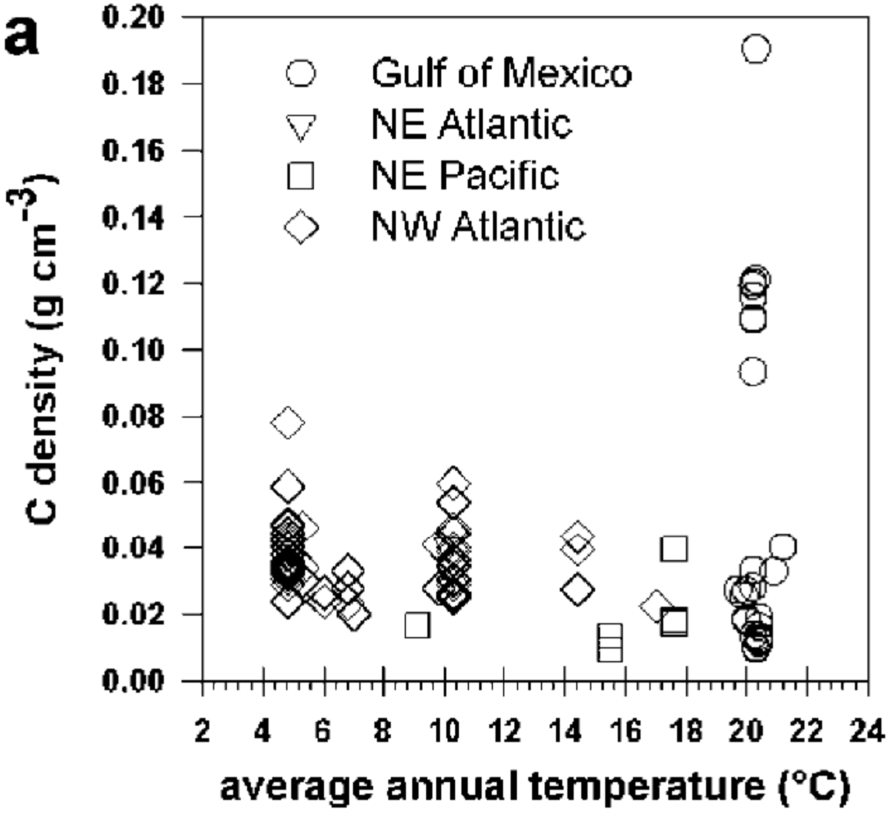
- Organic C content highest in fresh and brackish marshes, perhaps reflecting lower rates of decomposition (low $[SO_4^{2-}]$)

From GA study – 3 sites along 3 gradients



Craft 2007

C properties of sediments



Relationship of soil carbon density to annual average temperature in soils of all salt marshes.

Chmura et al. 2009

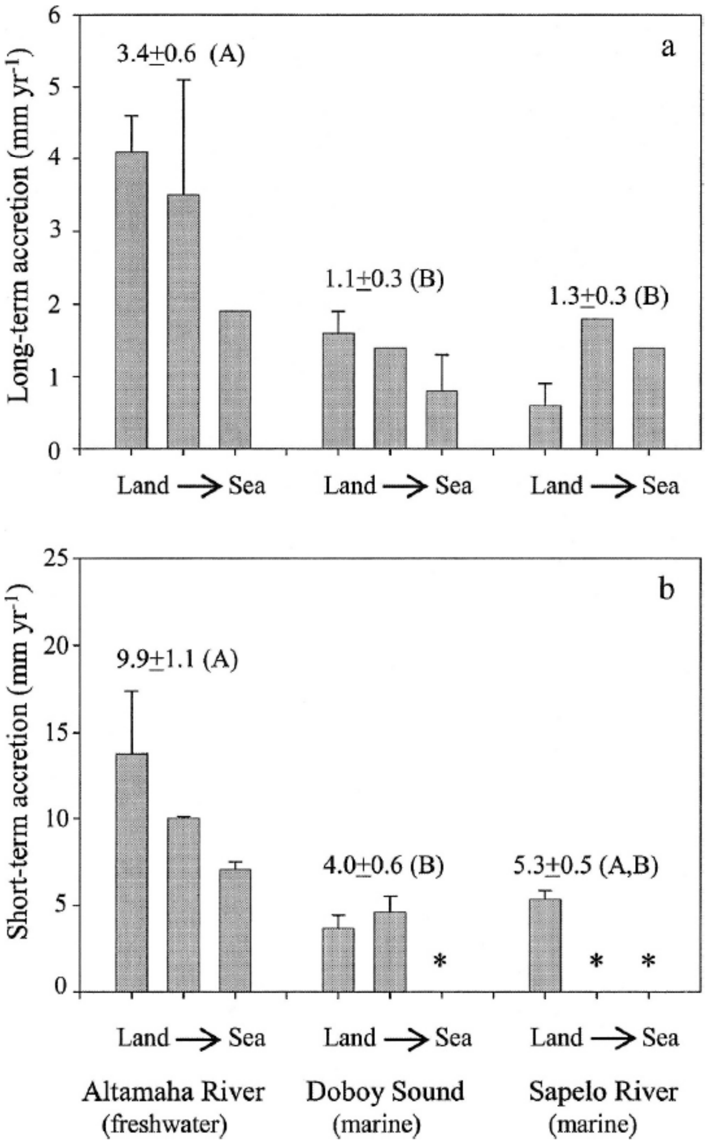
- C density average – 0.039 gC cm^{-3}
- C density decreases with Temp, but explains <25% of variability
- Relation driven by *S. patens*
- *S. alterniflora* – C vs T° R^2 only 0.05!!!
- While we can explain much local variation, when compiled globally relations fail.

Accretion – Sedimentation Rates

Best estimated from isotope profiles of
^{14}C – 1000 yrs,
^{210}Pb – 100 yrs,
^{137}Cs -50 yrs

- Short (marker) and long-term (isotope) accretion rates vary in space
    - Short term generally higher, doesn't reflect subsidence, decomposition, etc
    - In GA, rates highest in oligohaline and in areas with significant riverine inputs (sed? Or freshwater effect?)
- Global SLR – 2-3mm/yr last 100 yrs
- Accretion rates a function of SLR rate, sediment supply rate, sediment trapping by marsh vegetation, flooding frequency and duration, organic matter production and decomposition rates

Coastal Georgia

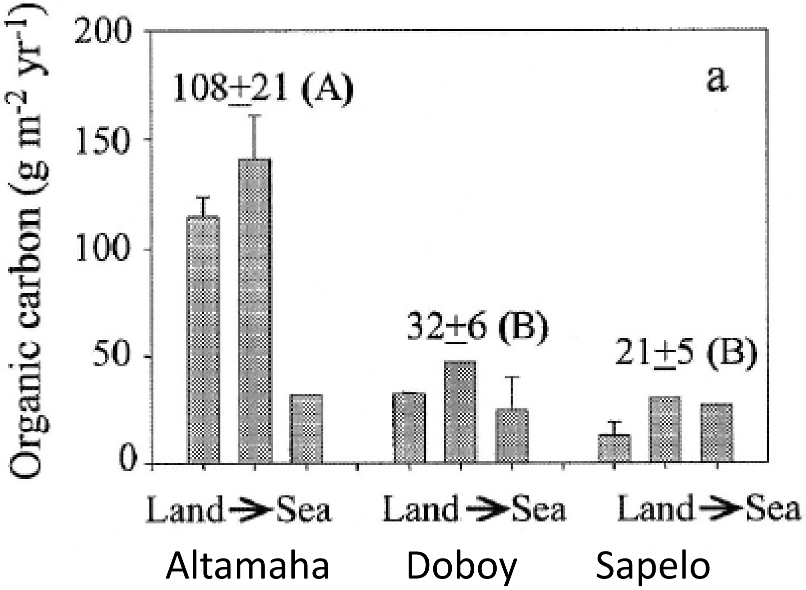


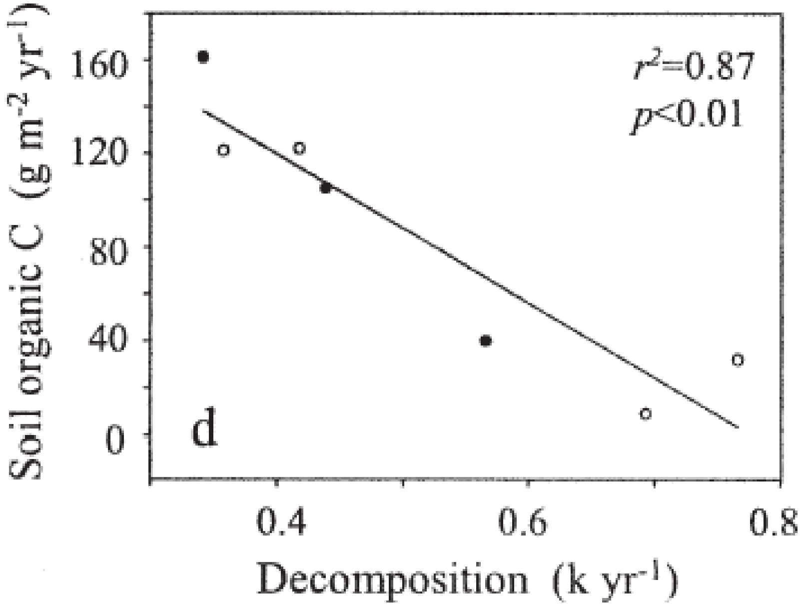
Craft 2007

C Burial Rates

[Sed C] X Accretion = C Burial

- C burial greatest in river dominated estuary
- C burial greatest in oligohaline region
- Reflects both sediment availability- hence accretion rate and
- C content, which is related to decomposition rate and perhaps low [SO_4^{2-}]





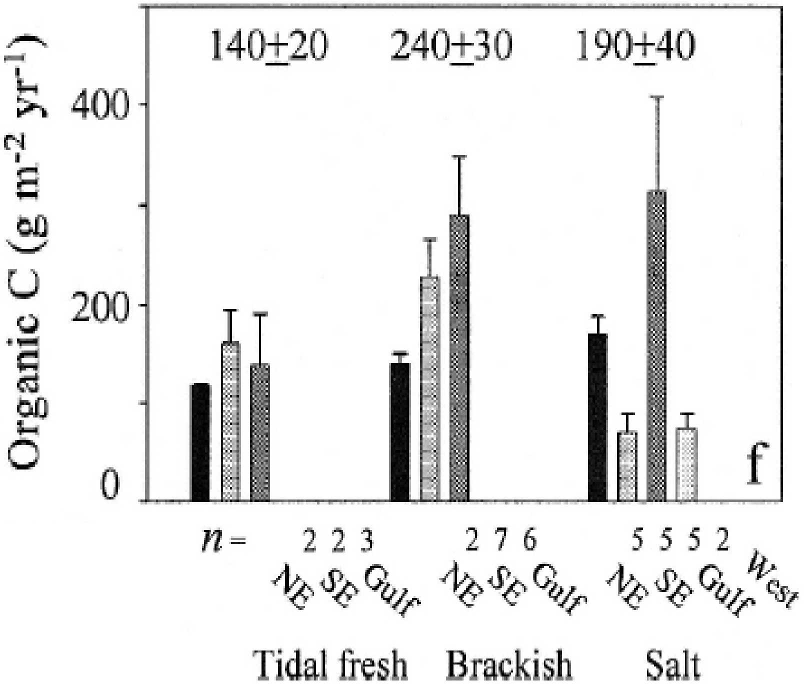
N. American and Global C Burial Rates

- Bulk density lower in tidal fresh and brackish marsh sediments
- Organic C content higher in tidal fresh and brackish sediments
- Accretion decreases with increasing salinity
- Organic C burial – no difference across geographic regions, unlike that observed in GA where there were gradients reflecting salinity and river location
- Global avg – 190 - 210 gC m^{-2} yr^{-1}

  Craft 2007 vs Chmura et al. 2003

4.4 x 10^{12} to 8 x 10^{13} gC/yr globally
4-80 Tg/yr

depending on area 22,000 to 400,000 km^2
(Chmura vs Nellemann)



Mangroves

Global Distribution of Mangroves

Source: UNEP-WCMC, 2009; Valiela *et al.*, 2001

Area:

170,000 km^2 Nellemann et al.

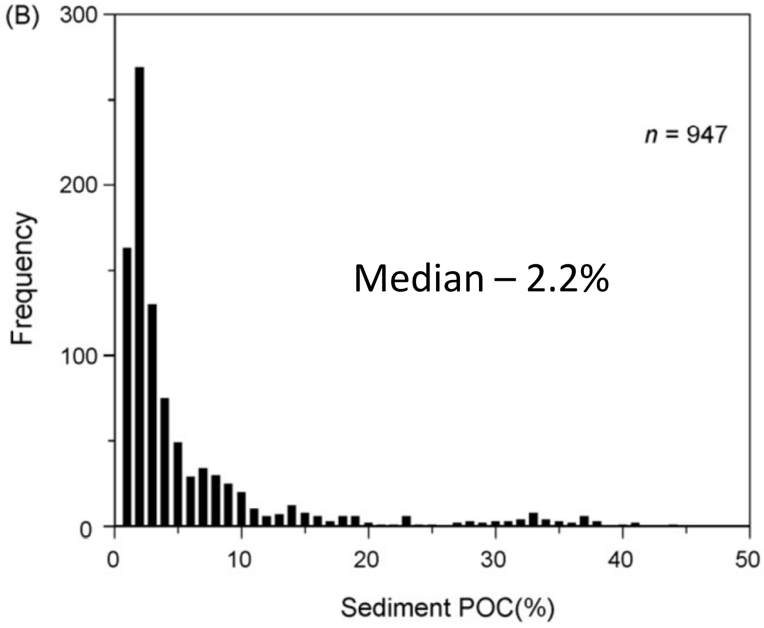
181,000 km^2 – Spaulding et al. 1997

200,000 km^2 – Duarte et al. 2005

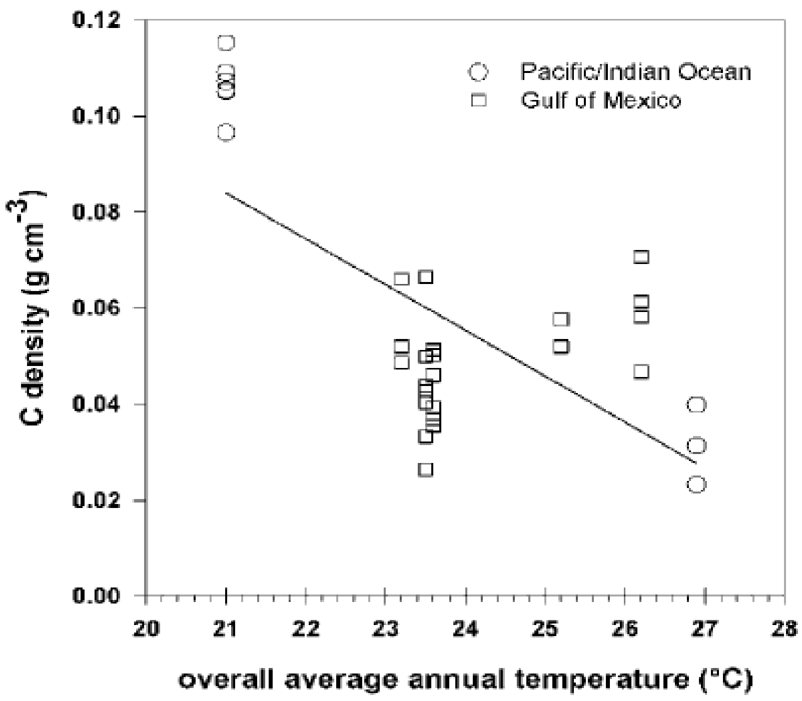
Are these estimates accurate to within 10X?

- Mangroves represent the tropical extension of intertidal wetlands – killing freezes prevent their spread to temperate regions
- Mangrove successional development identical to salt marshes – vertical accretion, lateral transgression and progradation all dependent on rates of SLR, sediment supply, organic matter net production, vegetation trapping of sediments, etc
- Mangroves far less studied than salt marshes – easily 100x less

Mangrove Sediment Properties



Median – 2.2%

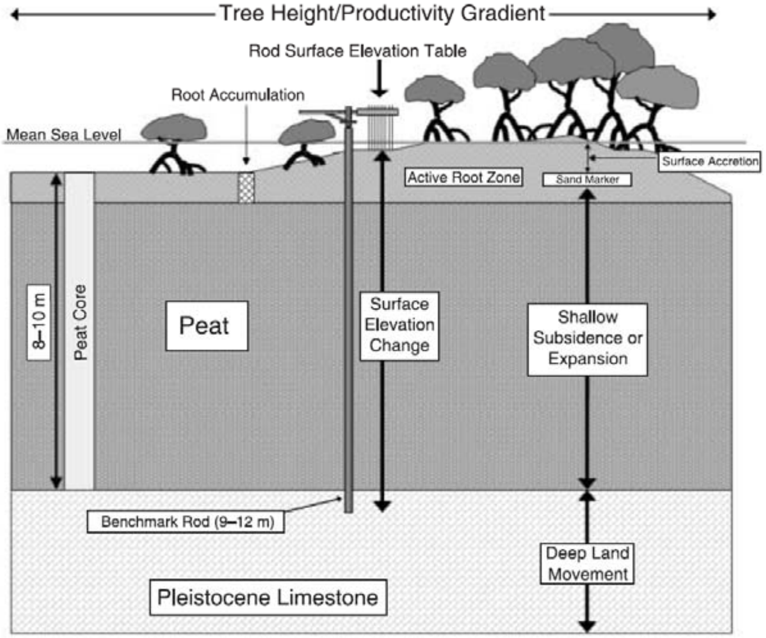


- Carbon content range –
  - <1 to >40% (Kristensen et al. 2008)
  - 2.2% to 8.5% (Duarte et al. 2005 vs Kristensen et al. 2008)
- Sediment C density –

0.055 ± 0.004 g cm^{-3} Chmura 2003

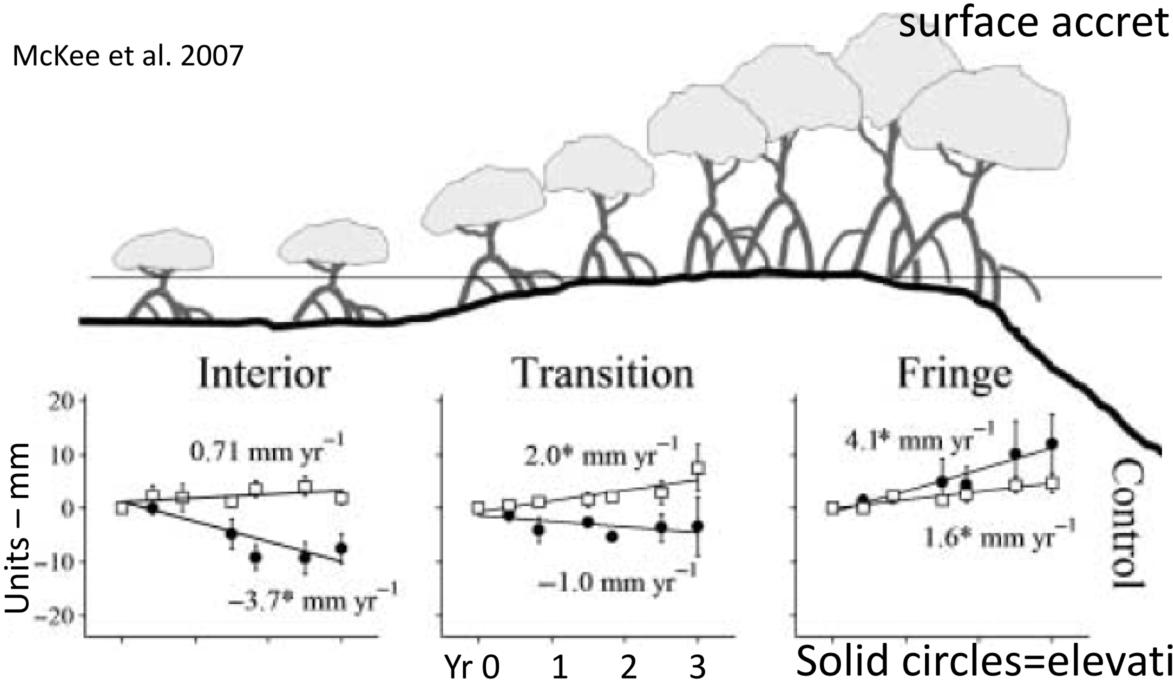
- C density decreases with increasing temp (R^2 – 0.49), perhaps reflecting increased decomposition

Current Elevation Change



McKee et al. 2007

- Fringe mangroves gain 4.1 mm y^{-1}, with surface accretion of 1.6 mm y^{-1}, indicating 2.5 mm y^{-1} subsurface expansion (peat accumulation
- Transition and interior mangroves losing elevation at 3.7 and 1.0 mm y^{-1} even with surface accretion of 0.7 to 2 mm y^{-1}
- Nutrient fert enhanced elevation rise and surface accretion



Solid circles=elevation

Conclusions:

- Elevation can increase or decrease in same system
- Elevation change varies with NPP
- Nutrients can increase elevation change – NPP relation

Factors contributing to elevation change

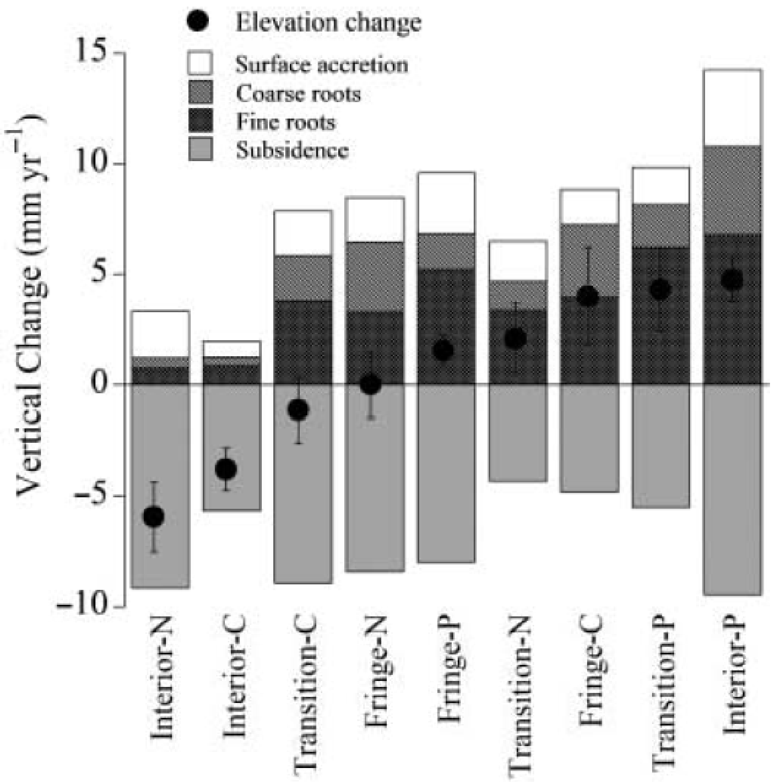


Figure 3 Variation in surface elevation change (●) relative to vertical change attributable to surface accretion, fine and coarse root production, and shallow subsidence (physical compaction and decomposition) across mangrove zones and nutrient treatments at Twin Cays, Belize; mean ± 1 SE (*n* = 3); SE not plotted on stacked bars for clarity.

McKee et al. 2007

- Course and fine roots most important factor in elevation change across sites
    - Esp. fine roots – which explain 42% of variation in step-wise regression
- Subsidence (decomposition and compaction) important negative factor everywhere
- Surface accretion, relatively similar across sites

Elevation change and SLR

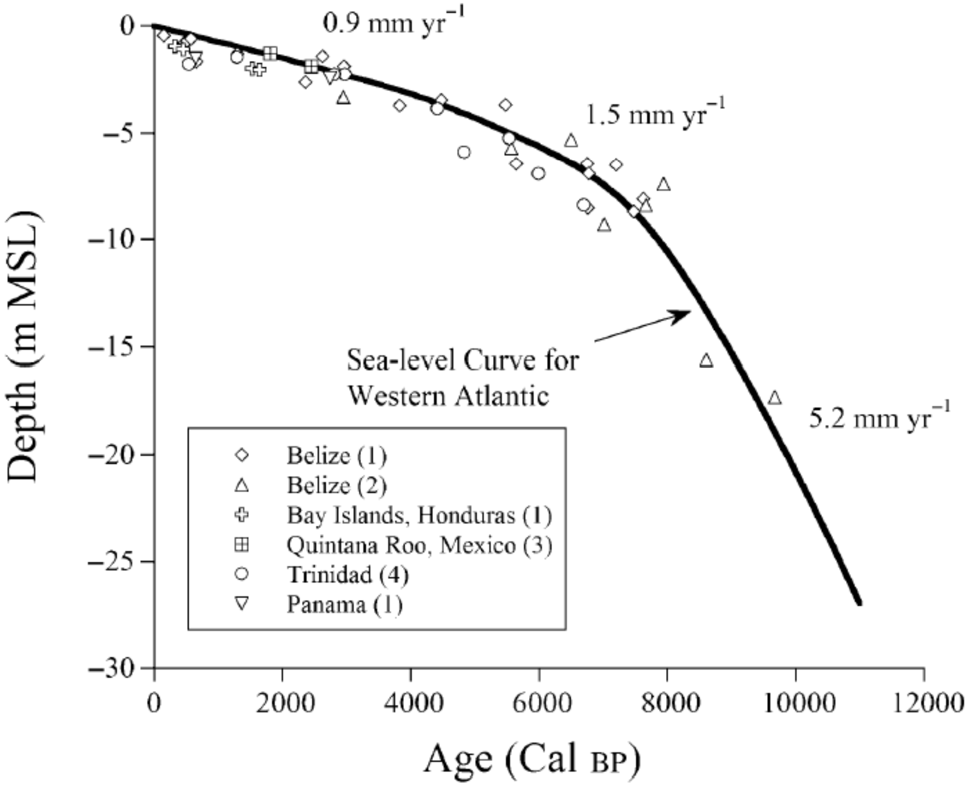


Figure 4 Time–depth plot of mangrove peat samples in relation to a sea-level curve for the western Atlantic. Data are from Twin Cays and Cat Cay, Belize; the Bay Islands of Roatán and Guanaja, Honduras; and Isla San Cristóbal, Panama (*1*) (this study);

McKee et al. 2007

- Peat thickness in Americas ranges from 0.4 to 10 m
- Avg OM – 65%
- Comprised of fine roots (40%), coarse roots, wood and leaves, OM (27%)
- ^{14}C – shows accum for 7-8000 yr
- Peat accumulation rate closely follows SLR
- No mangroves when SLR ≥ 5mm y^{-1}
- Accumulation occurred only when SLR ≤ 3.5 mm y^{-1}
- Rate of accumulation decreased as SLR decreased – now only 0.9 mm y^{-1}

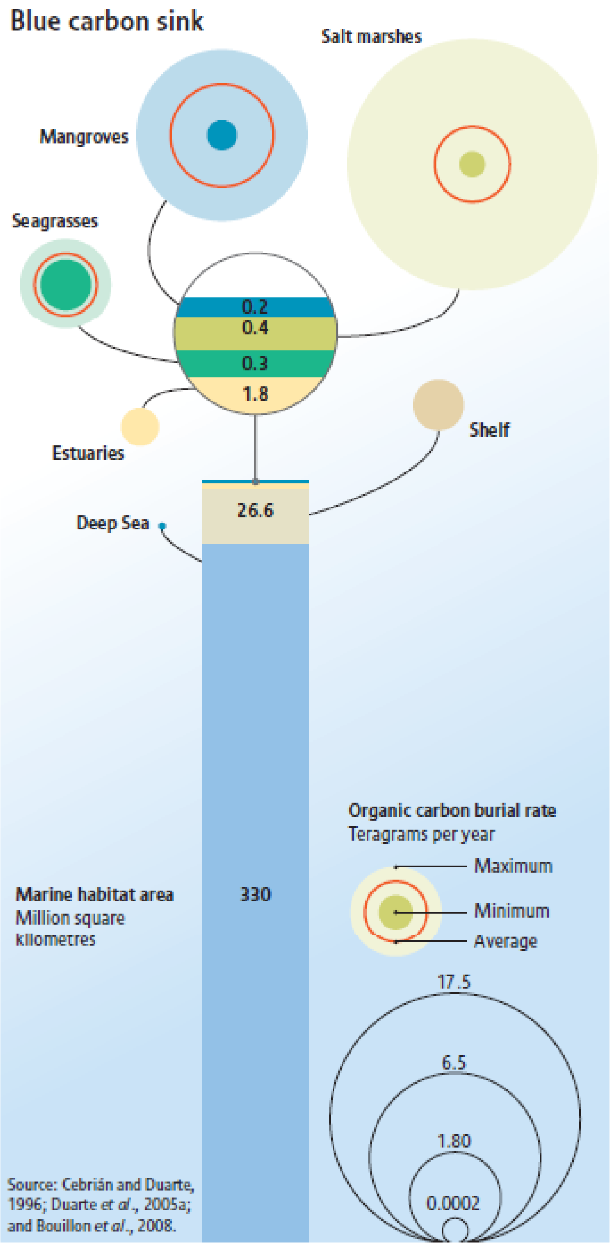
Mechanism – root accumulation vs elevation feedback, presumably by flooding effects on productivity – decomposition processes

Mangrove Organic C Accretion

- **210 gC m^{-2} y^{-1}** - Chmura et al 2003, based on limited Cs-137, Pb-210, and clay marker horizons and C density of 0.055.
- **139 gC m^{-2} y^{-1}**, Duarte et al. 2005, based on 8.5% OC and burial rate of Chmura et al. 2003
- **128 gC m^{-2} y^{-1}** – Jennerjahn and Ittekkot (2002), based on difference between litter fall, export and consumption, and neglecting that litterfall <50% of true NPP

- **Global Sequestration** –
  - 22 – 42 Tg C y^{-1} (10^{12} gC y^{-1})

Summary


Blue carbon sink

Source: Cebrián and Duarte, 1996; Duarte *et al.*, 2005a; and Bouillon *et al.*, 2008.

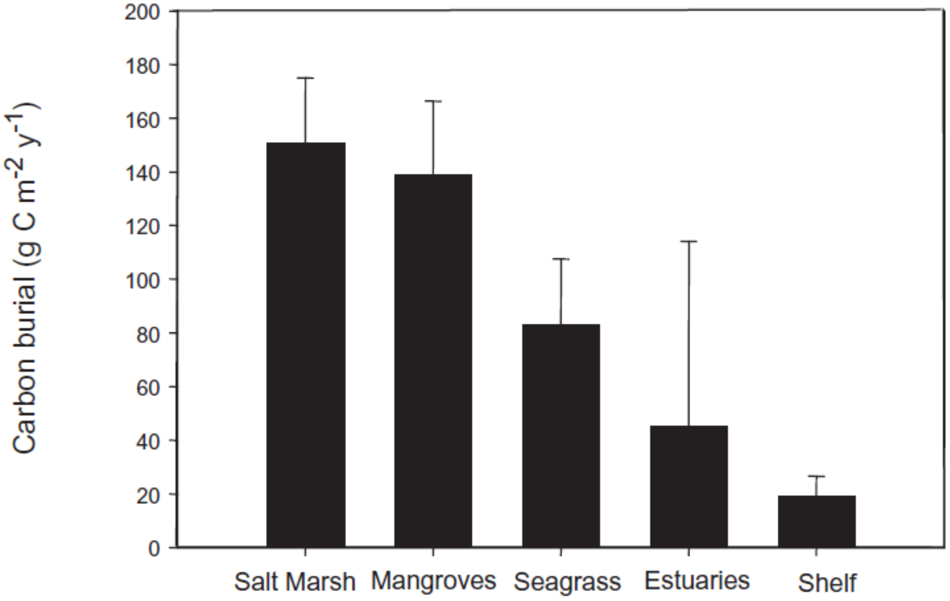
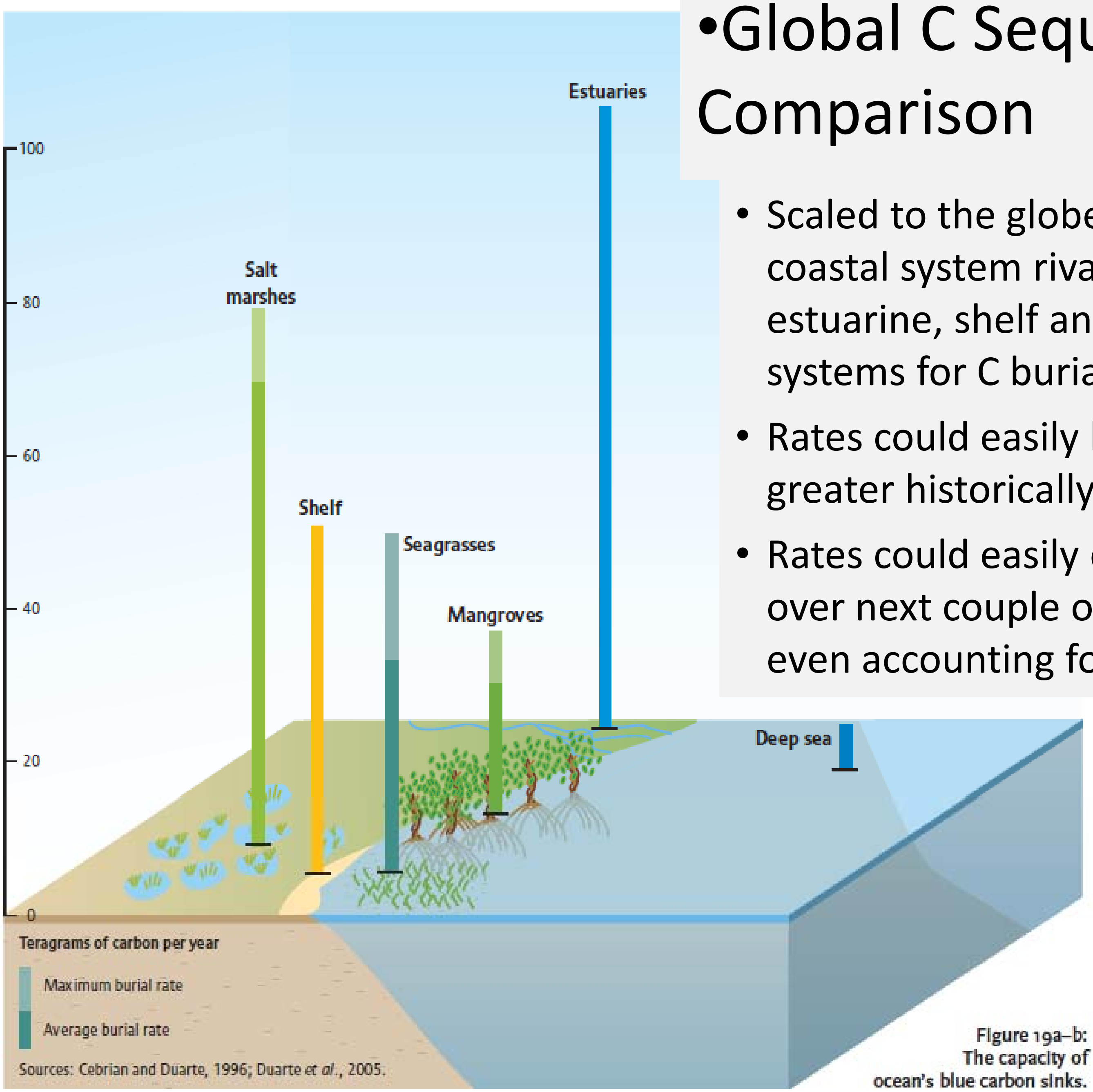


Fig. 1. Average (±SE) carbon burial rates in different coastal ecosystems. Data sources in Table 1. Duarte et al. 2005

While areal extent is very small, exceptional unit burial rates scale to global significance

•Global C Sequestration Comparison

- Scaled to the globe, vegetated coastal system rival classic estuarine, shelf and open ocean systems for C burial
- Rates could easily have been 2X greater historically
- Rates could easily decrease by 50% over next couple of decades, not even accounting for SLR

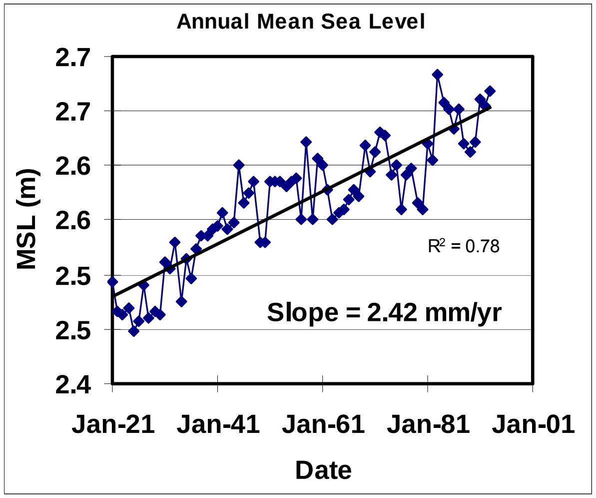


Sources: Cebrian and Duarte, 1996; Duarte *et al.*, 2005.

Figure 19a–b: The capacity of ocean's blue carbon sinks.

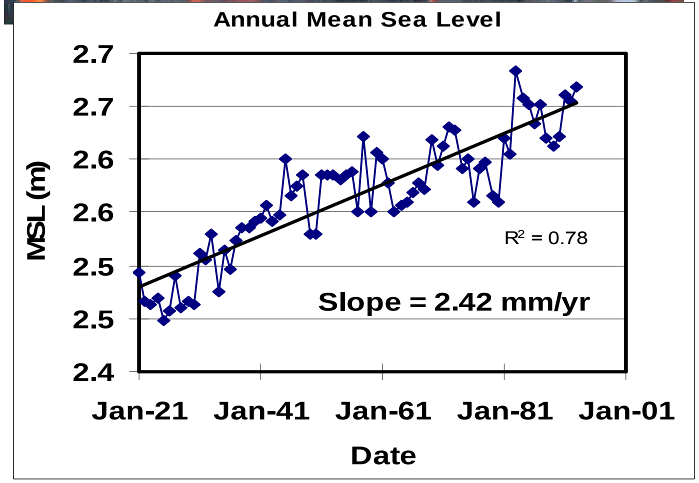
Fate of these systems

- Current sequestration rates small compared to historic rates – e.g., NJ has lost >70% of salt marshes
  - Estimates – global salt marsh down 25%
    - Filling, fish farming, diking/culverts
  - Global mangrove down 35% to 86% in 25 yrs
    - Filling, charcoal, fish farms
  - Global seagrass down 29% (Waycott et al. 2009)
    - Eutrophication, turbidity, sediment disturbance
- Being lost at 1-7% annually or 7X rate of loss 50 yrs ago
- Predicted loss does not factor in accelerated rates of sea level rise for next century



Threats

- Continued “reclamation”
- Eutrophication – as it affects light for seagrass, but also as it affects balance between P and R for mangroves and salt marshes and above-below biomass of macrophytes
- Alteration in watershed sediment runoff – look at Louisiana marshes!
    - What we see currently is a non-steady state condition with systems still trying to return to some equilibrium between past and current rates of sediment input (east coast agricultural abandonment and sediment runoff BMP)
- Increasing rate of SLR
- Coastal armoring as it prevents transgression and availability of sediment



Research Questions

Case studies are great, but we must seek generality in results, and predictive understanding of mechanisms so as to allow modeling future scenarios

- What controls sediment organic content?
  - What controls the balance in macrophyte P and R and root/shoot allocation? Nutrients,"stress" factors, plant chemical composition and defenses, across species
  - What role does vegetation play in trapping sediments and OM? And how does that vary with flooding depth, wave energy, currents, and species?
  - What role does sediment availability play in sediment C content? As it "protects" OM, as it affects porewater percolation, as it affects nutrient availability (Fe, S, PO4, NH4)
  - What are the effects of temperature, salinity ([SO4], flooding depth, frequency, duration, DO on organic matter decomposition

Research Questions

Case studies are great, but we must seek generality in results, and predictive understanding of mechanisms so as to allow modeling future scenarios

- What controls net increase in elevation of intertidal systems
  - Subsidence – compaction and decomposition
  - What controls peat accumulation – roots / rhizomes / leaves / allochthonous OM?
  - What controls surface accretion? [TSS], flooding frequency and duration, distance from source
  - As external sources of sediment decrease, are there homeostatic mechanisms that enhance OM burial and preservation?
  - Can biomass and elevation be remotely sensed? If live and dead C stores begin to decompose and erode, this could be a significant negative flux in a countries C balance.

Research Questions

Case studies are great, but we must seek generality in results, and predictive understanding of mechanisms so as to allow modeling future scenarios

- What are the social dynamics that lead to use and abuse of vegetated coastal ecosystems?
- What incentives can be created to promote their conservation and enhancement?
- How can the world pay for the ecosystem services these systems provide that are national or global in scale? Could payment reverse their direct and indirect destruction?

Acknowledgements: are extensive, ranging from REUs (Johnston, Cavatorta, Smith), GradStudents (Lemay), RAs (Weston, Garritt, Goldstein, Lawrence, Lee, Sundberg), Postdocs (Valentine), PIs (Morris, Millette, Friedrichs, Warren), Funding Agencies (NSF, EPA Starr, SG)

Non-equilibrium dynamics and the fate of coastal vegetated systems in the face of accelerated SLR, climate change and watershed land use change

Evidence suggests that present day intertidal wetlands are still adjusting to historic rates of watershed sediment runoff and always responding to variations in sea level, including accelerating rates of SLR

Idealized cross-section of a marsh following continuous rise in sea level

Redfield 1967

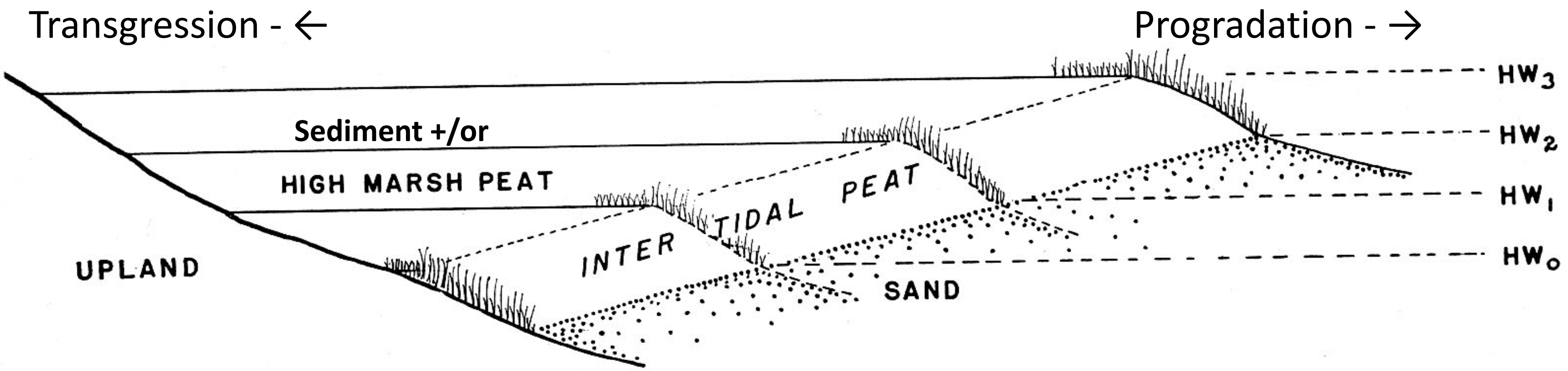


Fig. 1. Development of a typical New England salt marsh with rising sea level and continued sedimentation.

As sea level rises, elevation of the marsh surface increases as increased tidal flooding promotes 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

Peat Depths in Barnstable Marsh

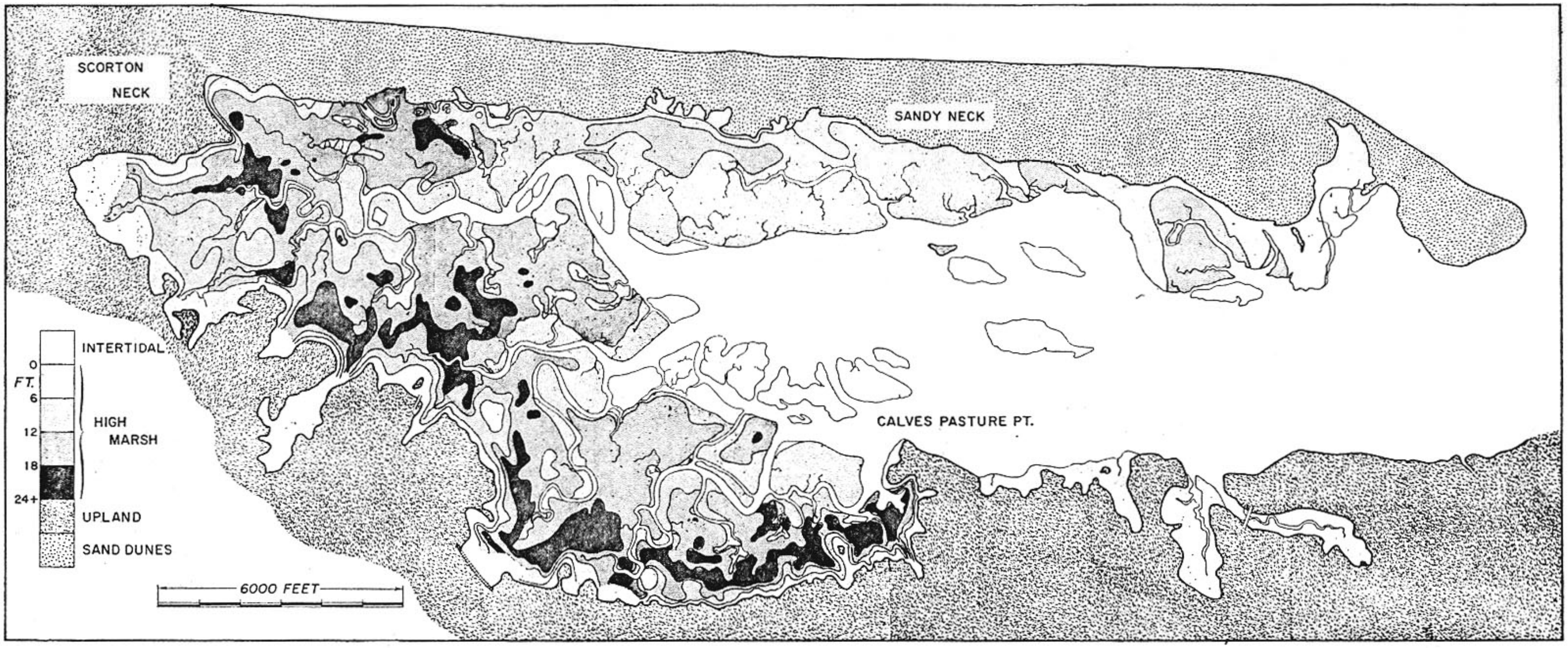
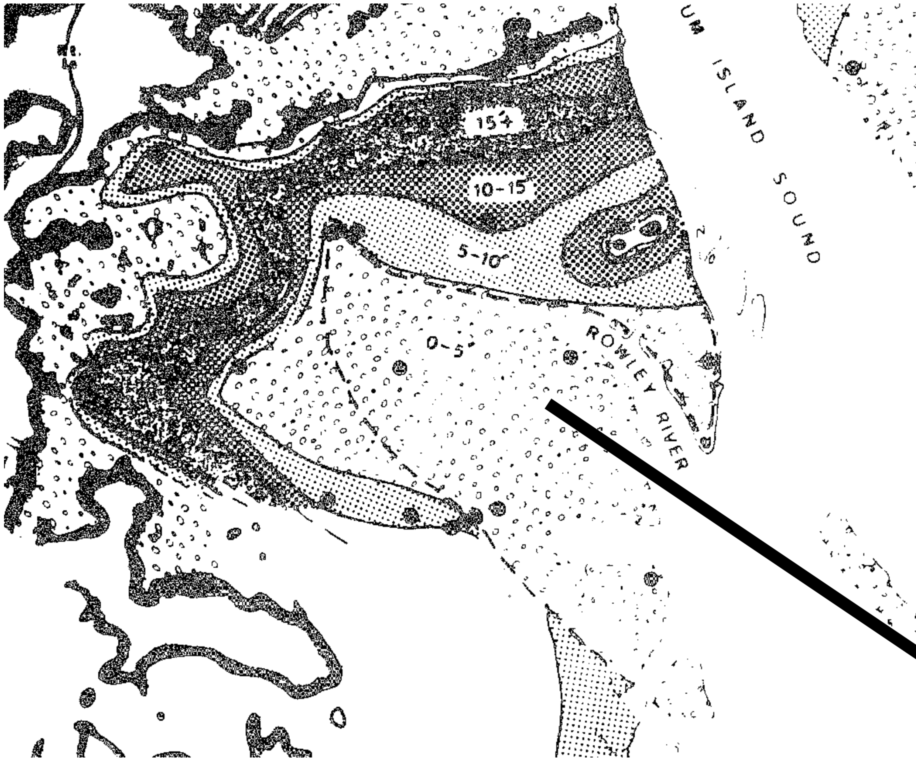


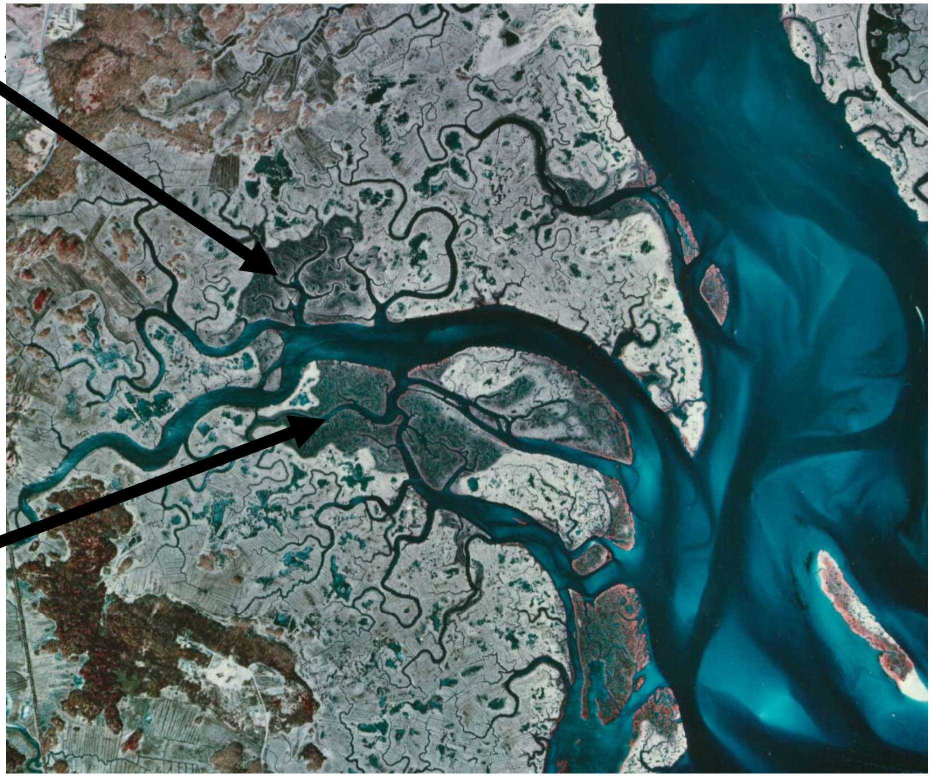
Fig. 2. The Barnstable Estuary, showing the distribution of depth of peat in the high marsh. Contour intervals, 6 feet.

What processes create these patterns?
PIE LTER studies

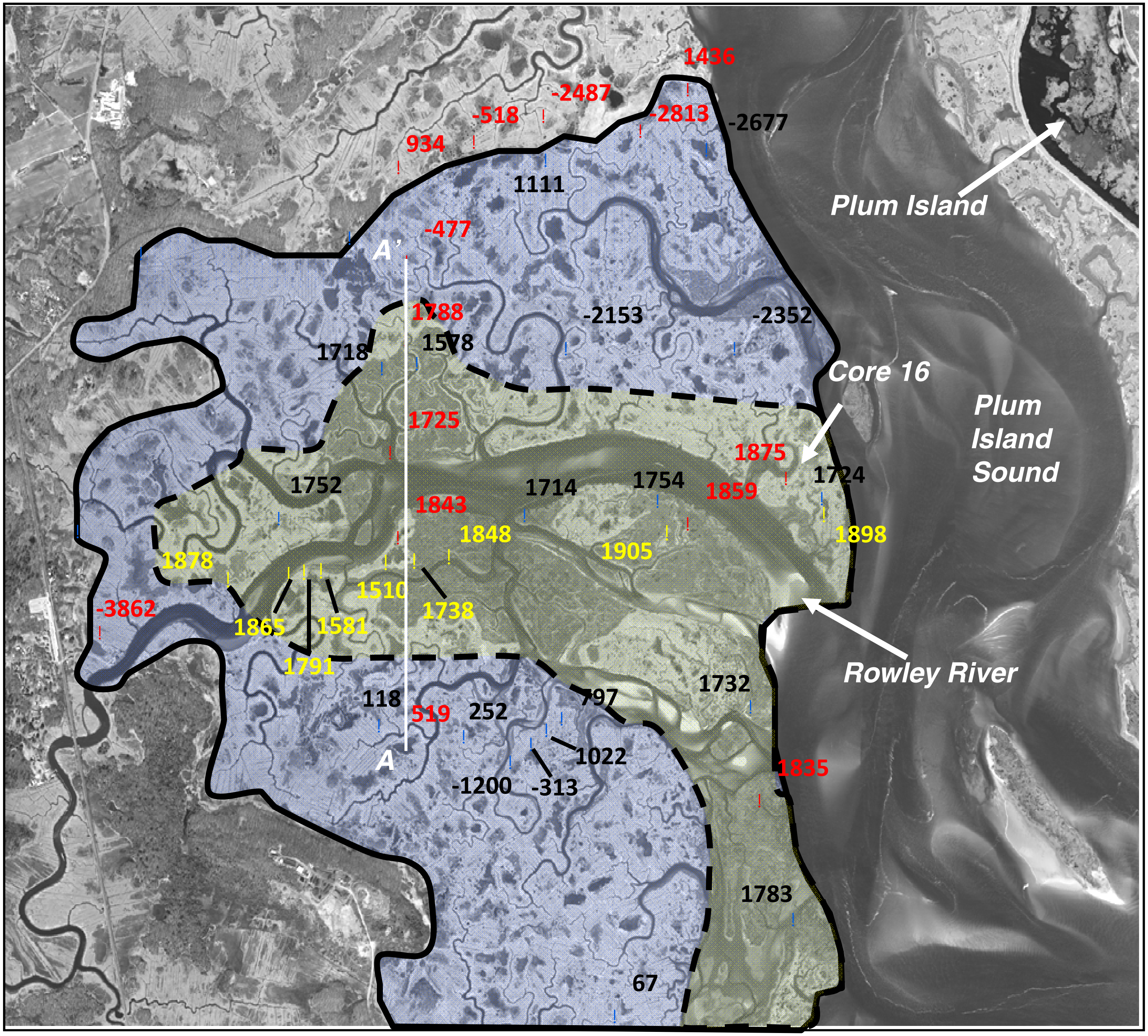


Peat Isopachs from McCormick 1969

mid-March 1992 Color Infrared photograph



Dark marsh regions highlight low elevation marshes that flood on every high tide

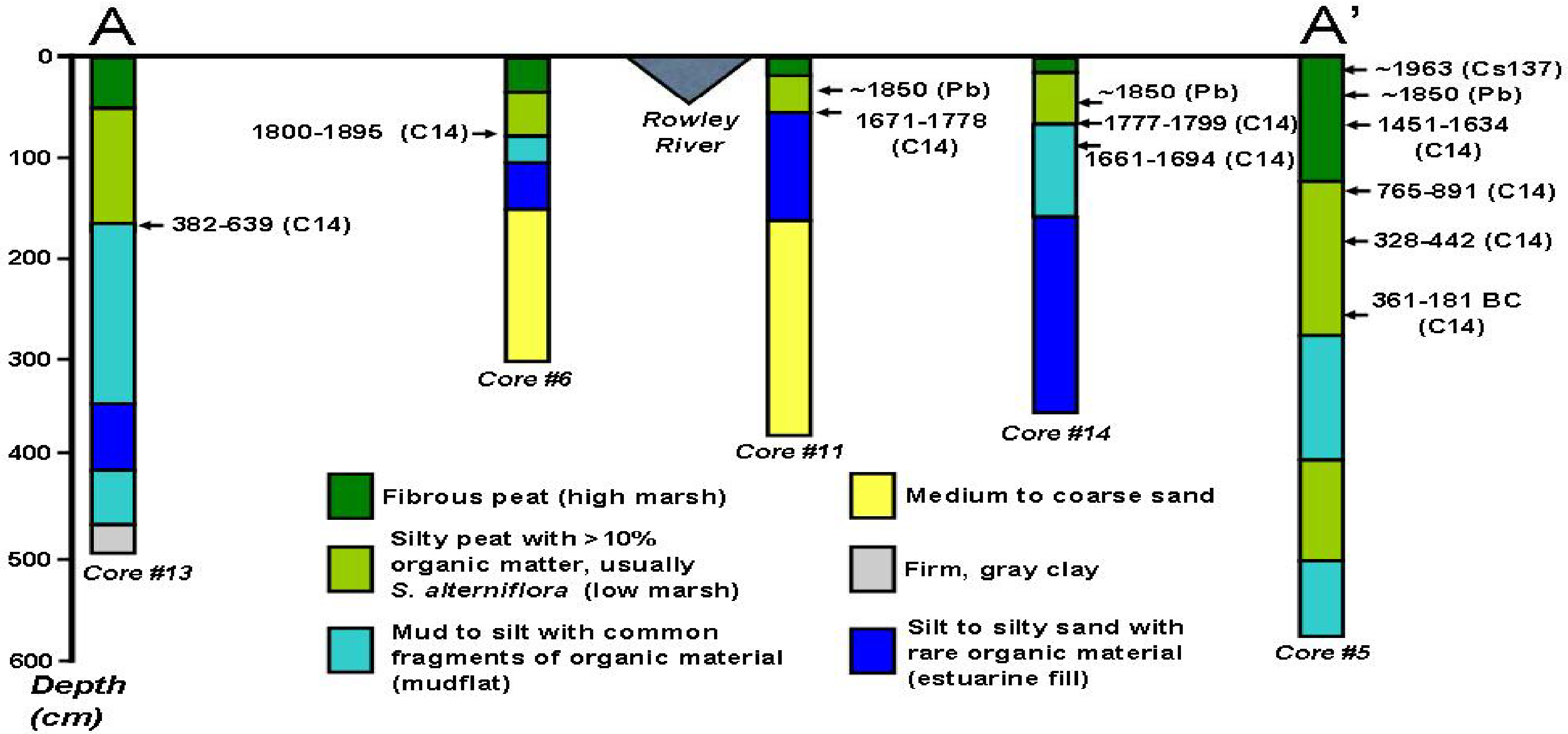


Map of peat age (calendar years AD)

Old peat around basin perimeter (1000s yrs)

Young marsh closer to river (1700-1900 AD)

Kirwan et al. 2009
McIntire and Morgan McCormick



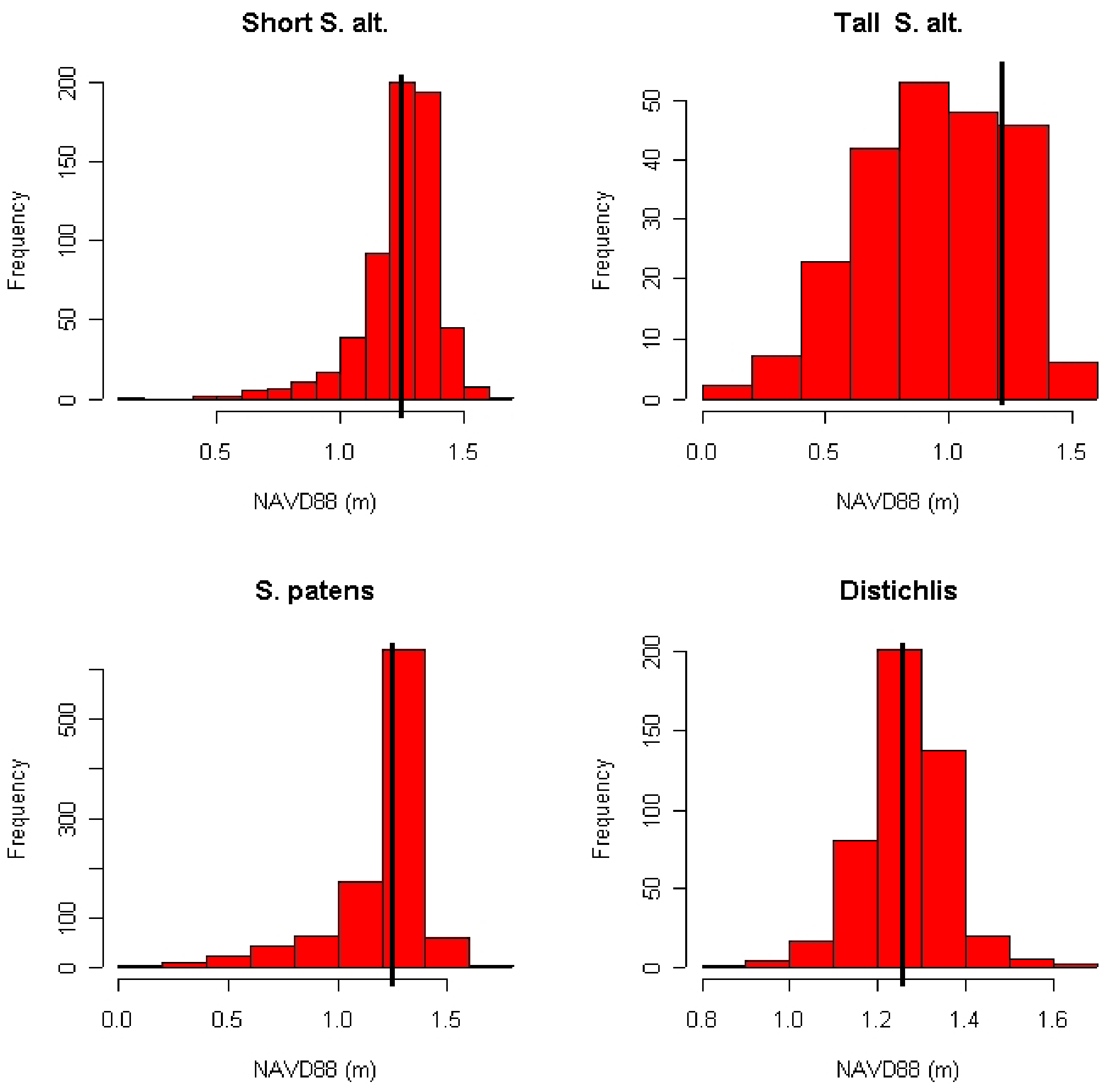
Cross section records basin infilling: marsh replacing mudflats

Progradation (lateral expansion) across basin sometime after ~1800 AD

Like Redfield, except the timing is during a period of SL acceleration

WHY?

Distribution of dominant plants

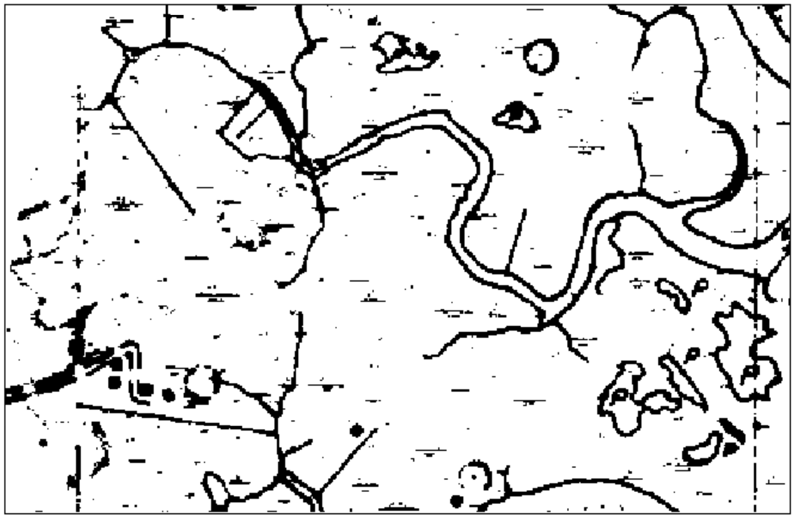


Low marsh colonized with S. alterniflora, non-peat accumulator, but efficient sediment trap.

High marsh mostly S. patens and D. spicata, peat accumulators that enable marsh to build to elevations rarely flooded

With watershed sediment sources dried up, and SLR continusing, lateral erosion is major current source in lower estuary

Pond change analysis



1952 Courtesy of Mass CZM

2001 Source: Mass GIS

Ponded marsh with S. alterniflora marked by star in 2001 image

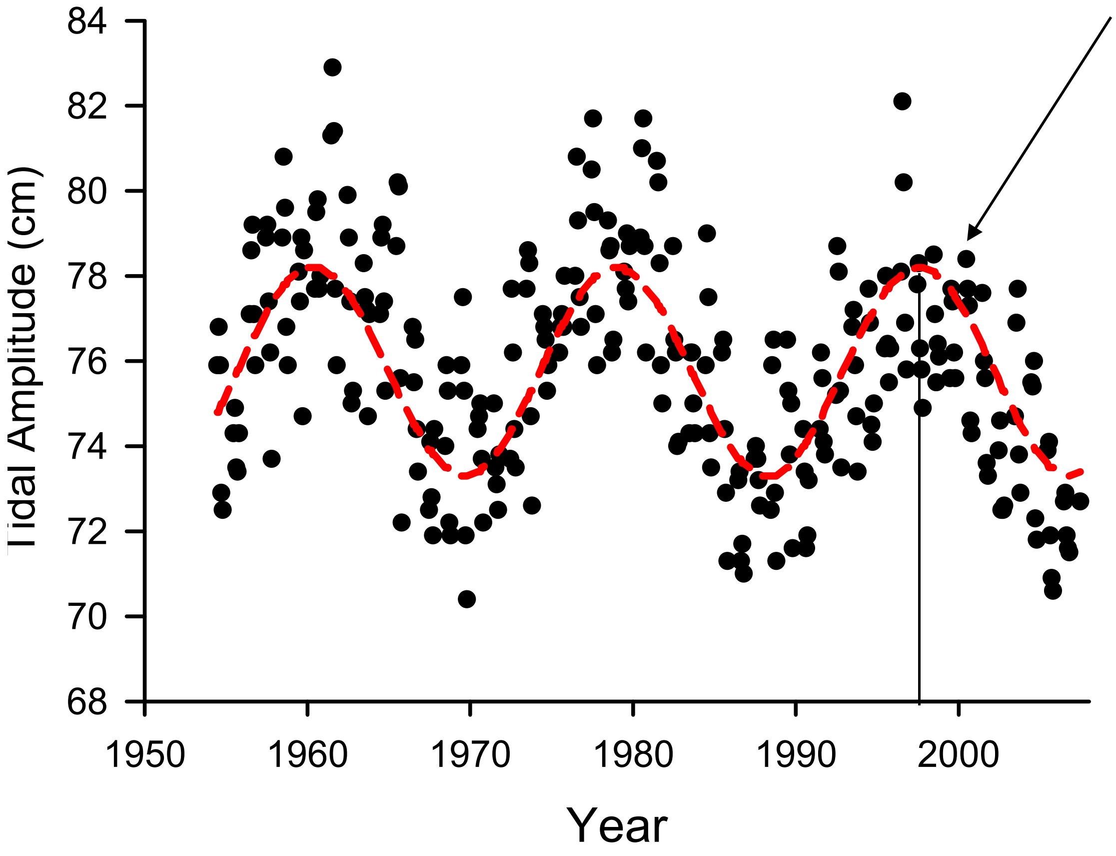
Note dead regions around periphery

Once marsh plant dies – peat decomposes leaving a depression that respires itself larger over time

Ponding of intertidal marshes has been extensive over the past 48 years

1953 NOAA T-Sheet overlaid on 2001 MA color orthophotograph

Monthly tidal amplitude during the months of June-October in Charleston Harbor, SC. Also shown is the result of a harmonic regression with a periodicity of 18.6 years. This is known as the lunar-nodal cycle, and it affects marsh biogeochemistry and productivity.

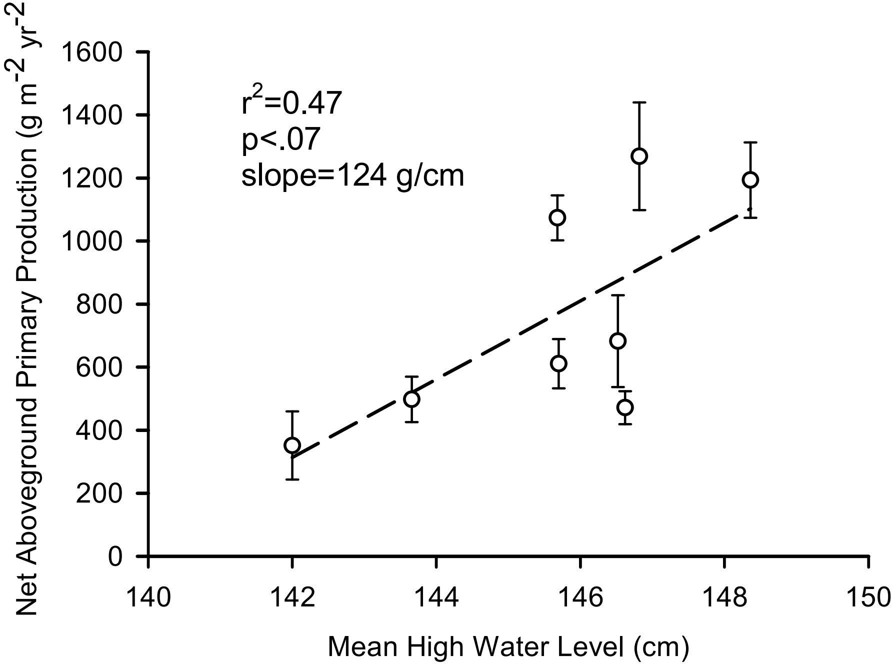


Note the time of the last maximum

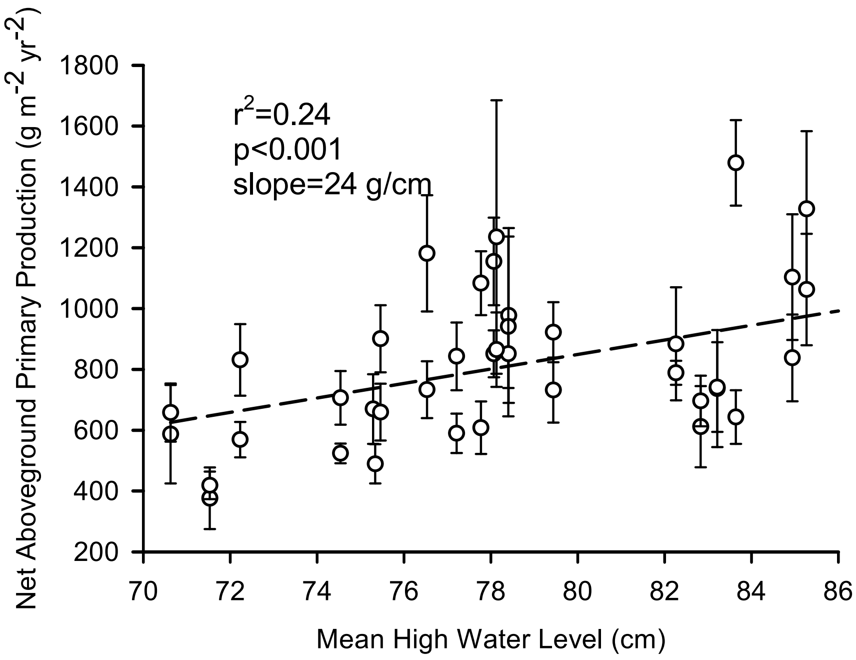
Jim Morris – Univ. S. Carolina

Sea level anomalies contribute to the interannual variability in marsh biogeochemical function. Shown here is the annual NPP of *Spartina alteriflora* in the low marsh as a function of mean high water level at Plum Island (left) and North Inlet, SC (right).

Plum Island



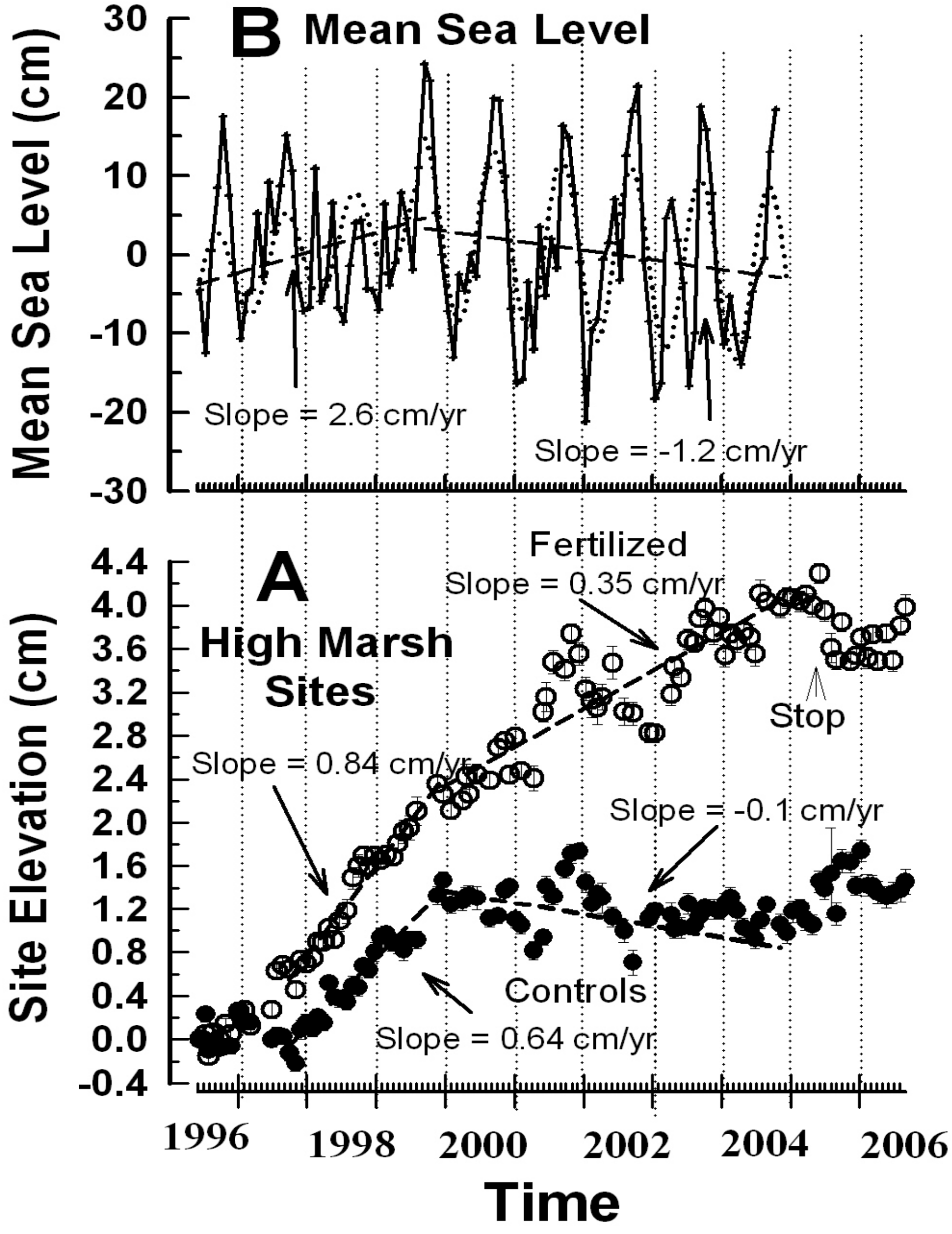
North Inlet



Jim Morris – Univ. S. Carolina

Marsh planters (marsh organs) like this one at PIE are being used to define the response of marsh vegetation to relative elevation.

Jim Morris – Univ. S. Carolina



MSL changed direction in 1999/2000

Sediment accretion is a function of biomass density on the marsh surface and flood frequency & duration.

Note that the marsh was not able to keep up with the rapid rate of SLR prior to 2000. 0.8-1.0 cm/yr is probably about the limit in this area.

Jim Morris – Univ. S. Carolina

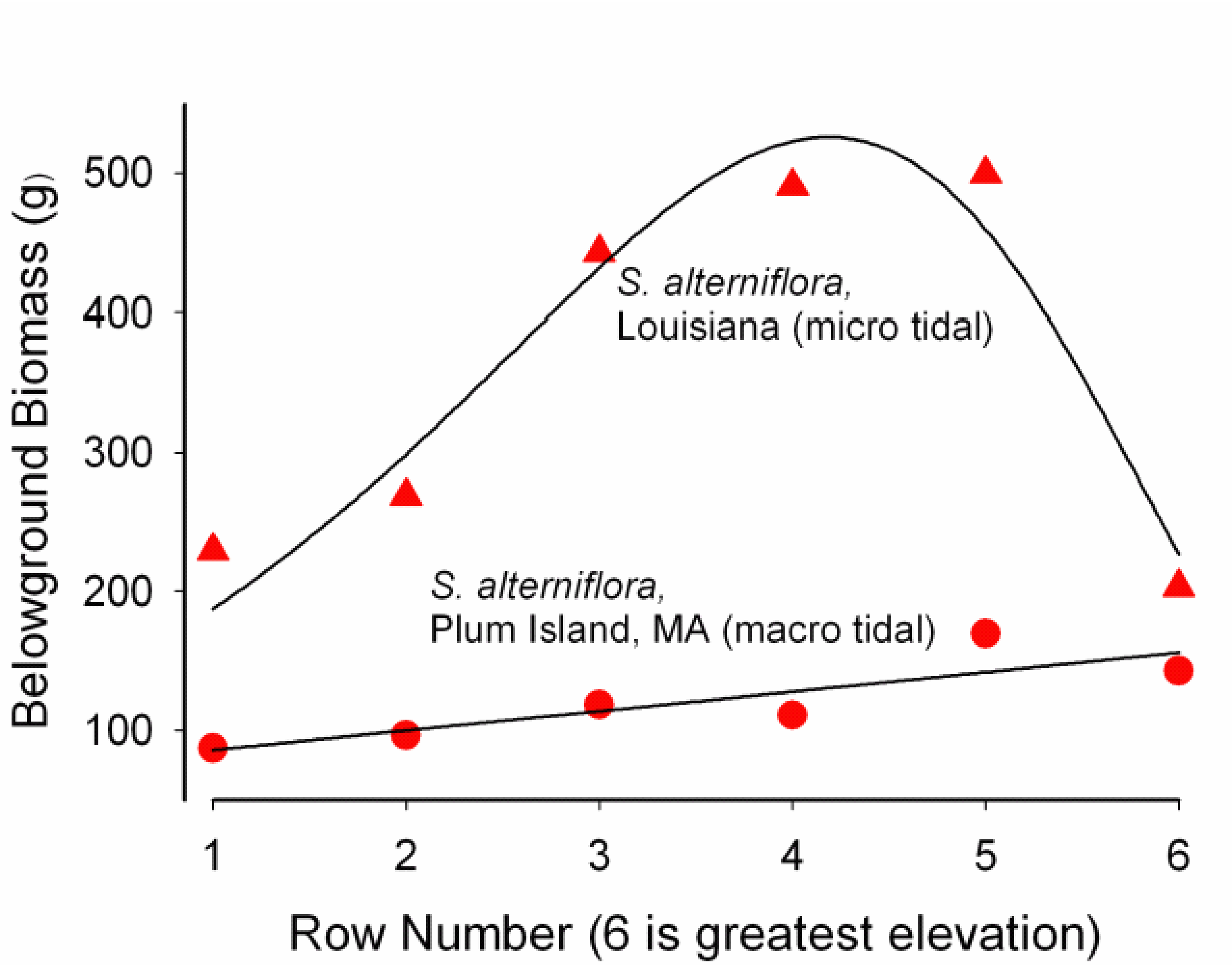
The future

- Research needed to evaluate the system-wide dynamics of marsh response to changing sediment delivery, varying water levels, and an acceleration of SLR.
- What is the fate of current C stores?
- What is their long-term C balance and could historic burial patterns be reversed?

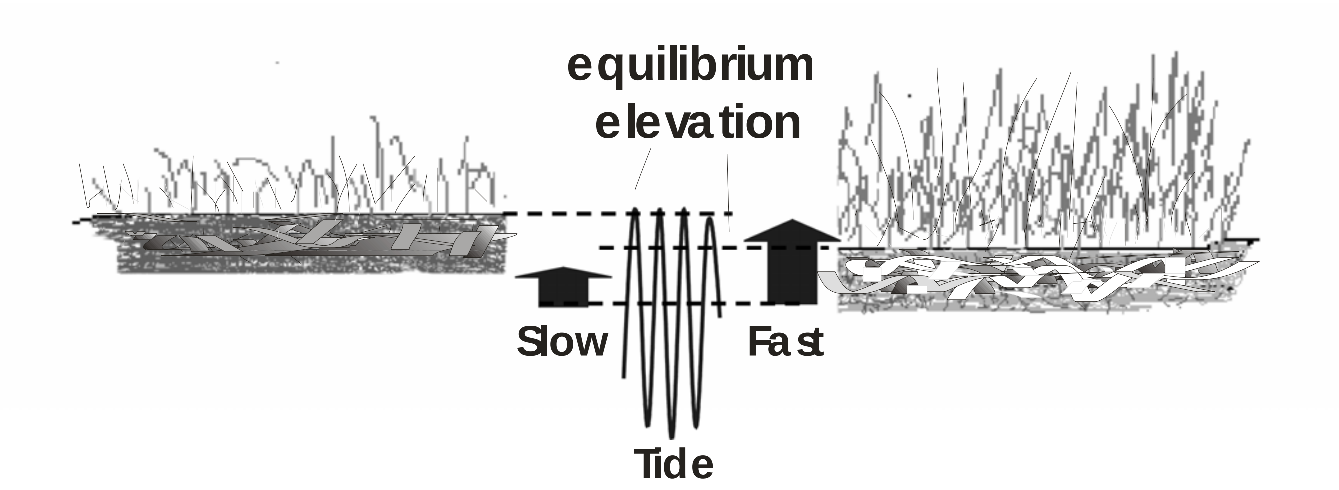
Normal Transgression

ARMORING prevents transgression and future marsh migration

Plant production in microtidal estuaries is more sensitive to change in relative elevation than is production in macrotidal estuaries.

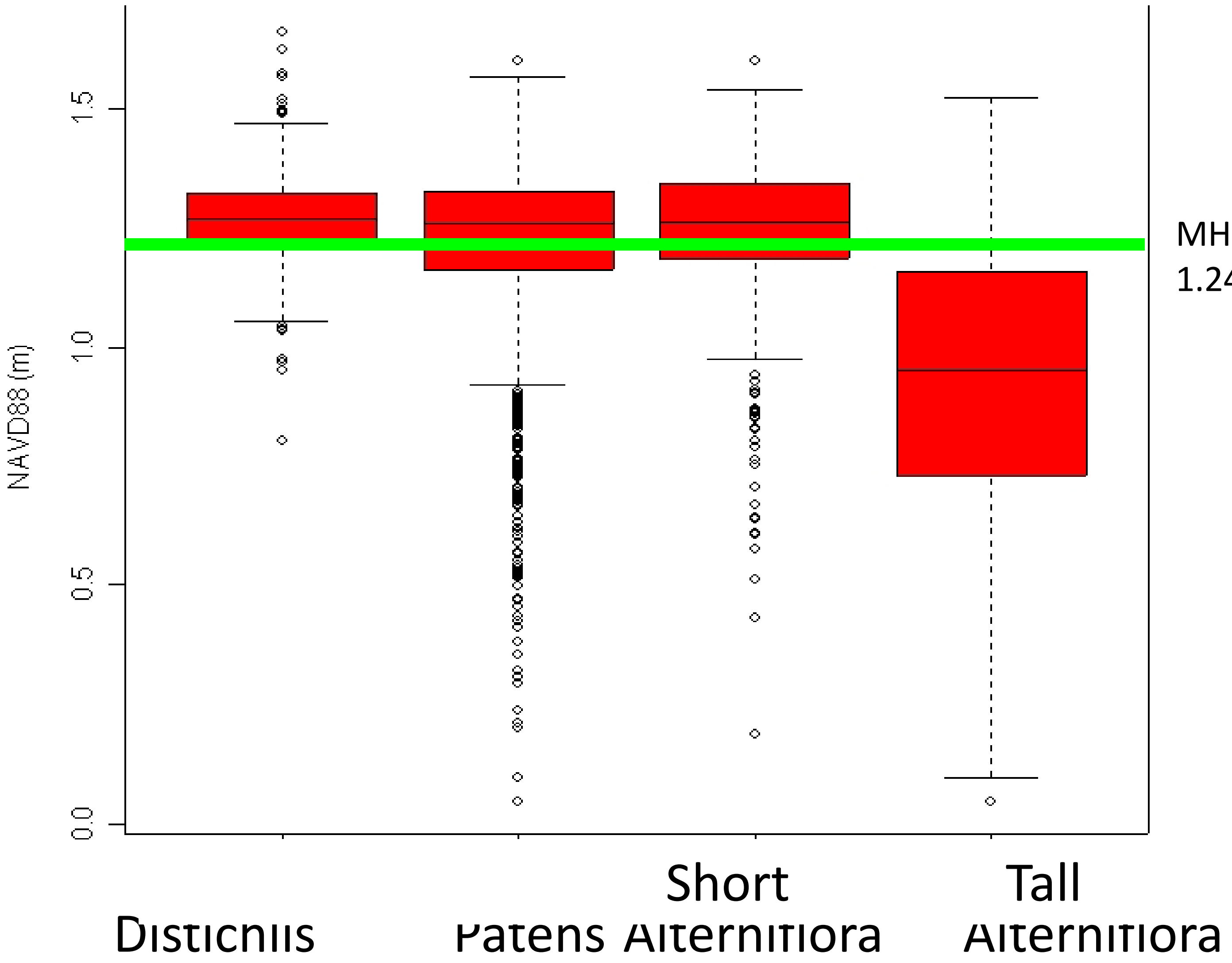


A Conceptual Model of Salt Marsh Responses to Sea-Level Rise



Slow relative sea level rise	Rapid sea level rise
High relative elevation	Low relative elevation
Low mineral sediment input	High mineral sediment input
Low aboveground productivity	High aboveground productivity
High root productivity	Low root productivity
High SOM content	Low SOM content

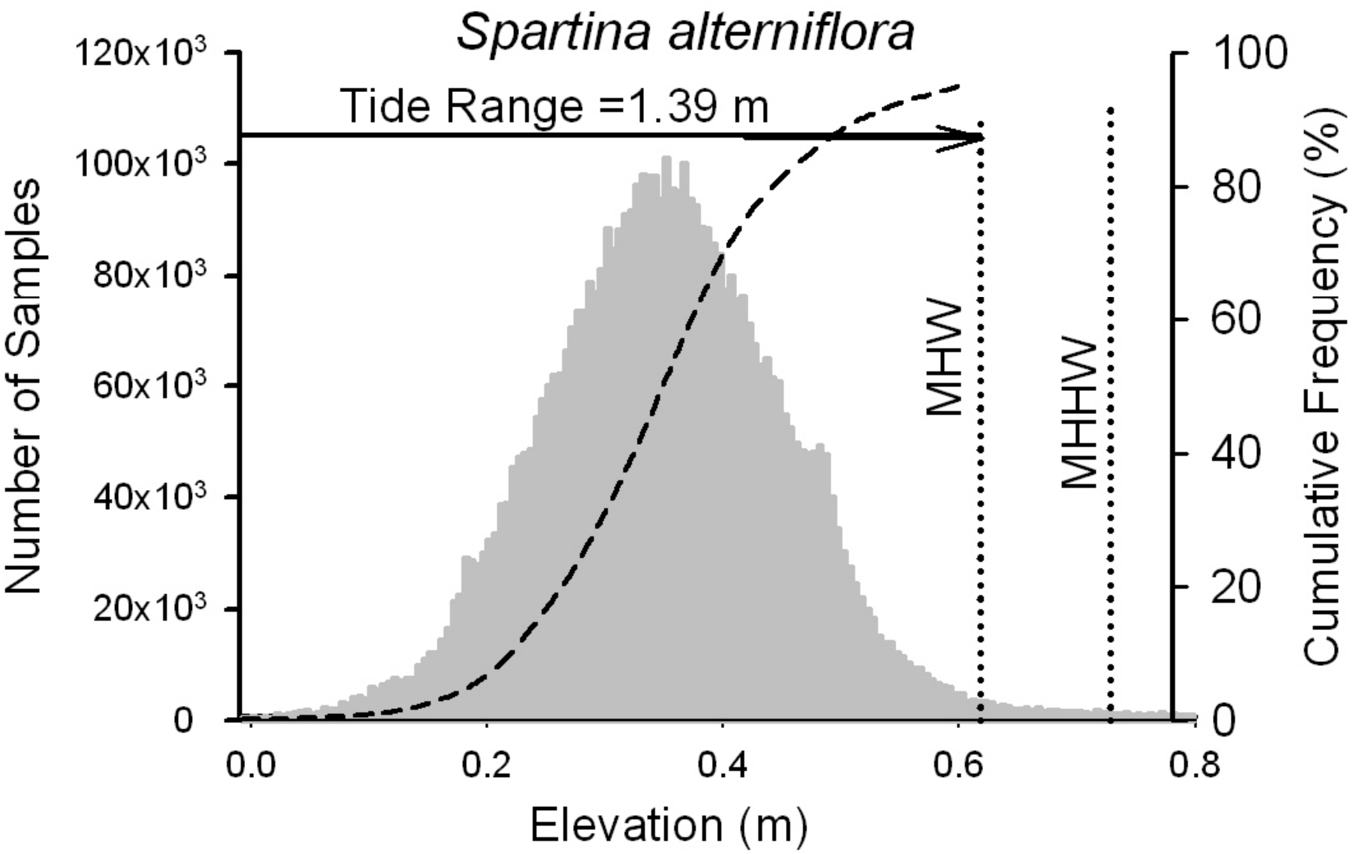
Marsh Elevation of Dominant Plants



MHW = 1.243

A marsh dominated by high marsh plants is characteristic of a geomorphically mature or old age marsh – infilled marsh

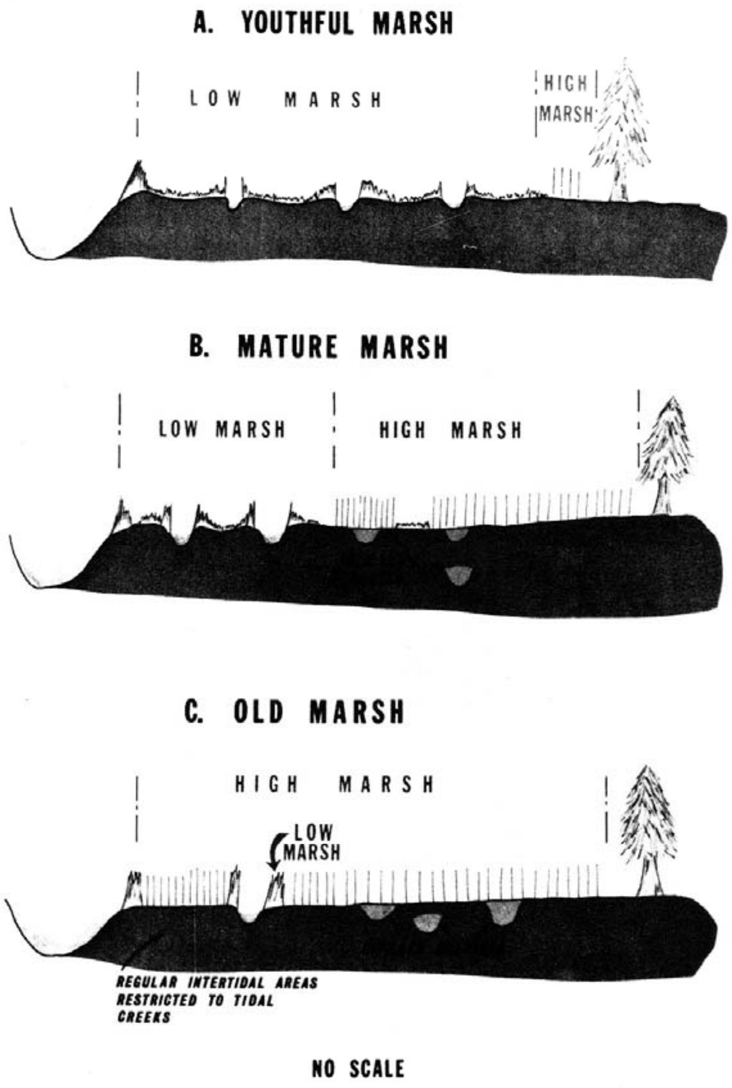
The distribution of Spartina habitat elevations at North Inlet (Morris). Distribution reflects developmental stage, which is a function of sediment availability and the rates of sea level rise and land subsidence.



How are Sapelo marshes distributed – youthful, mature and old?

Why aren’t marsh plants focused at MHW mark? Can southern marshes build to MHW mark absent OM accumulation? Will sedimentation alone lead to creekbank levees?

Frey Classification of Marsh Developmental Stages



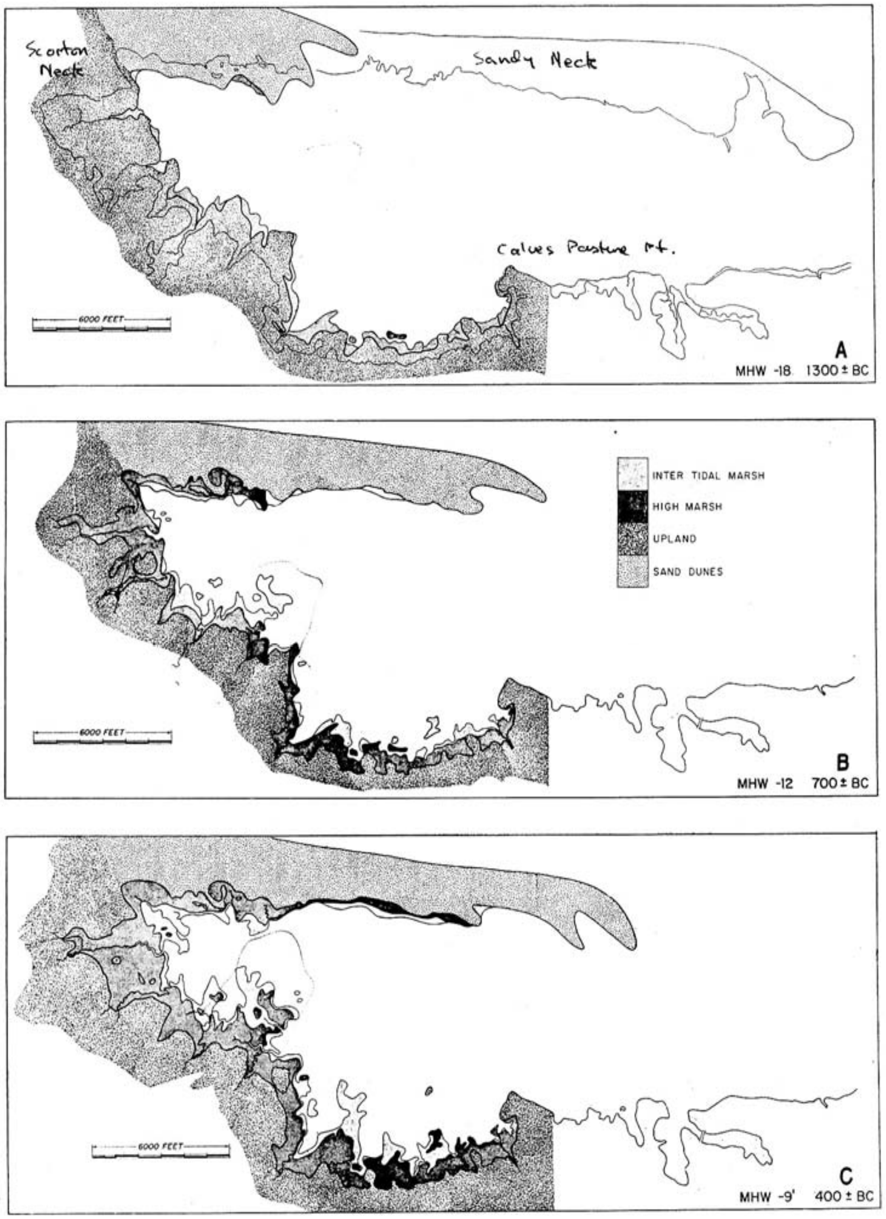
Mostly low marsh, well developed, high density drainage systems, pronounced topography, rapid sedimentation rates

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,

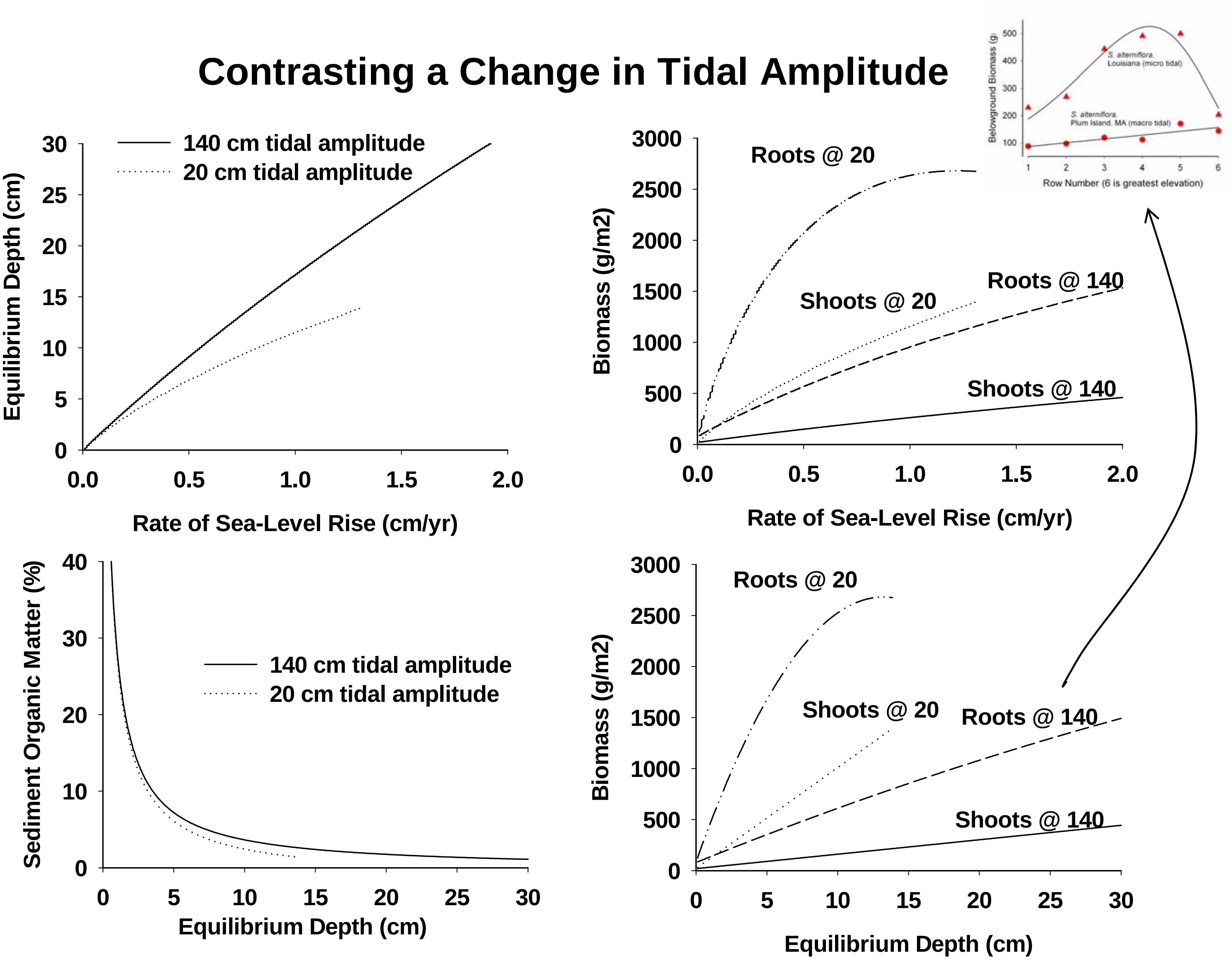
Accretion can be increasingly controlled by organic matter accumulation as hi-lo marsh and marsh-H_2O ratios increase. But is this true in both northern and southern marshes?

Temporal Sequence of Salt Marsh Development-Barnstable Marsh



1300 BC

Contrasting a Change in Tidal Amplitude



Development

- Edge length decreases as creeks infill
- Low:High marsh decreases as average elevation increases
- Does marsh production decrease?
- Does system value decrease – e.g., less edge habitat?
- Are ponds a natural phenomenon during development?
- Do marshes enter an oscillatory cycle towards the end of the developmental sequence?

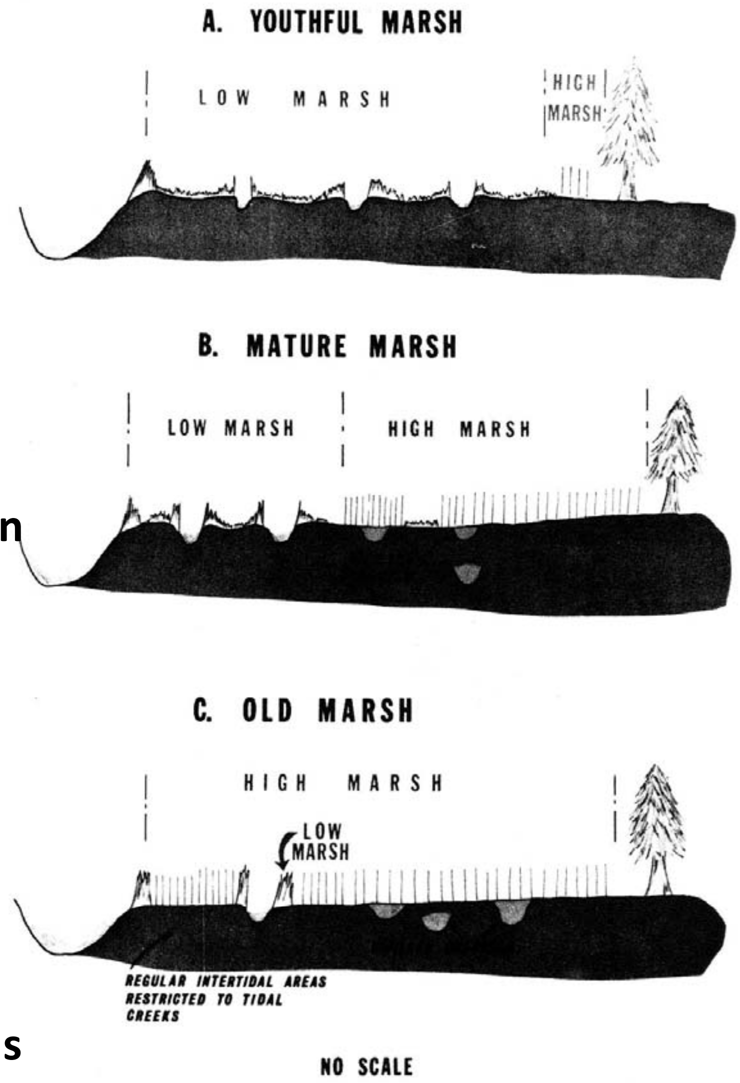


Figure 6. Schematic diagram of three major stages in Georgia marsh maturation (see Table 1). (a) Domination of low marsh; numerous active tidal channels exhibit minimal migration or fill; pronounced microtopography. (b) Low and high marsh of approximately equal importance. (c) Domination of high marsh; most channels are filled and marsh surface becomes increasingly planar.

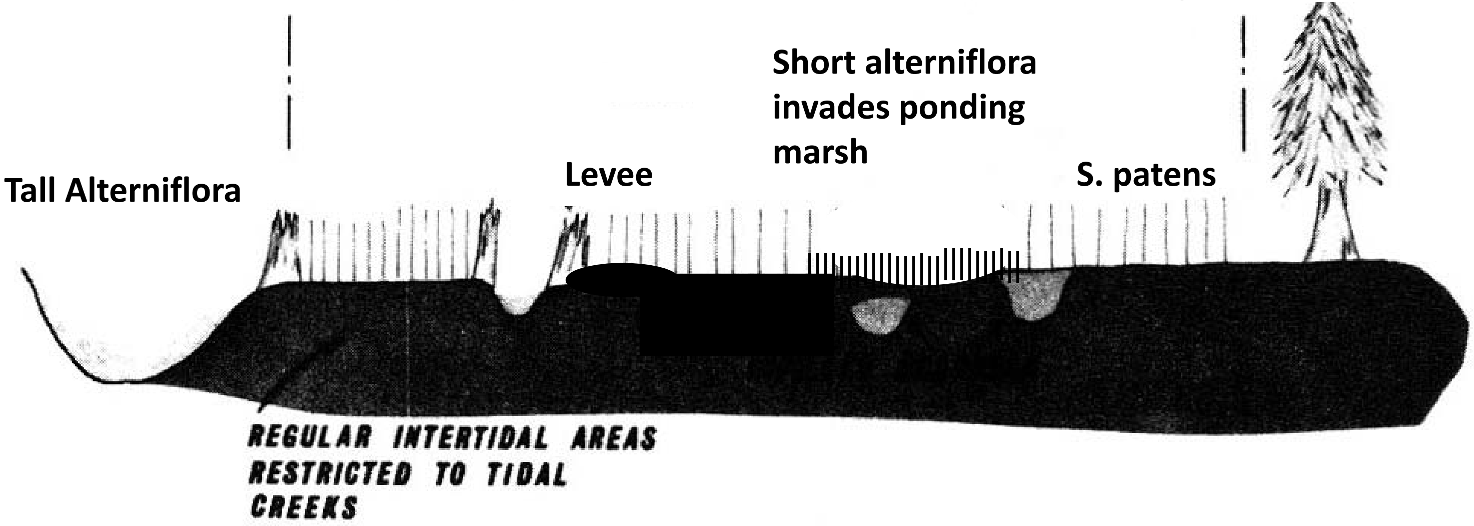
Degradation

- Higher SL stimulates low marsh production and creekside deposition – levee results
- Interior marsh drainage interrupted – water ponds
- Patens succeeded by alterniflora
- Peat accumulation decreases – impoundment
- Stress kills alterniflora
- Pond metabolizes itself larger
- Does system value increase?

Formation of Ponds – next cyclical phase of succession or 1st phase of degradation?

TSS
Distance
Elevation
Species
Lethal stress
-NEP

Early Stage



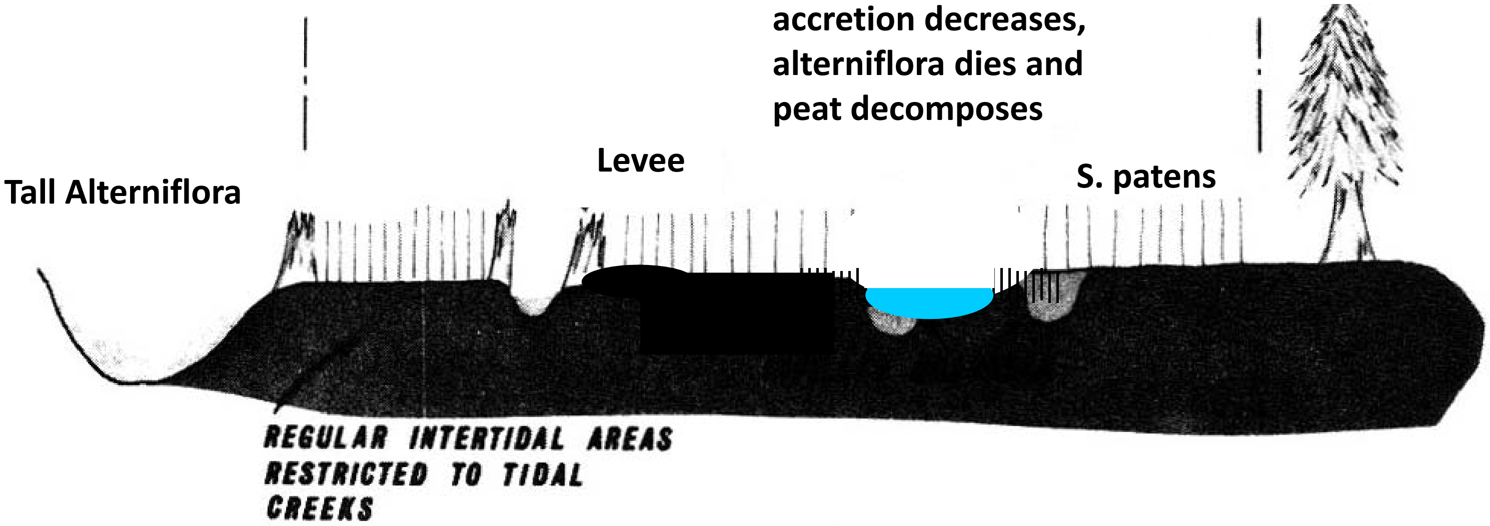
Tall Alterniflora

Levee

Short alterniflora invades ponding marsh

S. patens

Later Stage



Ponds form as accretion decreases, alterniflora dies and peat decomposes

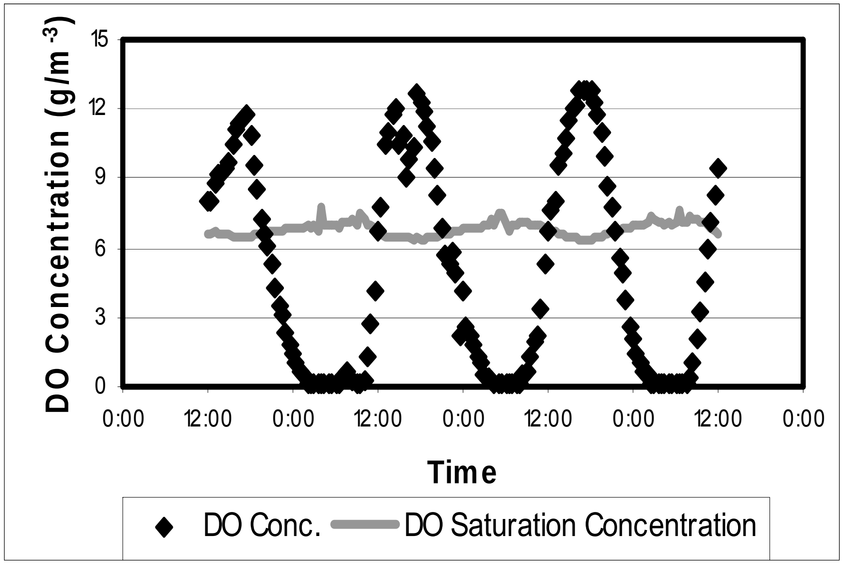
Tall Alterniflora

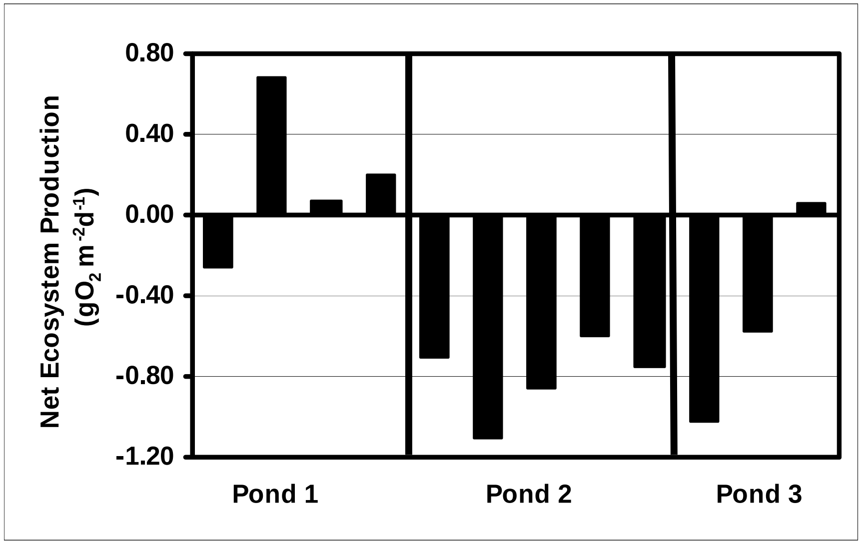
Levee

S. patens

What role do mosquito ditches play? Do they retard succession or degradation?

Mechanism of pond enlargement - decomposition

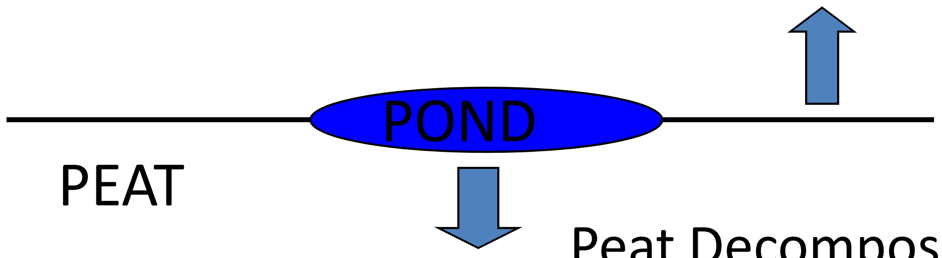




Quantified by free-water O_2 diurnals in marsh ponds

Two Mechanisms Responsible for Pond Depth Increase

- Accretion of Organic and Inorganic Material in Marsh Adjacent to Ponds
- Decomposition of Inundated Peat



Marsh Accretion:
8 cm/50 yr

Peat Decomposition:
12 cm/50 yr

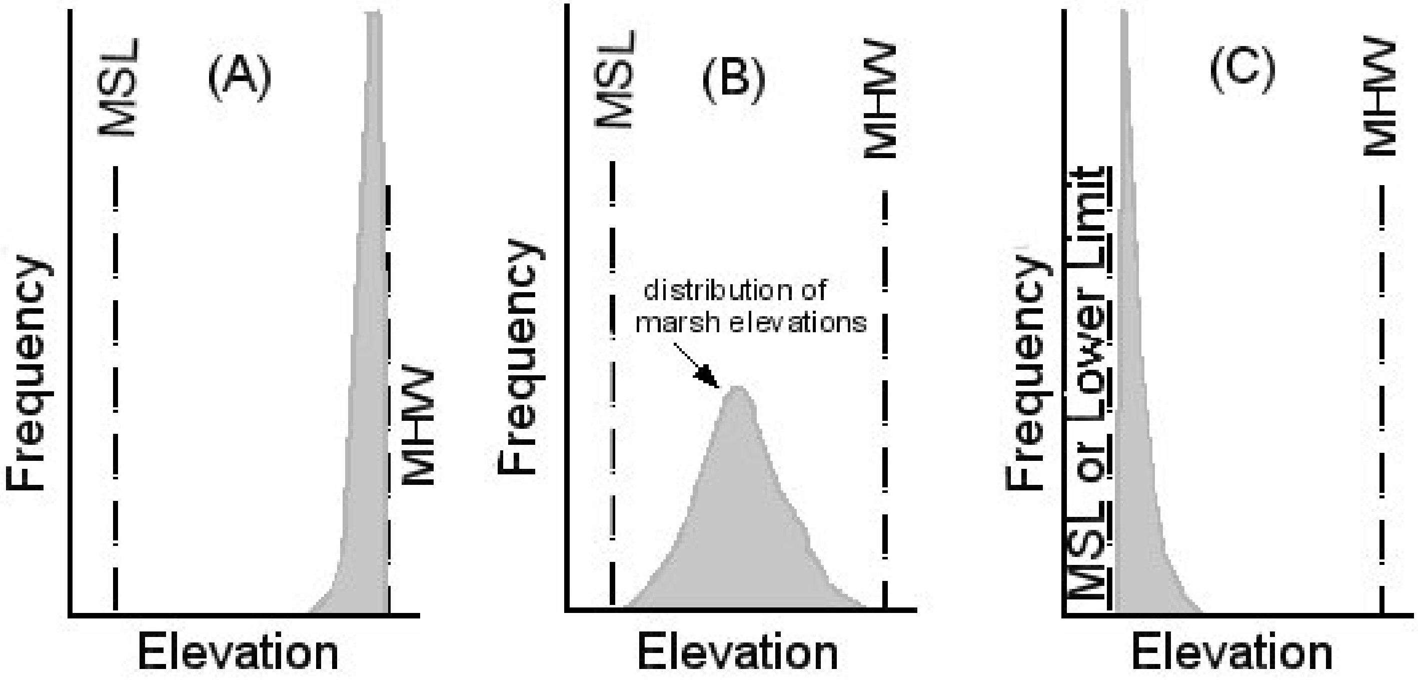
- Ponds are currently 20 cm deep on average

The metabolic bottom line

- Decomposition rate of 0.67 g O_2 m^{-2} d^{-1} required to decompose 12 cm peat over 50 years
- For two of the three ponds in our study, respiration could account for nearly 100% of required carbon decomposition over the 50 year period

PREDICTIONS

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

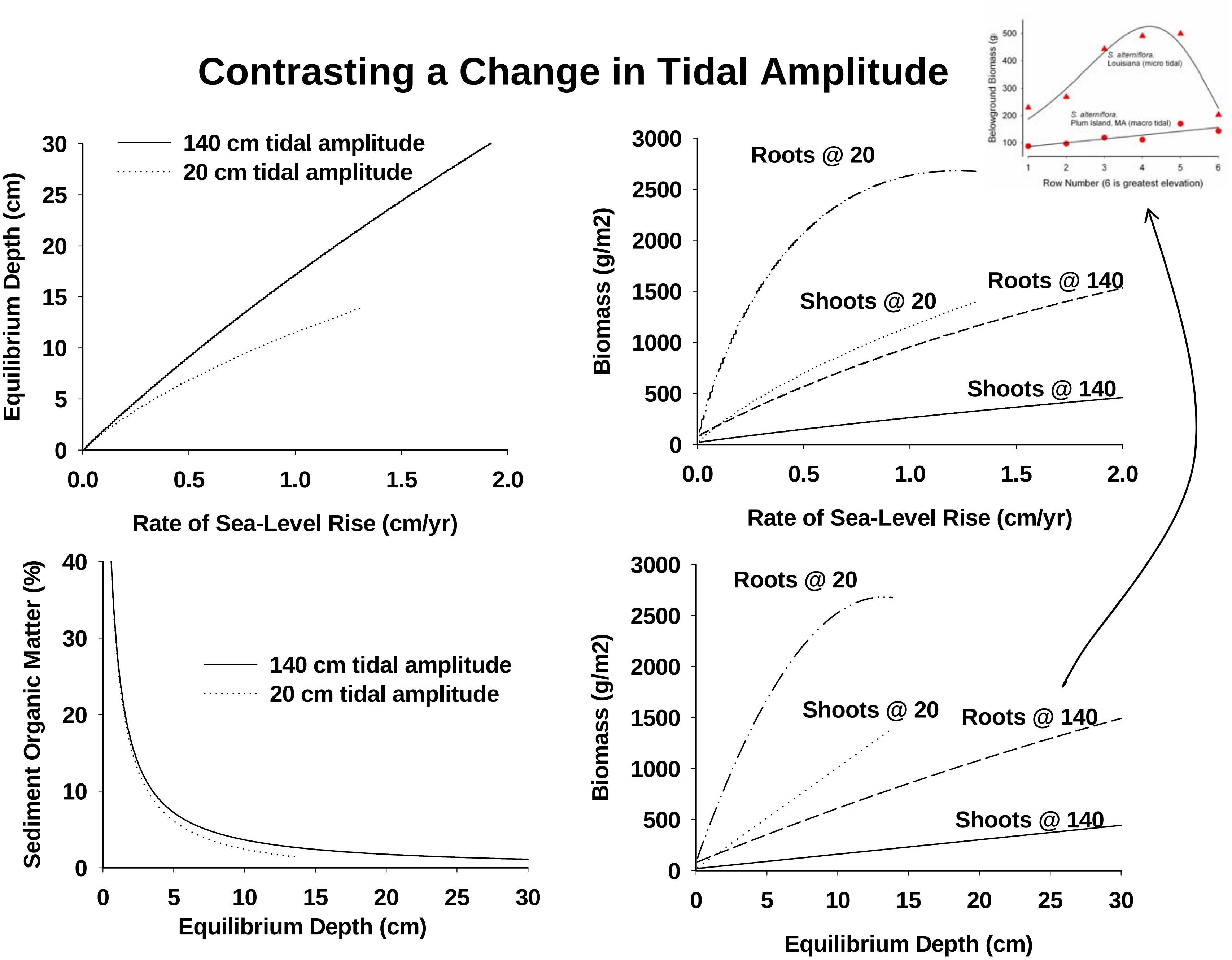


Increasing Rates of Sea Level Rise and Subsidence

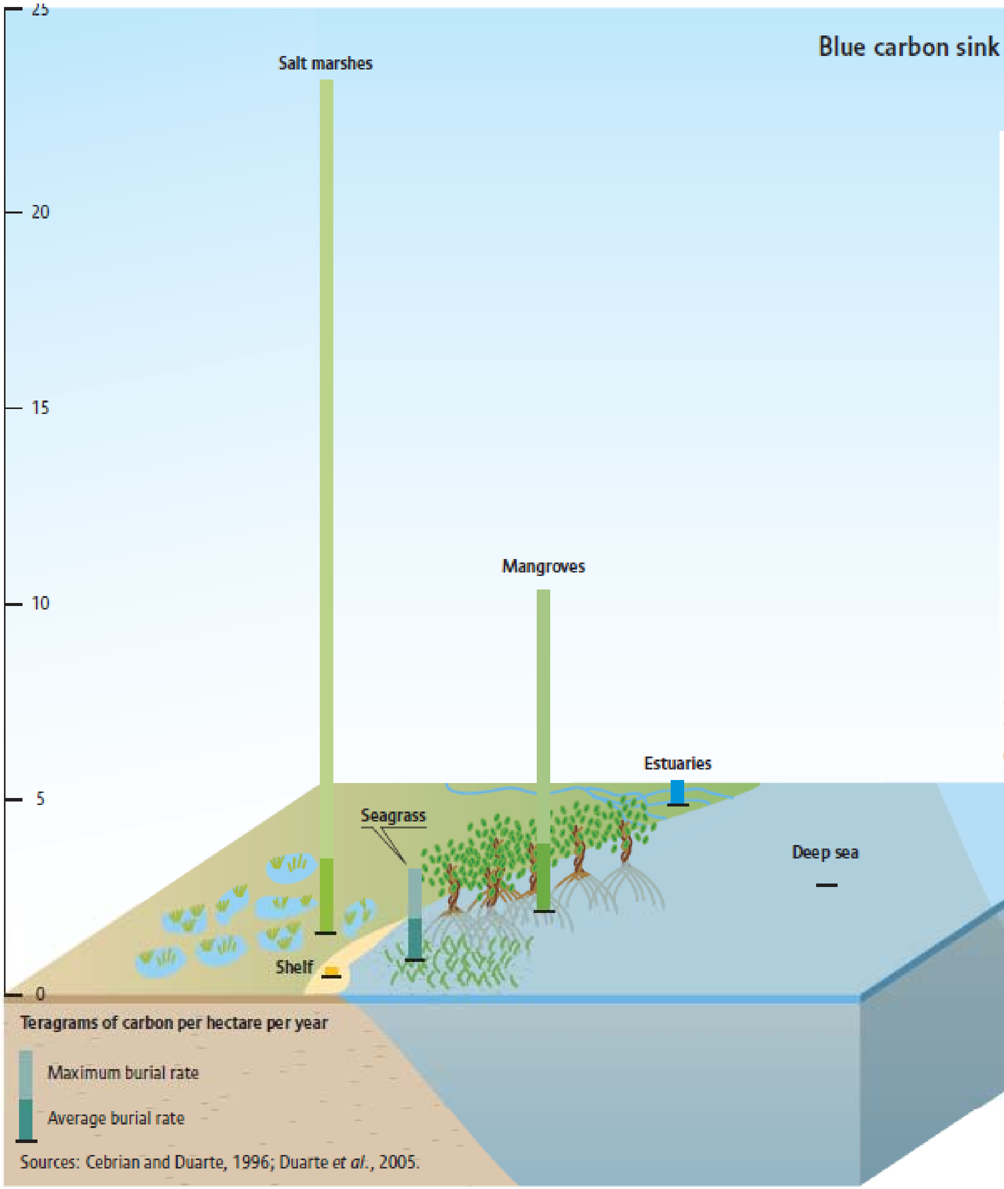
Increasing Productivity per Unit Area

Increasing Ratio of Subtidal:Intertidal Area

Contrasting a Change in Tidal Amplitude



Areal C Burial Comparison



Sources: Cebrian and Duarte, 1996; Duarte *et al.*, 2005.

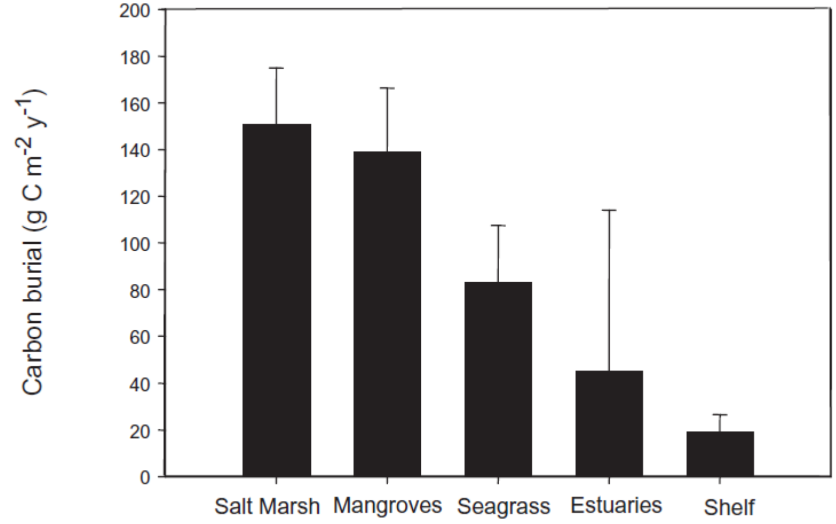
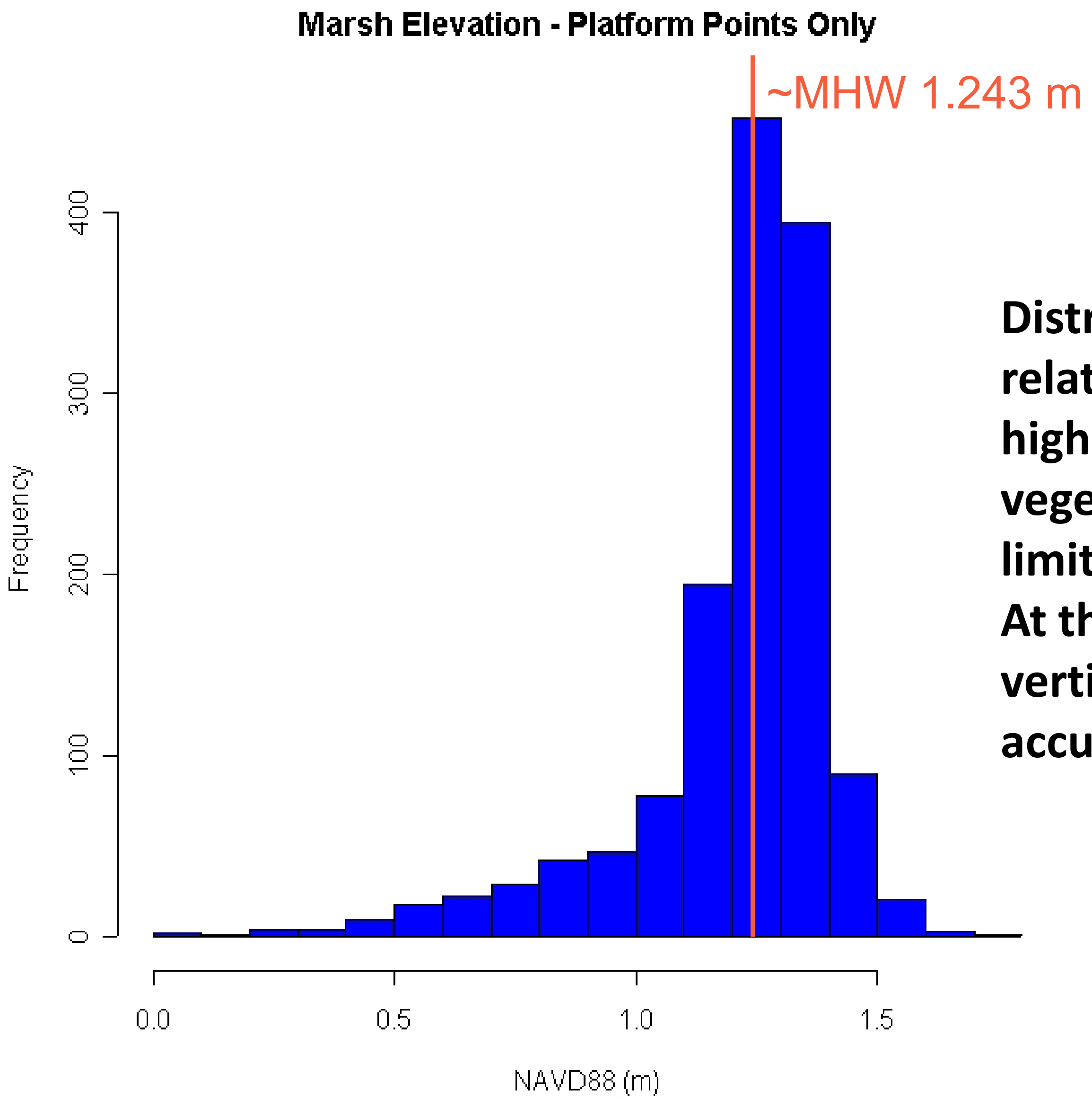


Fig. 1. Average (±SE) carbon burial rates in different coastal ecosystems. Data sources in Table 1.

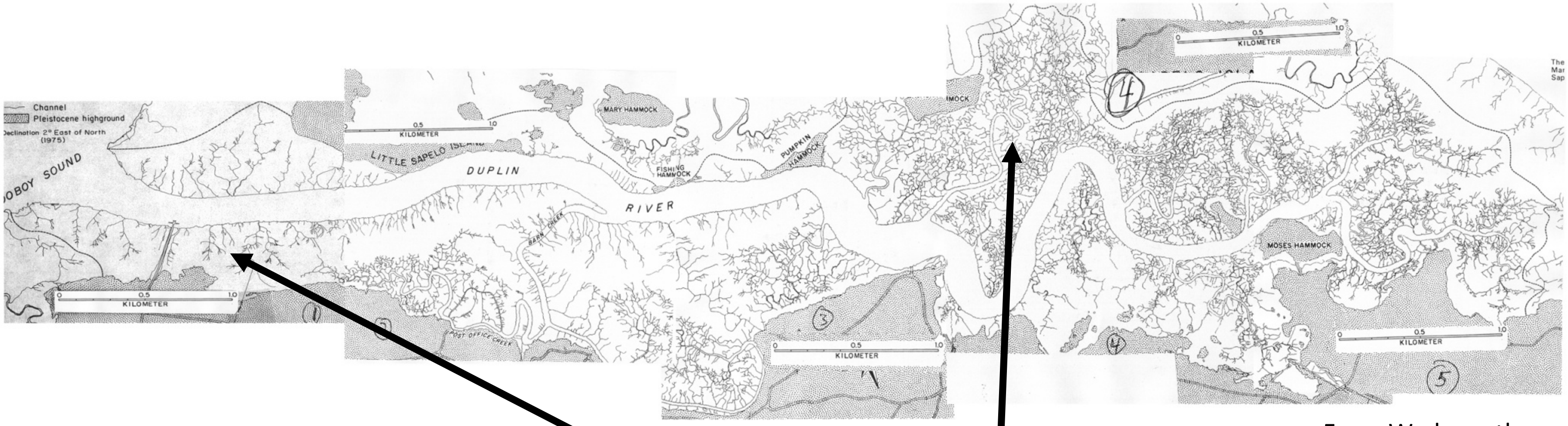


Distribution of marsh plants relative to MHW suggests a high marsh platform, with vegetation at its uppermost limit

At this elevation, further vertical growth due to peat accumulation exclusively

Threats to Coastal Systems' C Burial

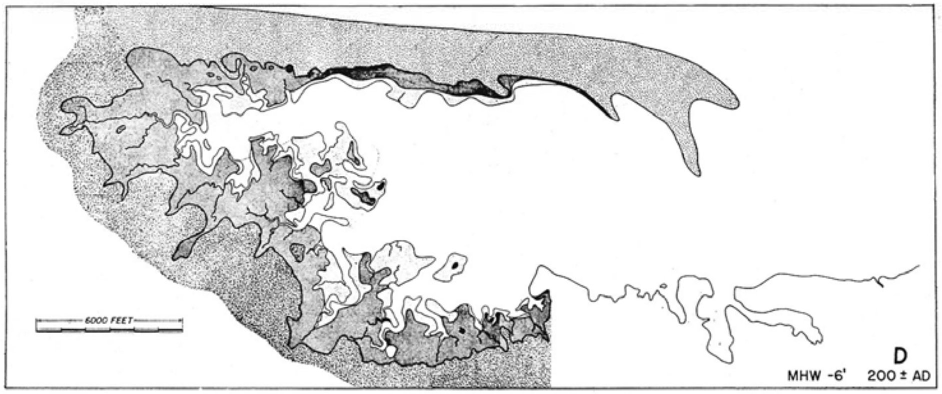
Drainage Network – Duplin River Marshes

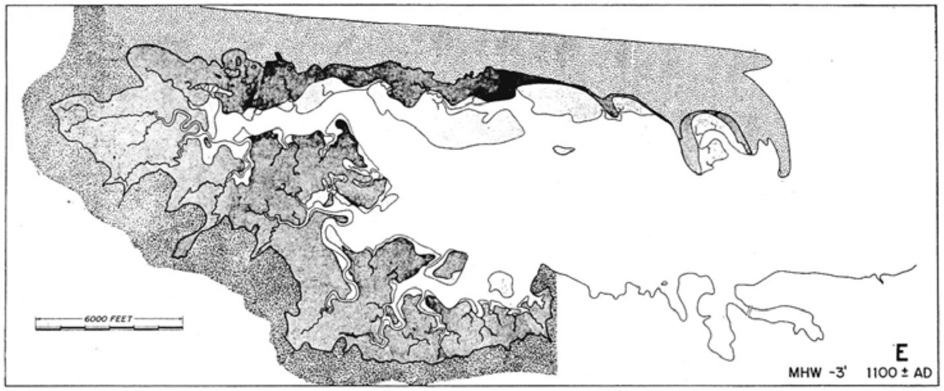


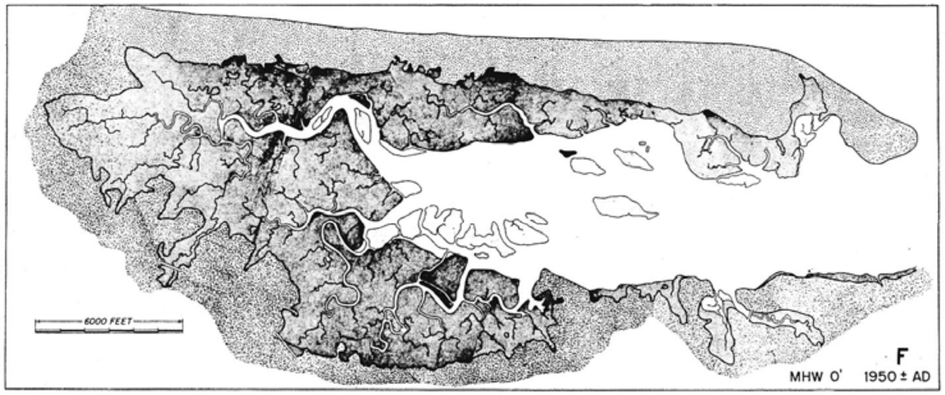
From Wadsworth

Two drainage types of interest: discrete and reticulated

Bay Infilling and Marsh Progradation







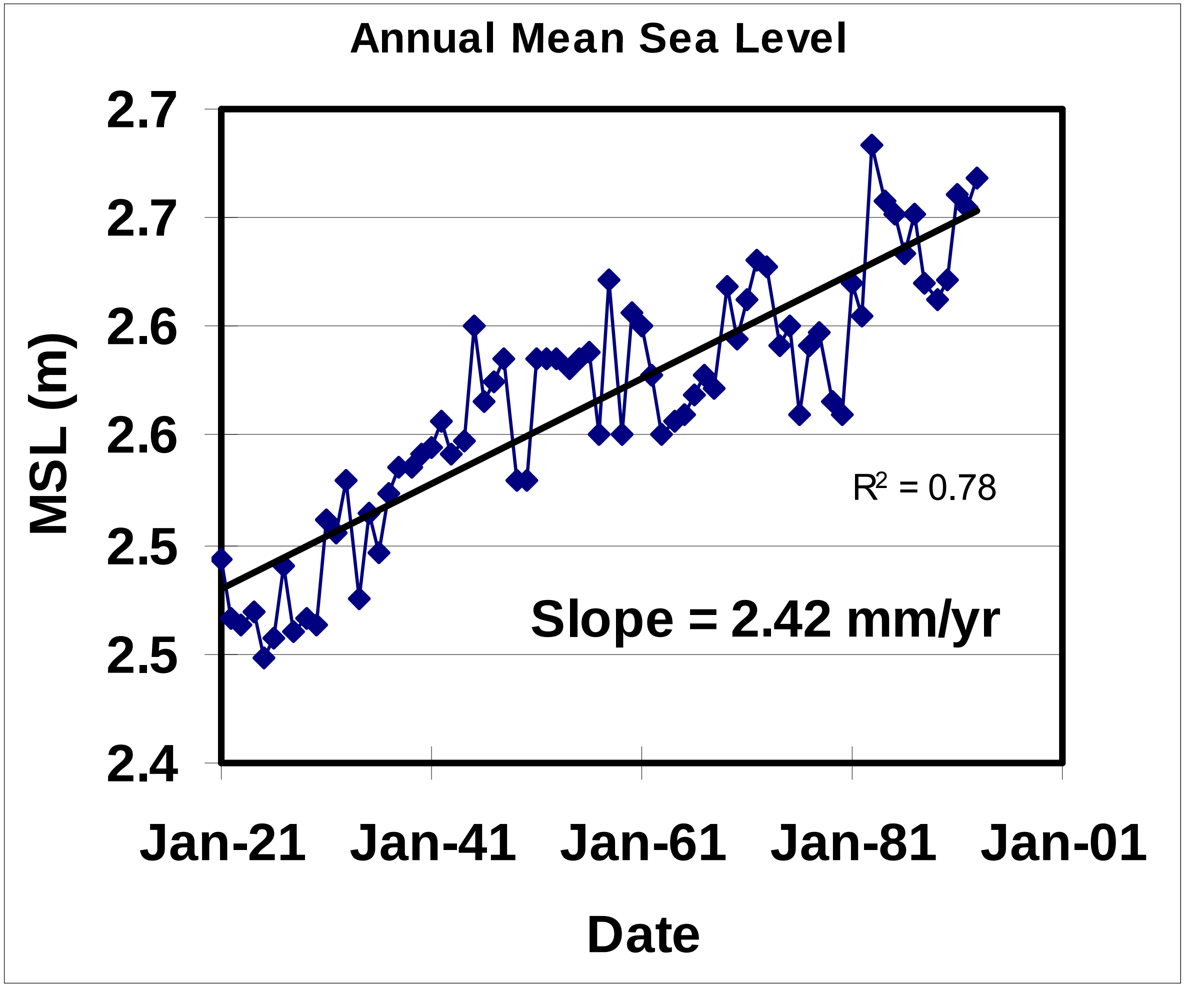
1950

Mangrove Issues

Same as for salt marshes

- Evidence suggests elevation increases only as fast as SLR, except during infilling stages
- Limited capacity for landward transgression
- Sediment supply often blocked, hence dependent on cannibalizing existing stores
- Global loss from anthropogenic activities – 1-2% y^{-1}.
- Loss of 35-86% in past 25 yrs (Valiela et al. 2001, Duke et al. 2007)

Long-term Increase in Sea Level
Boston Tide Gauge



Coastal Ecosystems With Potentially Significant CO_2 Sequestration

Intertidal wetlands

- Temperate zone salt marshes
- Tropical mangrove forests

Submerged aquatic vegetation:

- Seagrass beds
- Kelp Forests?

NOT CORAL REEFS