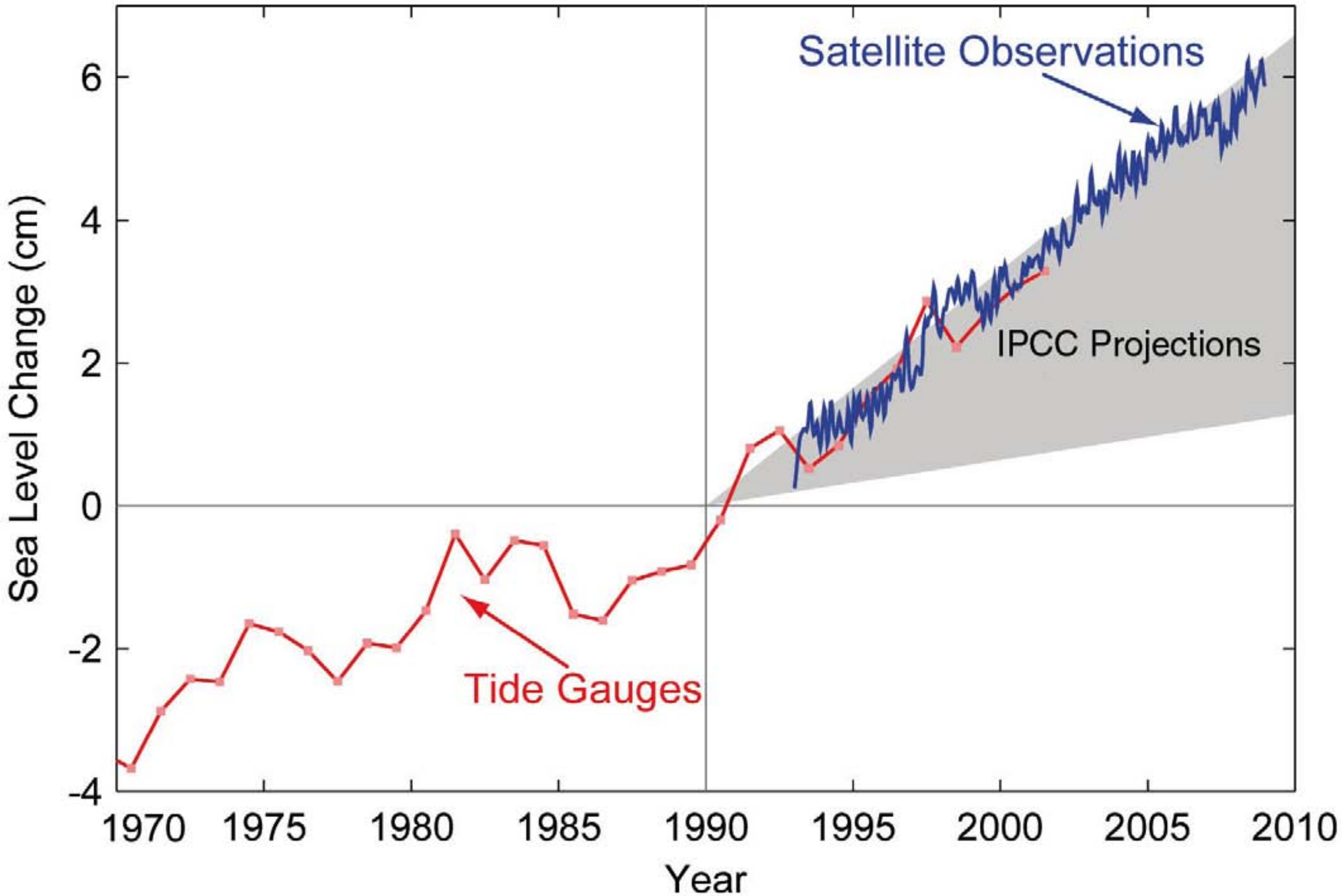
Sustainable Estuarine Habitat Restoration in the Pacific Northwest: Modeling and Managing the Effects, Feedbacks, and Risks Associated with Climate Change

John Rybczyk, Western Washington University
Tarang Khangaonkar, Pacific Northwest National Laboratory
Greg Hood, Skagit River System Cooperative
Enrique Reyes, East Carolina University

EPA STAR

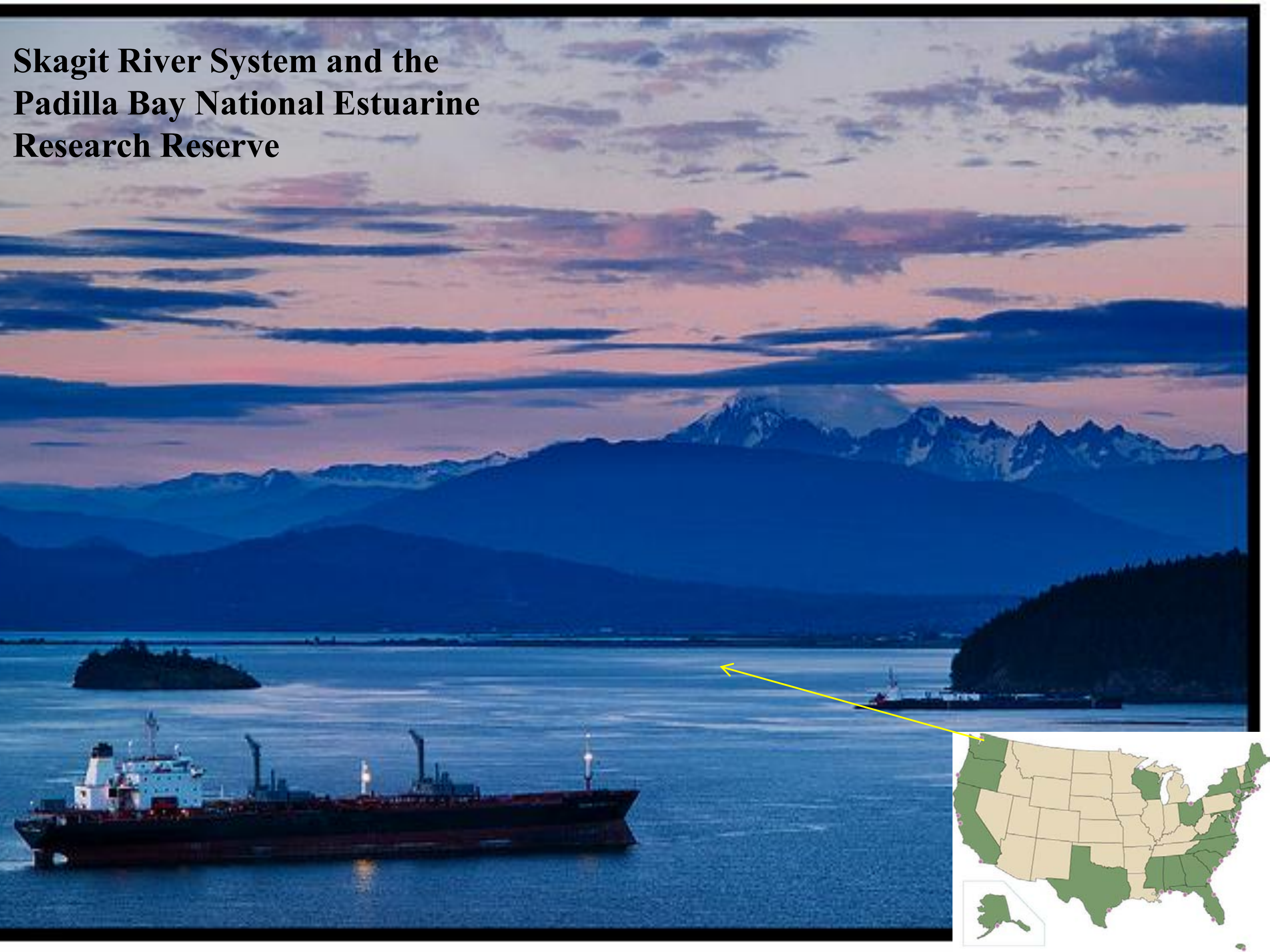


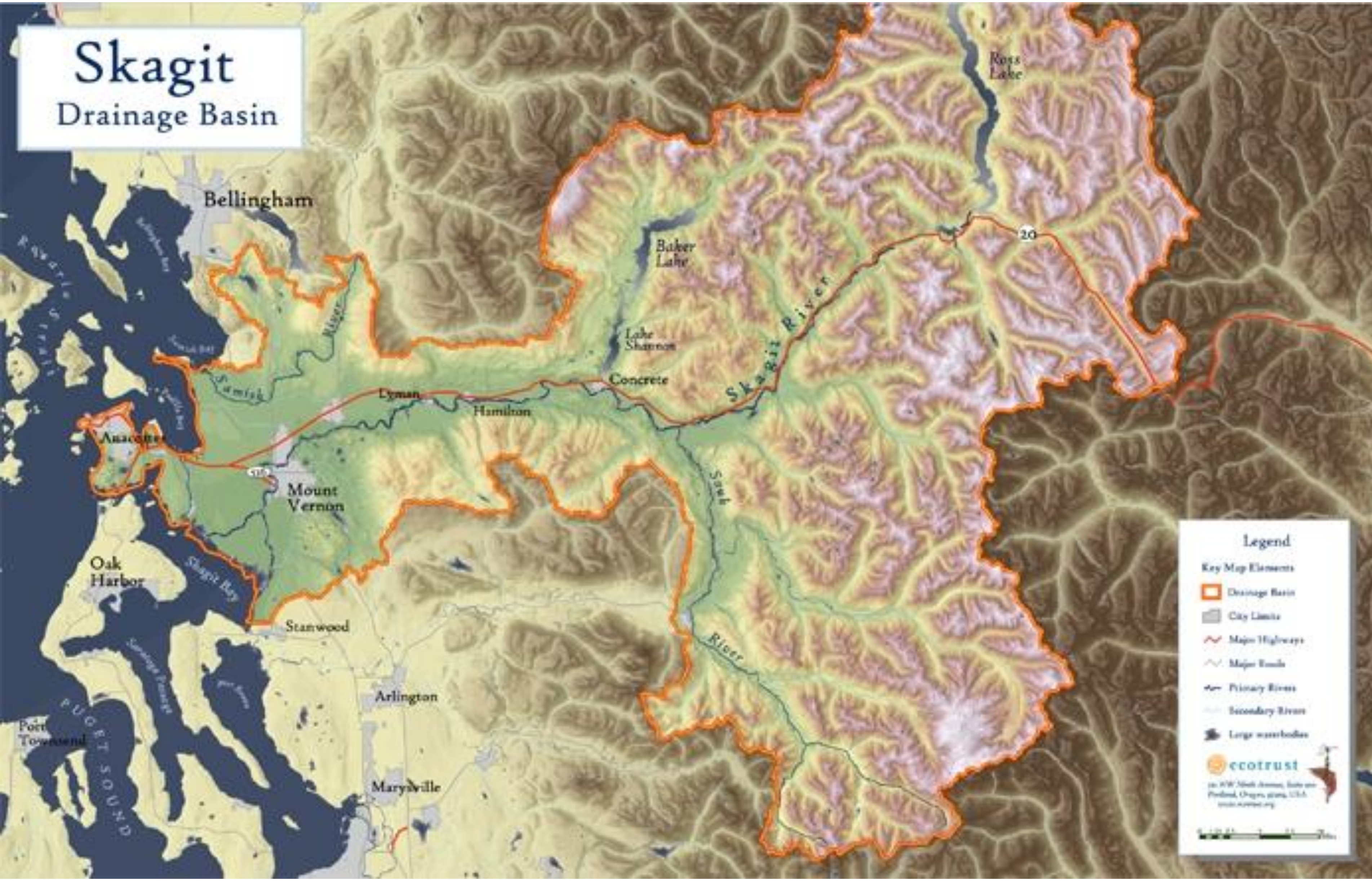
Sea level change during 1970-2010. The tide gauge data are indicated in red (Church and White 2006) and satellite data in blue (Cazenave et al. 2008). The grey band shows the projections of the IPCC Third Assessment report for comparison.

Project Objectives

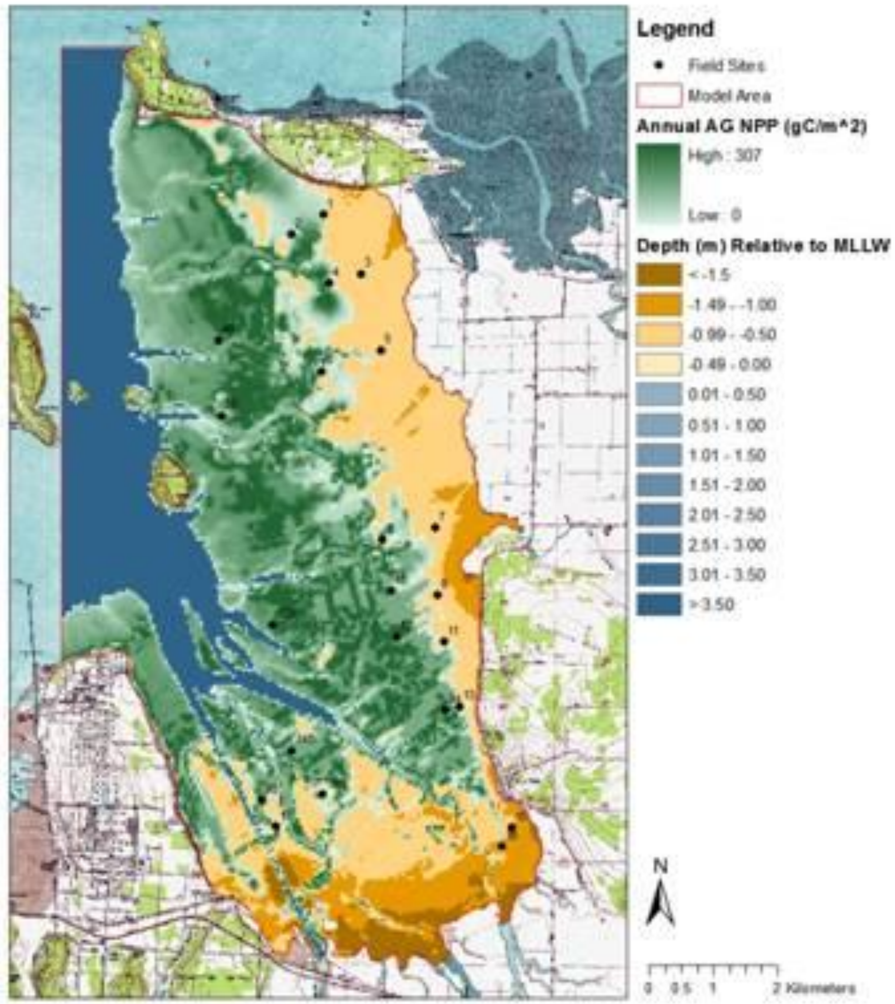
- Objective:
  - Develop a predictive landscape simulation model, incorporating non-linear feedbacks, of the ecogeomorphic consequences of climate-induced sea-level rise and river flow alteration in Skagit-Padilla system
  - Use the model to guide restoration efforts in the face of rising sea levels.

Skagit River System and the Padilla Bay National Estuarine Research Reserve

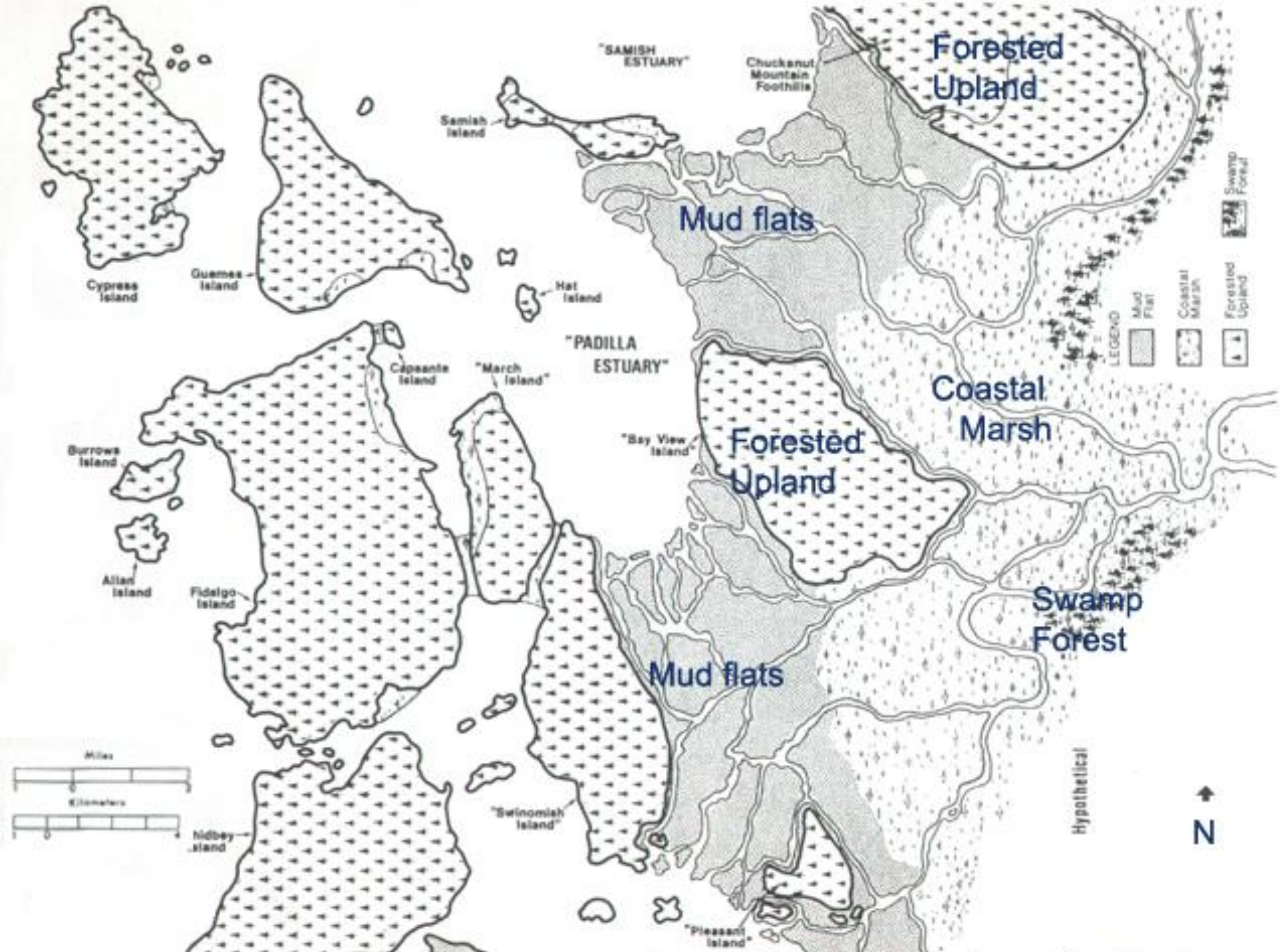



Skagit
Drainage Basin
Bellingham
Ross Lake
Baker Lake
Lake Shannon
Concrete
Lyman
Hamilton
Skagit River
Samish
River
Anacortes
Mount Vernon
Sauk
River
Oak Harbor
Skagit Bay
Stanwood
Arlington
Marysville
Port Townsend
PUGET SOUND
20
Legend
Key Map Elements
Drainage Basin
City Limits
Major Highways
Major Roads
Primary Rivers
Secondary Rivers
Large waterbodies
ecotrust

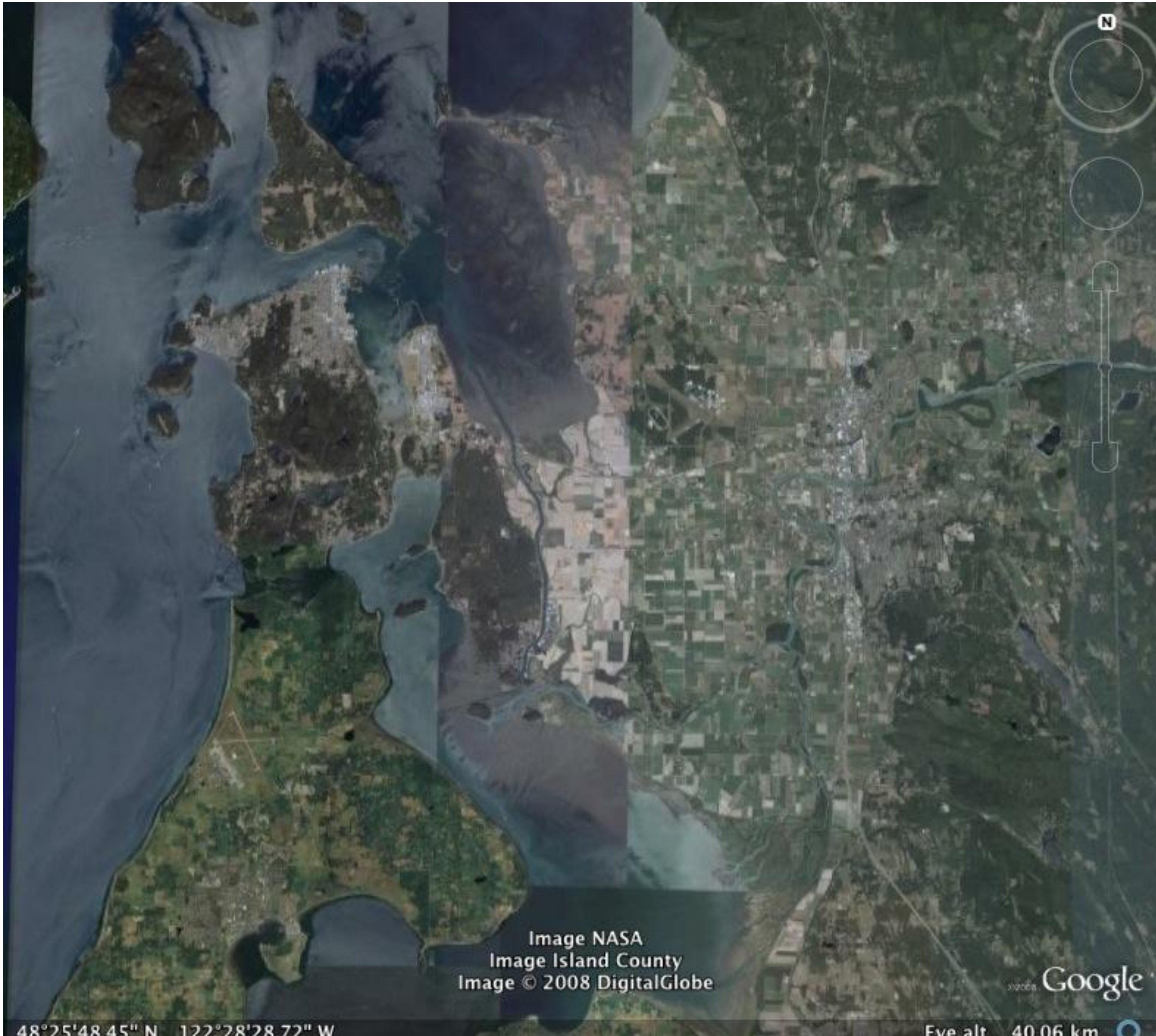
- 3000 ha intertidal eel grass
- - 3.0 - + 0.75 m MLLW



Skagit River Delta 10,000 years ago



courtesy of Padilla Bay Interpretive Center


N
Image NASA
Image Island County
Image © 2008 DigitalGlobe
Google
48°25'48.45" N 122°28'28.72" W
Eye alt 40.06 km

1) Cutoff from historical sources of sediment
2) No opportunity for upslope migration
3) Sea level rise


Are the eelgrass beds in Padilla Bay at risk from rising sea levels?
Are they accreting at rate that keeps pace sea level rise?

Wetland Response to Rising Sea Levels

- Accrete at a rate that keeps pace with SLR
- Habitat switching, convert to open water
- Migrate upslope

Annual Elevation Surplus or Deficit = Mineral Matter Accretion + Organic Matter Accumulation - Shallow Subsidence ± Deep Subsidence or Uplift - Eustatic Sea-Level Rise

Factors Affecting Wetland Elevation Relative to Sea Level

- O.M. Production (above and belowground)
- Allogenic Sediment Deposition

Horizon Markers

Tide Gauge

- Eustatic Sea Level Rise
- Deep Subsidence
- Shallow Subsidence (Primary Compaction and Decomposition)

SET and Horizon Markers

Padilla Bay

- ESLR (- 0.33 cm/yr)
- Uplift (+ 0.09 cm/yr)
- Elevation Change
  mean = -0.22 cm/yr

Elevation Deficit = $-0.33 + -0.22 + 0.09 = -0.46$ cm/yr

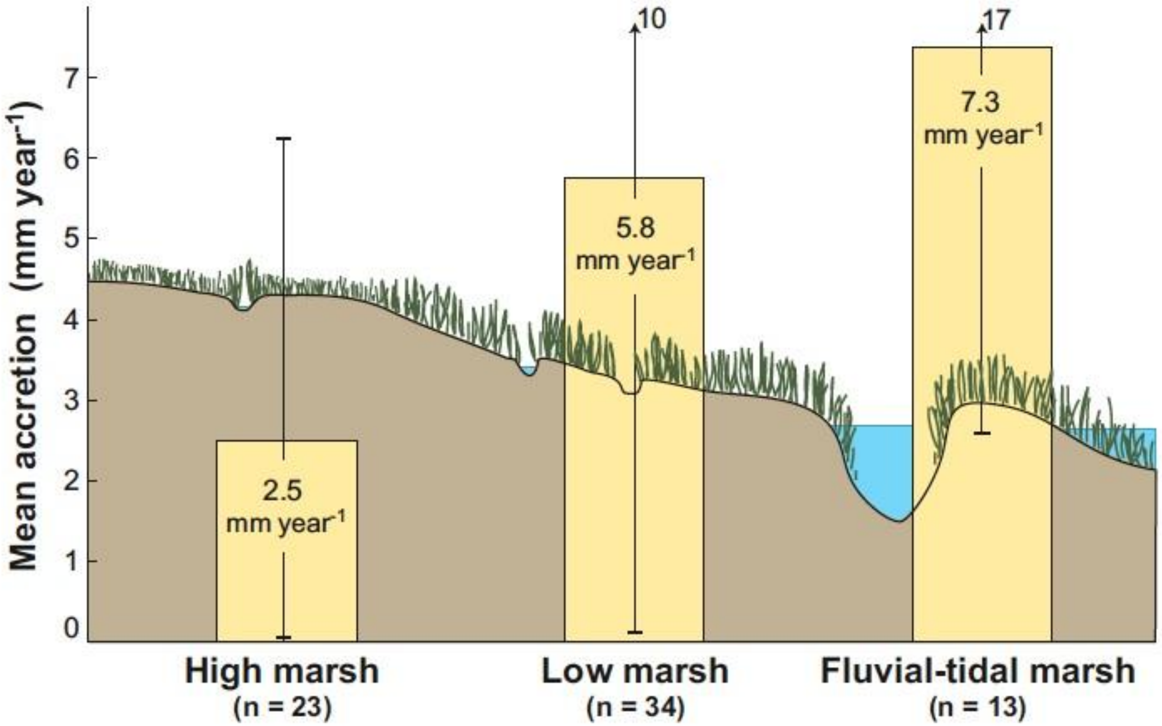
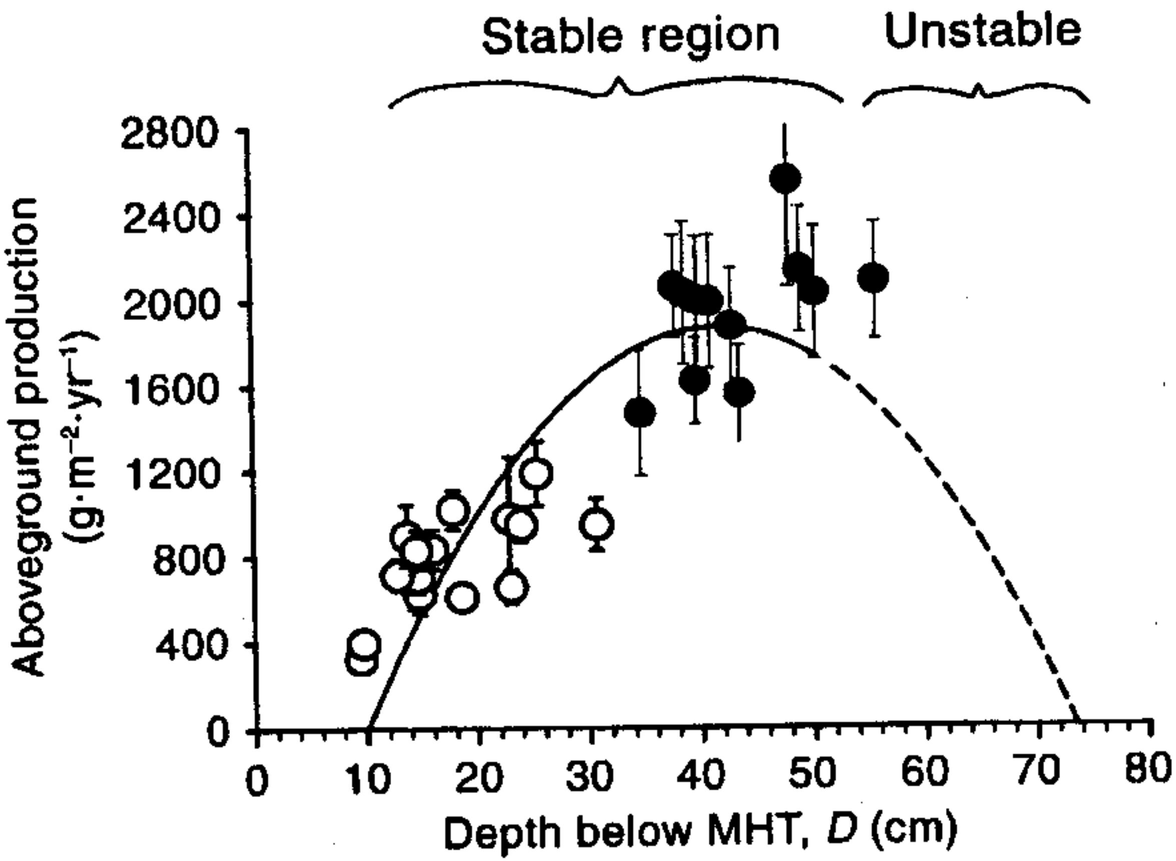


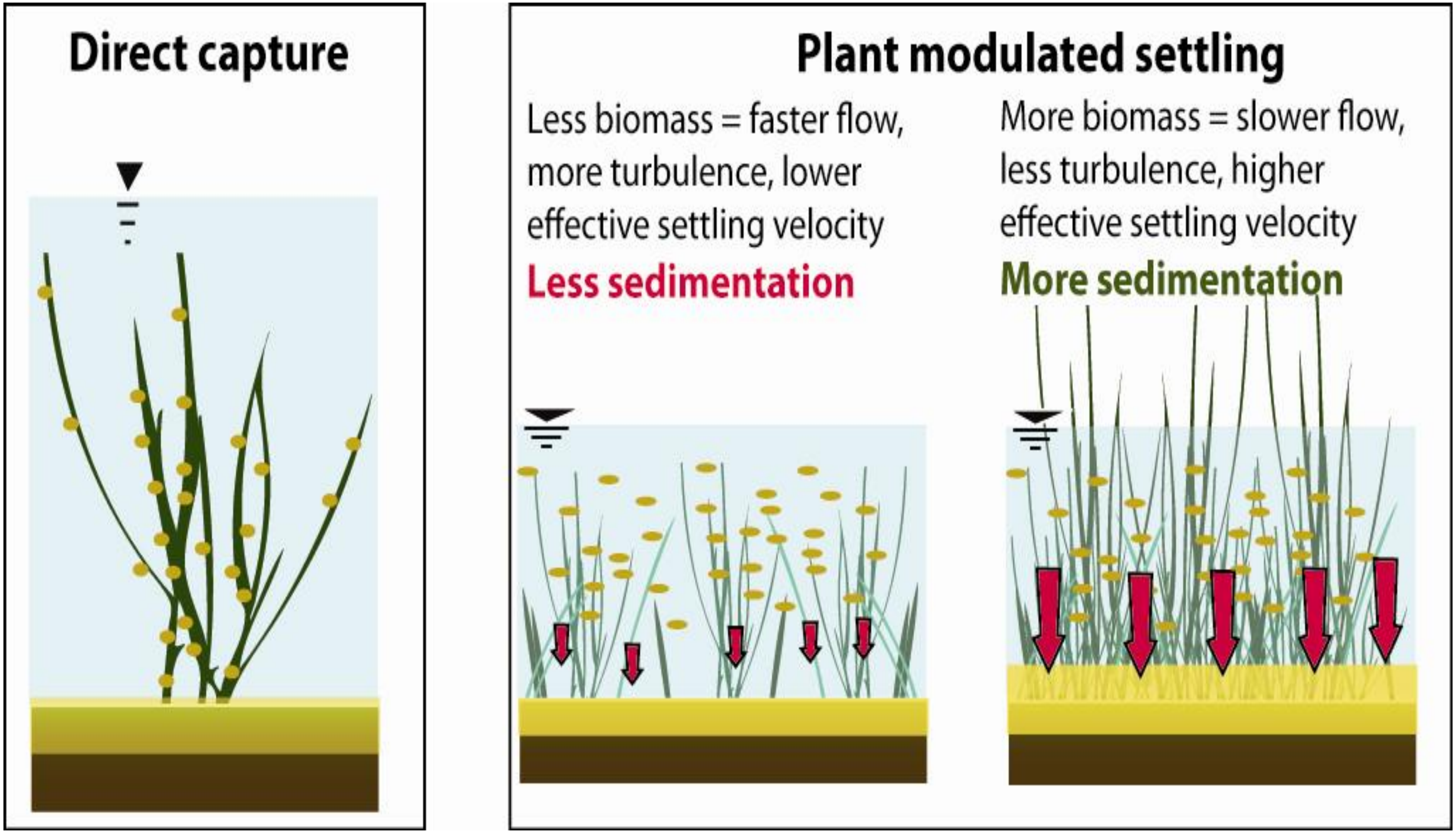
Figure 9

Rates of vertical accretion on tidal marshes based on a survey of the published literature, subdivided by type of marsh. Yellow bars represent mean vertical accretion; whiskers represent the range of reported data. Means ± standard deviation are as follows: high marsh, 2.5 ± 1.4 mm year^{-1}; low marsh, 5.8 ± 2.8 mm year^{-1}; fluvially influenced marsh, 7.3 ± 3.2 mm year^{-1}. After Argow 2006.

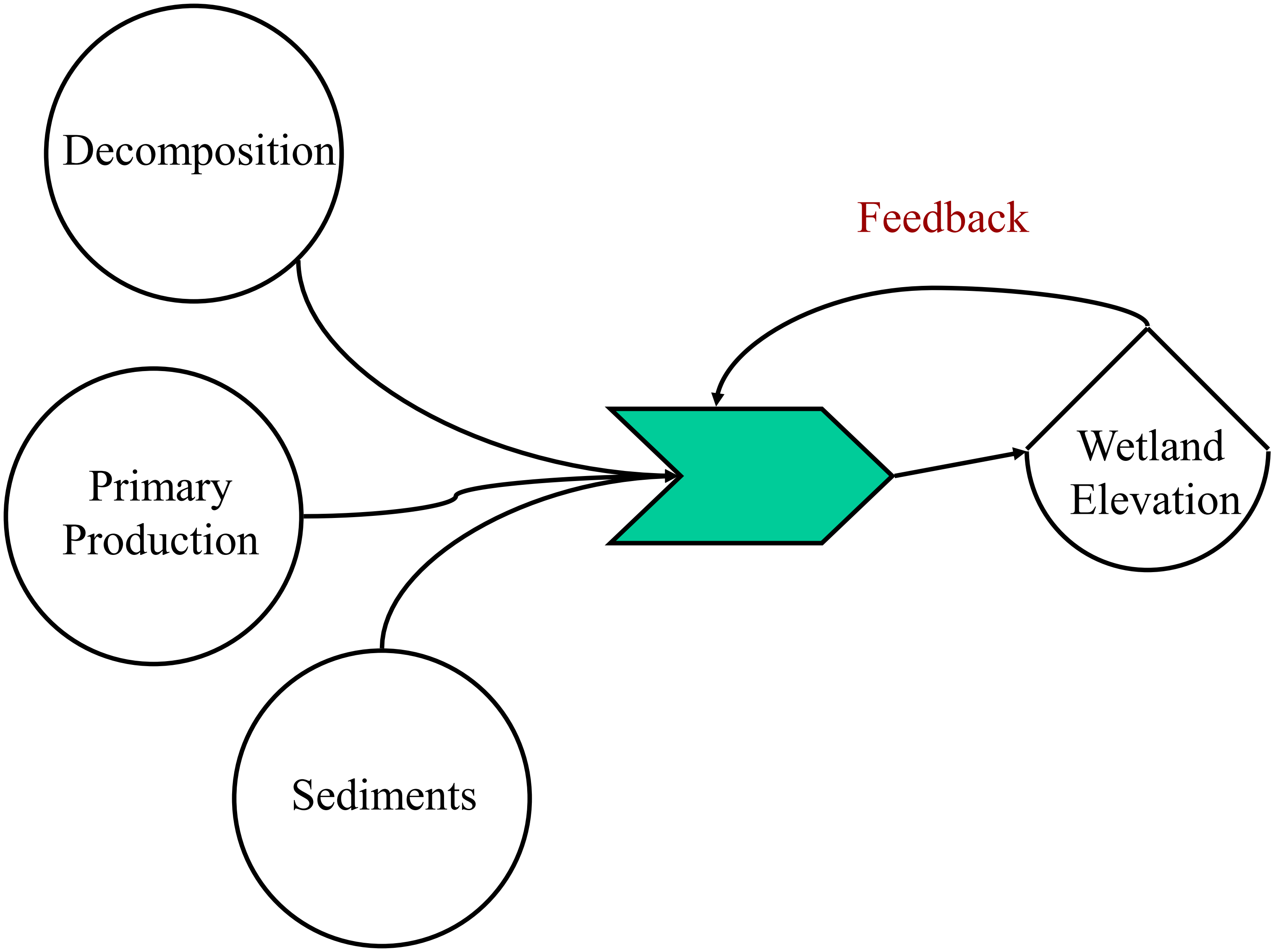
From Fitzgerald et al. 2008.

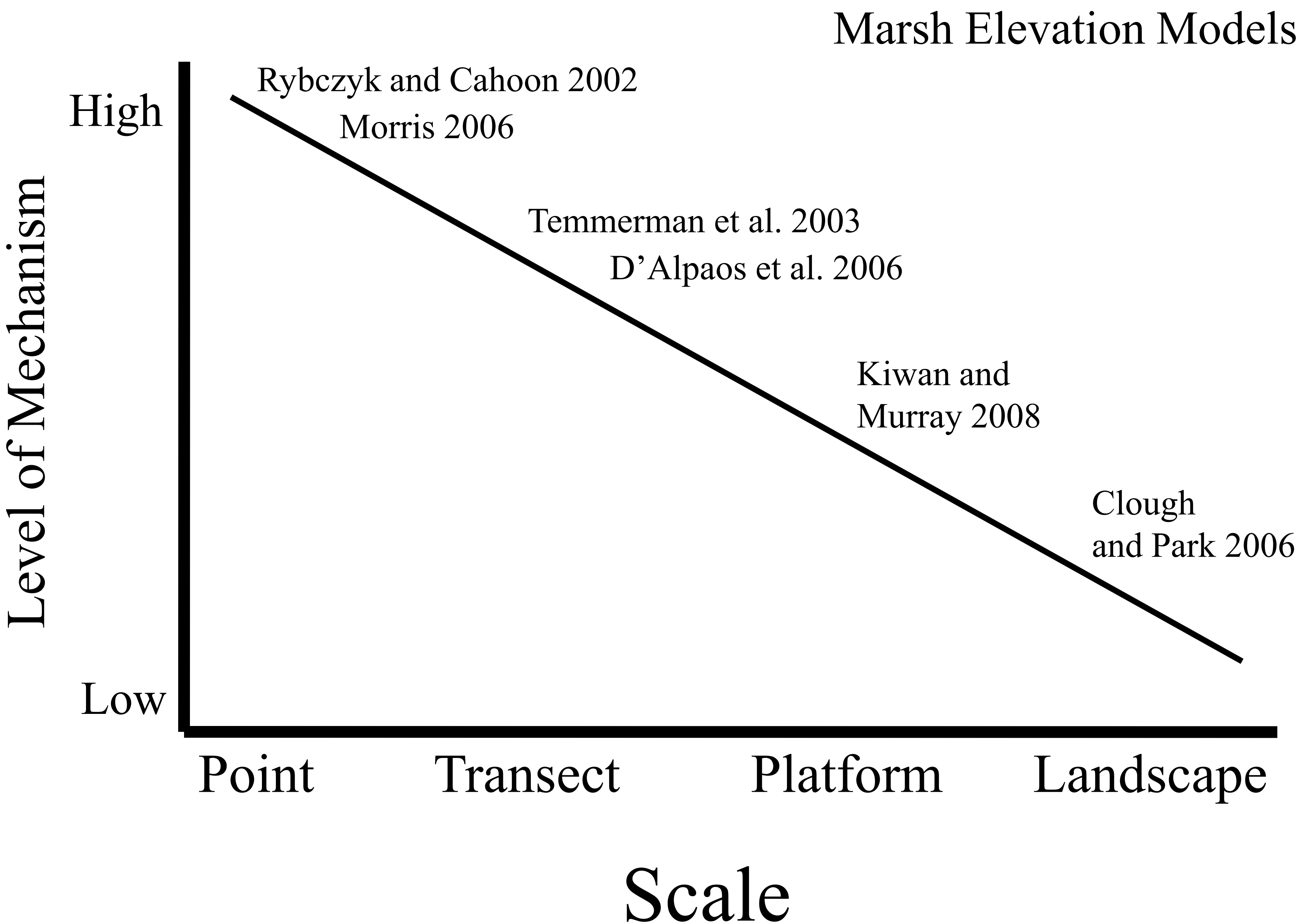


Morris et al. 2002

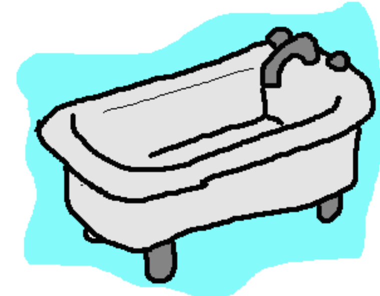


Direct capture
Plant modulated settling
Less biomass = faster flow, more turbulence, lower effective settling velocity
Less sedimentation
More biomass = slower flow, less turbulence, higher effective settling velocity
More sedimentation


Decomposition
Feedback
Primary Production
Wetland Elevation
Sediments



Marsh Elevation Models
High
Low
Level of Mechanism
Rybczyk and Cahoon 2002
Morris 2006
Temmerman et al. 2003
D'Alpaos et al. 2006
Kiwan and
Murray 2008
Clough
and Park 2006
Point
Transect
Platform
Landscape
Scale



New York City,
5 M SLR

NATIONAL WILDLIFE FEDERATION

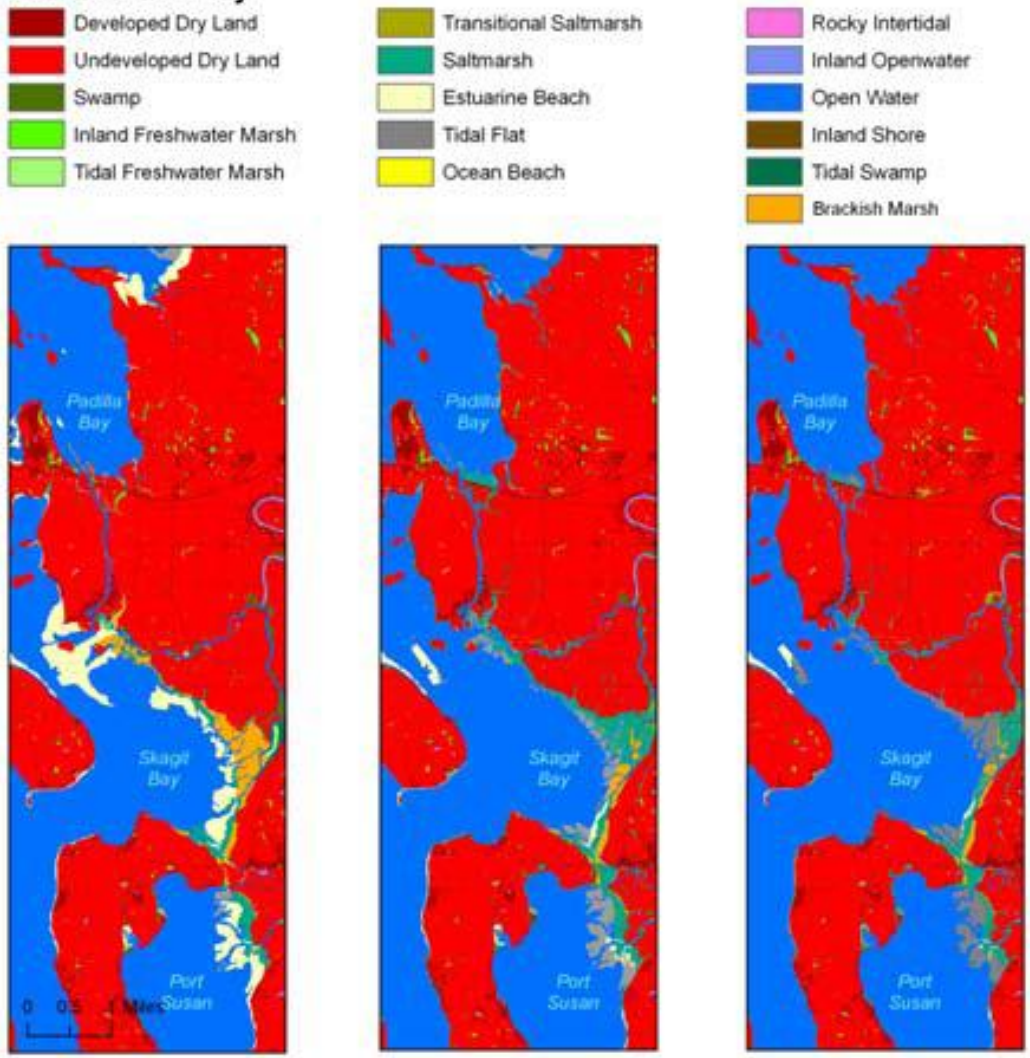
Sea-level Rise and Coastal Habitats in the Pacific Northwest

An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon

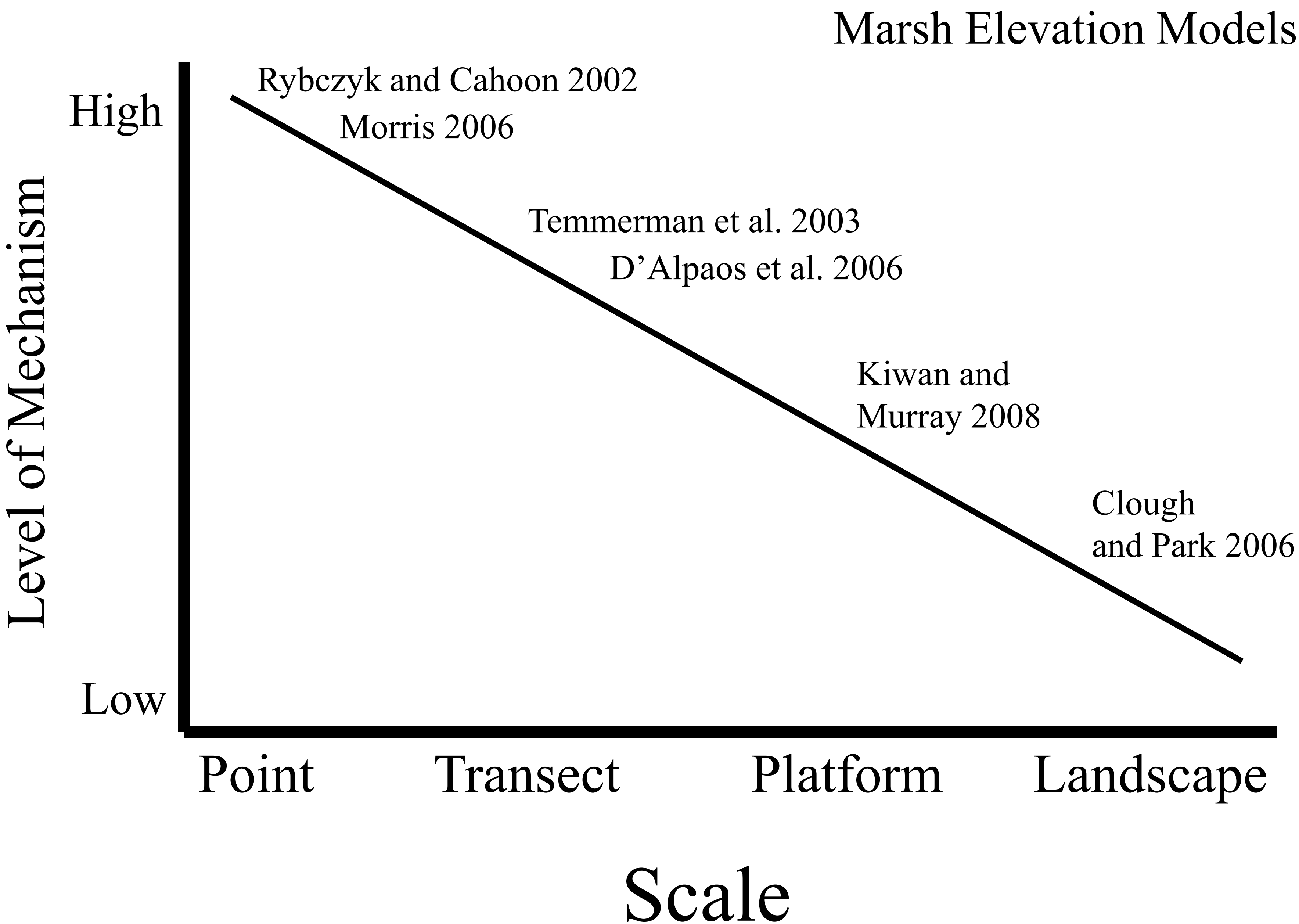
Table 2. Projections of Habitat Changes for All Sites Combined

	Area of Habitat Type in Hectares (Acres)				Percentage Change (Relative to Totals Across All Sites)		
	Initial Condition	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+ 1.5 meters/ 59.1 inches)	2050 (+0.28 meters/11.2 inches)	2100 (+0.69 meters/27.3 inches)	2100 (+1.5 meters/59.1 inches)
Undeveloped Dry Land	601,102 (1,485,355)	589,245 (1,456,056)	587,588 (1,456,056)	585,729 (1,447,350)	2% loss	2% loss	3% loss
Developed	89,717 (221,696)	89,717 (221,696)	89,717 (221,696)	89,717 (221,696)	No change	No change	No change
Swamp	18,518 (45,759)	17,788 (43,950)	16,511 (40,800)	15,418 (38,099)	4% loss	11% loss	17% loss
Inland Fresh Marsh	18,381 (45,420)	17,300 (42,749)	15,967 (39,455)	14,976 (37,007)	6% loss	13% loss	19% loss
Tidal Fresh Marsh	468 (1156)	383 (946)	352 (870)	329 (815)	18% loss	25% loss	30% loss
Transitional Marsh	56 (138)	5,020 (12,405)	7,181 (17,745)	3,874 (9,573)	8,940% expansion	12,832% expansion	6,878% expansion
Saltmarsh	6,701 (16,559)	13,655 (33,742)	10,324 (25,511)	11,470 (28,343)	104% expansion	52% expansion	71% expansion
Estuarine Beach	16,071 (39,712)	8,357 (20,651)	5,625 (13,900)	2,160 (5,337)	48% loss	65% loss	87% loss
Tidal Flat	24,369 (60,217)	20,227 (49,982)	13,548 (33,478)	14,408 (35,603)	17% loss	44% loss	41% loss
Ocean Beach	3,297 (8,147)	3,520 (8,698)	3,088 (7,631)	60 (148)	7% expansion	6% loss	98% loss
Inland Open Water	6,466 (15,978)	5,770 (14,258)	5,653 (13,969)	5,543 (13,697)	11% loss	13% loss	14% loss
Estuarine Open Water	220,787 (545,527)	232,941 (575,610)	245,728 (607,207)	254,308 (628,399)	6% expansion	11% expansion	15% expansion
Open Ocean	203,191 (502,096)	207,224 (512,062)	210,350 (519,786)	214,687 (530,505)	2% expansion	4% expansion	6% expansion
Brackish Marsh	3,030 (7,487)	1,801 (4,450)	1,443 (3,566)	576 (1,423)	41% loss	52% loss	81% loss
Inland Shore	123 (304)	120 (297)	120 (297)	118 (292)	3% loss	3% loss	4% loss
Tidal Swamp	748 (1,848)	346 (855)	292 (722)	186 (460)	54% loss	61% loss	75% loss
Rocky Intertidal	76 (188)	65 (161)	50 (124)	23 (57)	13% loss	34% loss	70% loss
Riverine Tidal	1,059 (2,617)	604 (1,641)	604 (1,493)	566 (1,399)	37% loss	43% loss	47% loss

Site 2: Padilla Bay, Skagit Bay & Port Susan Bay

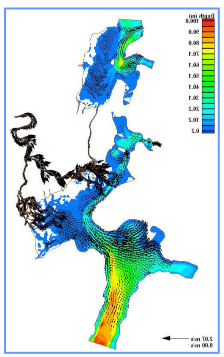


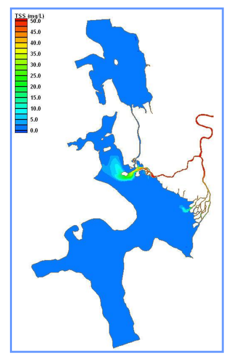
Initial Condition **Year 2050, A1B-Max** **Year 2100, A1B-Max**

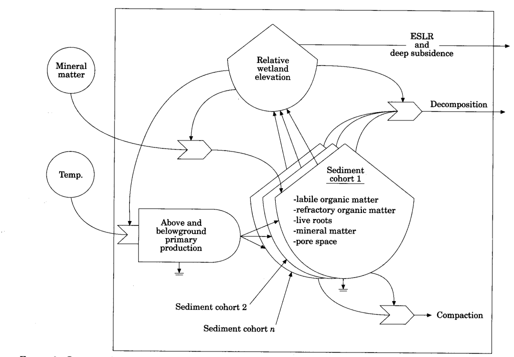

Marsh Elevation Models
High
Low
Level of Mechanism
Rybczyk and Cahoon 2002
Morris 2006
Temmerman et al. 2003
D'Alpaos et al. 2006
Kiwan and
Murray 2008
Clough
and Park 2006
Point
Transect
Platform
Landscape
Scale

1. Field Data Collection For Model Development, Initialization, Calibration, and Validation

2. Model Development





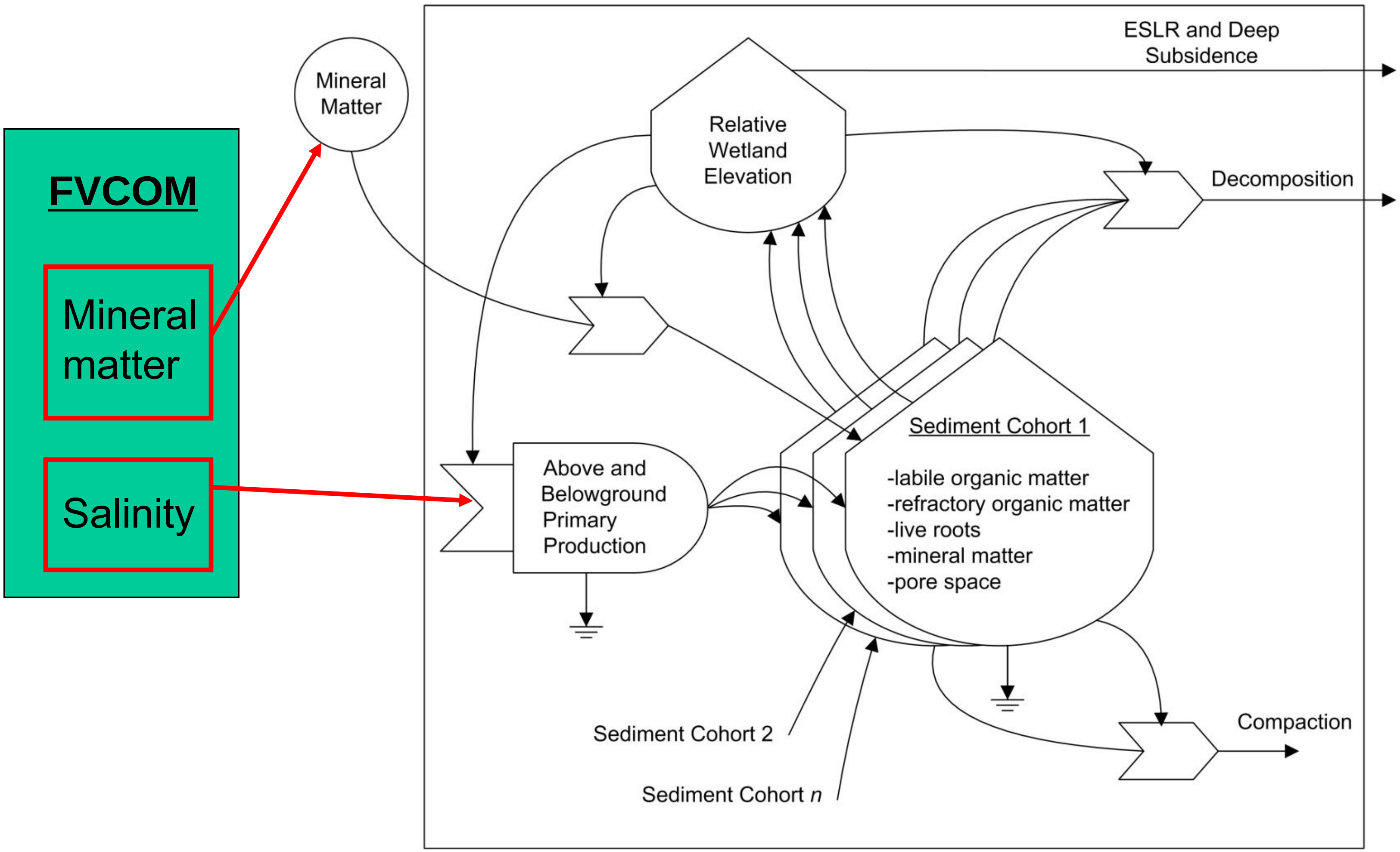


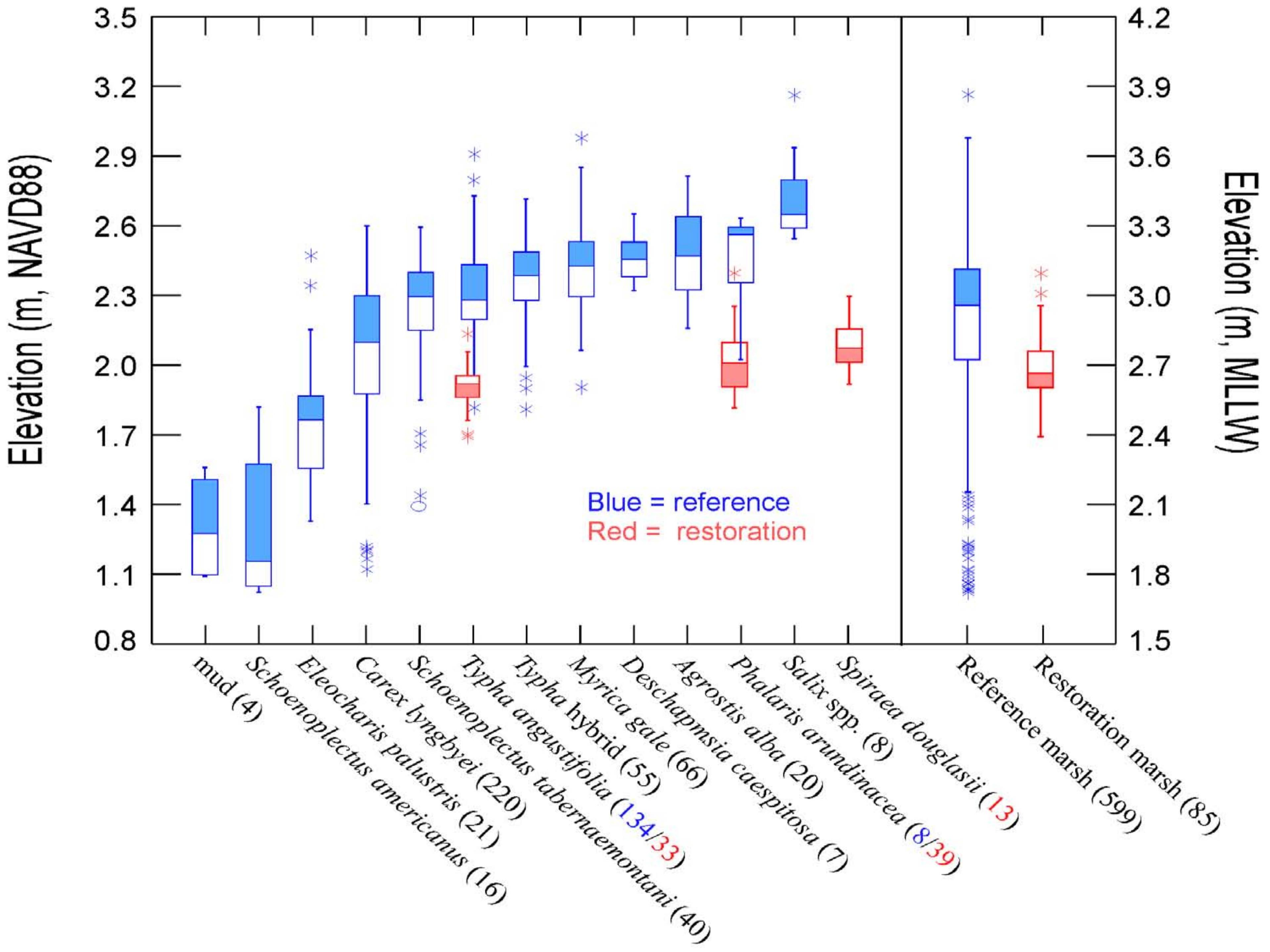
Hydrodynamic Model

Sediment Transport Model

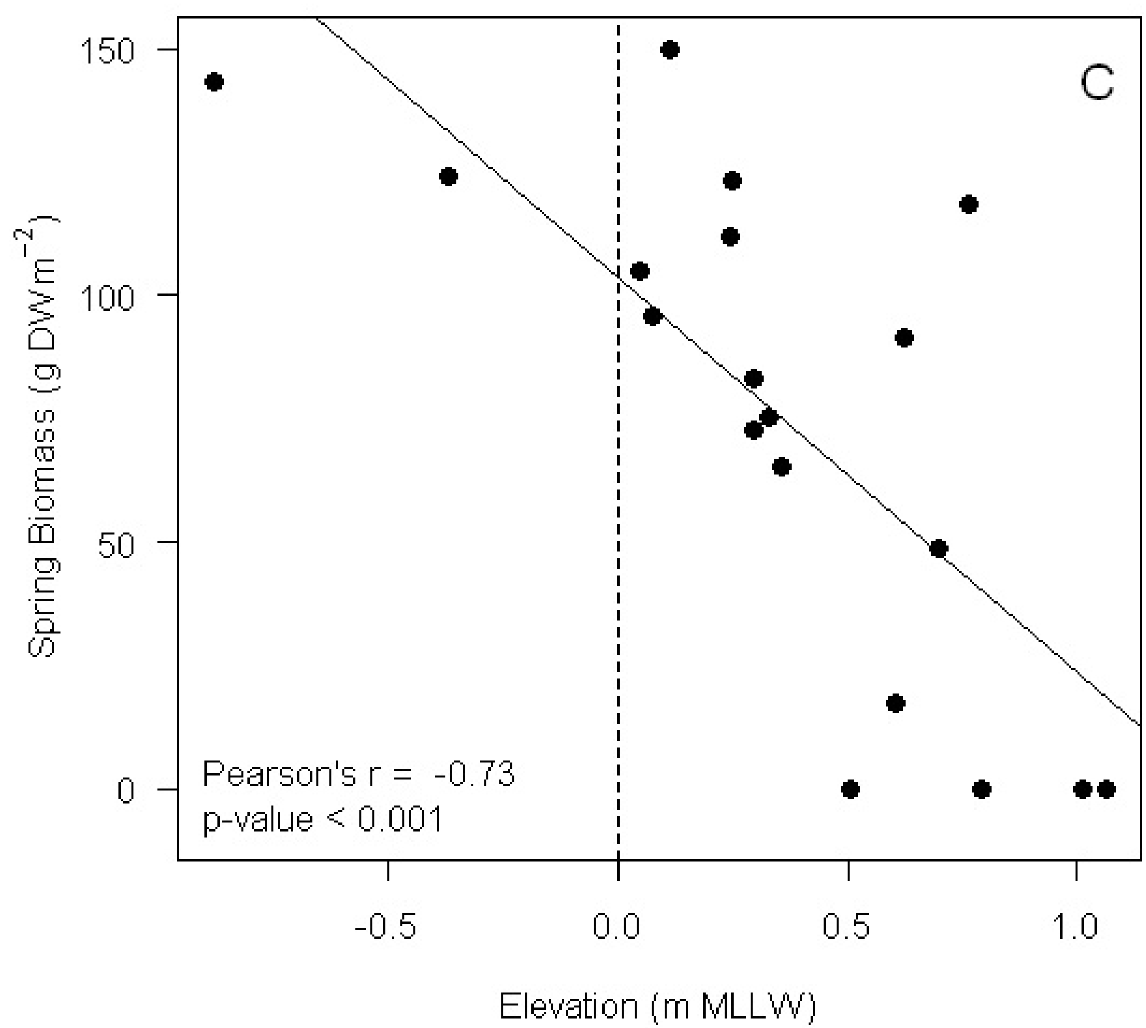
Relative Elevation and Habitat Model

3. Sea Level Rise and Restoration Scenarios

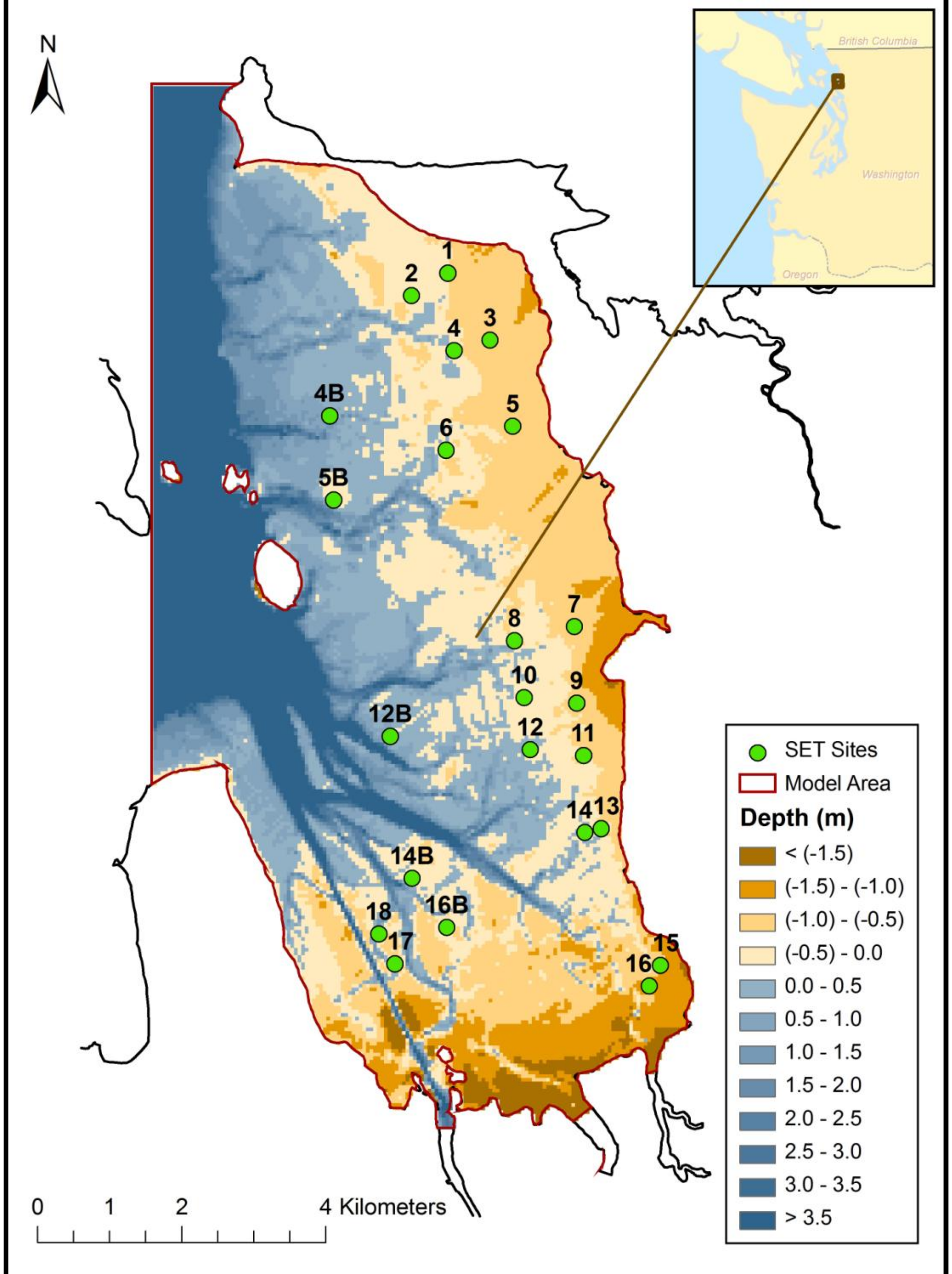

FVCOM
Mineral matter
Salinity
Mineral Matter
Relative Wetland Elevation
ESLR and Deep Subsidence
Decomposition
Above and Belowground Primary Production
Sediment Cohort 1
-labile organic matter
-refractory organic matter
-live roots
-mineral matter
-pore space
Sediment Cohort 2
Sediment Cohort n
Compaction

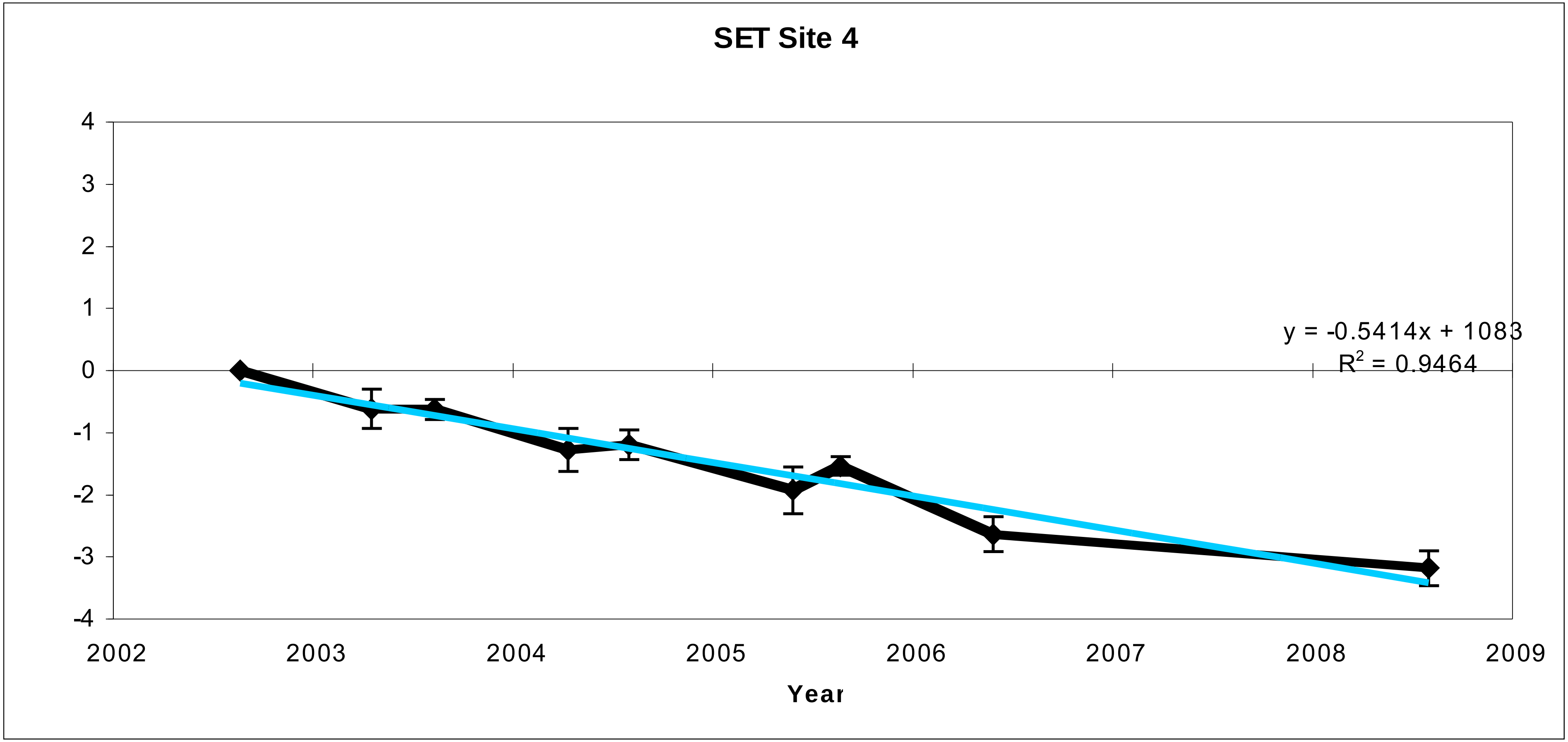


Elevation (m, NAVD88)
Elevation (m, MLLW)
3.5
3.2
2.9
2.6
2.3
2.0
1.7
1.4
1.1
0.8
4.2
3.9
3.6
3.3
3.0
2.7
2.4
2.1
1.8
1.5
Blue = reference
Red = restoration
mud (4)
Schoenoplectus americanus (16)
Eleocharis palustris (21)
Carex lyngbyei (220)
Schoenoplectus tabernaemontani (40)
Typha angustifolia (134/33)
Typha hybrid (55)
Myrica gale (66)
Deschapmsia caespitosa (7)
Agrostis alba (20)
Phalaris arundinacea (8/39)
Salix spp. (8)
Spiraea douglasii (13)
Reference marsh (599)
Restoration marsh (85)



C
Pearson's r = -0.73
p-value < 0.001
150
100
50
0
-0.5
0.0
0.5
1.0
Elevation (m MLLW)
Spring Biomass (g DW m^{-2})


N
British Columbia
Washington
Oregon
1
2
3
4
4B
5
6
5B
7
8
10
9
12B
12
11
14
13
14B
16B
18
17
15
16
SET Sites
Model Area
Depth (m)
< (-1.5)
(-1.5) - (-1.0)
(-1.0) - (-0.5)
(-0.5) - 0.0
0.0 - 0.5
0.5 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 3.5
> 3.5
0 1 2 4 Kilometers



SET Site 4
4
3
2
1
0
-1
-2
-3
-4
2002
2003
2004
2005
2006
2007
2008
2009
Year
y = -0.5414x + 1083
$R^2 = 0.9464$

Field Data Required for Initialization

<u>Vegetation</u>

- Net primary productivity as a function of elevation
- Root/shoot production ratio
- Labile/refractory matter ratio for leaf and root litter
- Decomposition rate of labile and refractory organic matter
- Plant matter conversion factor (g.d.w. to gC)
- Root distribution with depth coefficient

<u>Sediment</u>

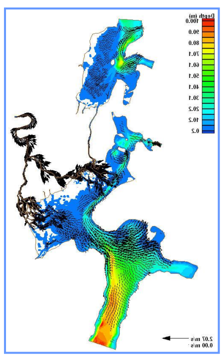
- Accretion rate
- Minimum/maximum pore space
- Sediment compaction constant (based on bulk density and pore space measurements from cores)

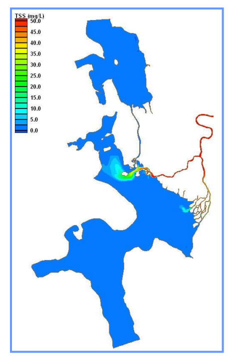
<u>Miscellaneous</u>

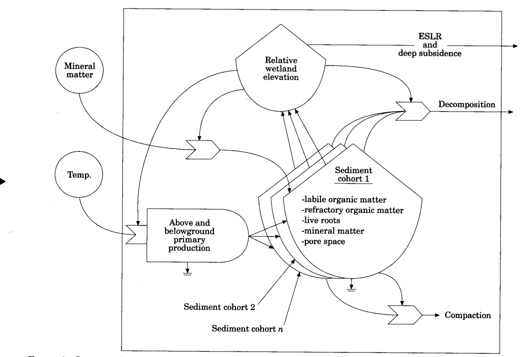
- Deep subsidence rate
- Eustatic sea level rise rate
- Initial elevation at a representative point

1. Field Data Collection For Model Development, Initialization, Calibration, and Validation

2. Model Development





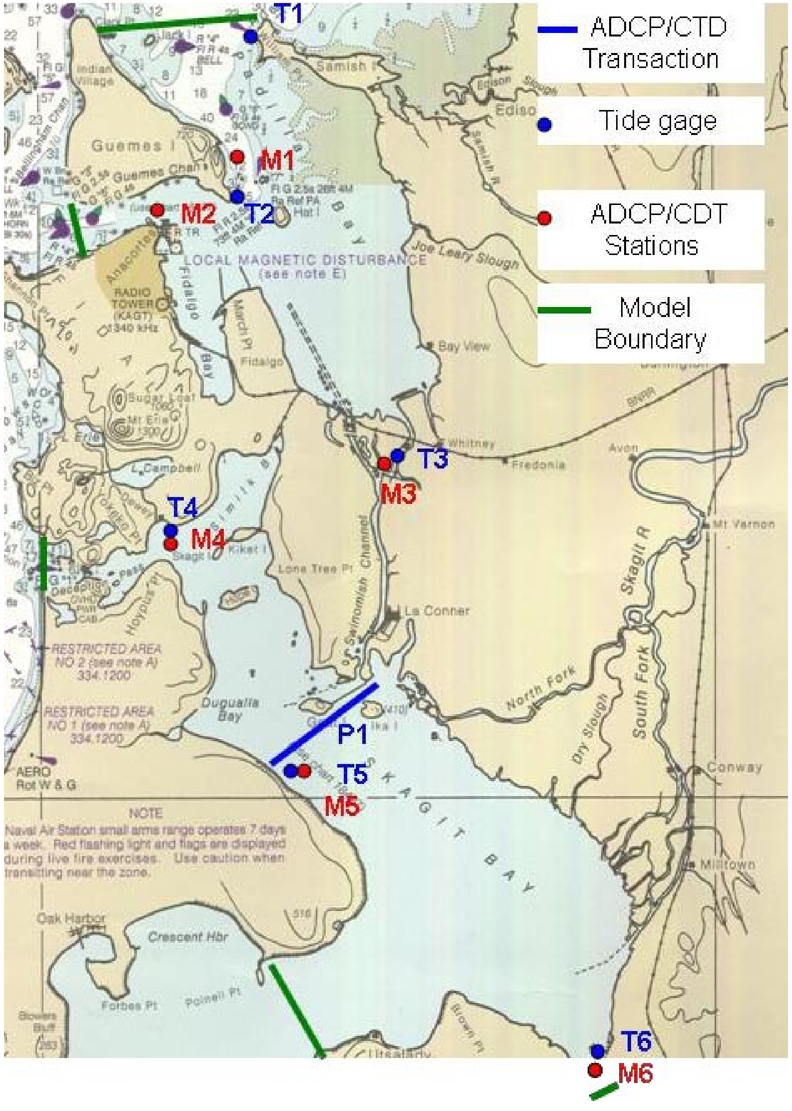


Hydrodynamic Model

Sediment Transport Model

Relative Elevation and Habitat Model

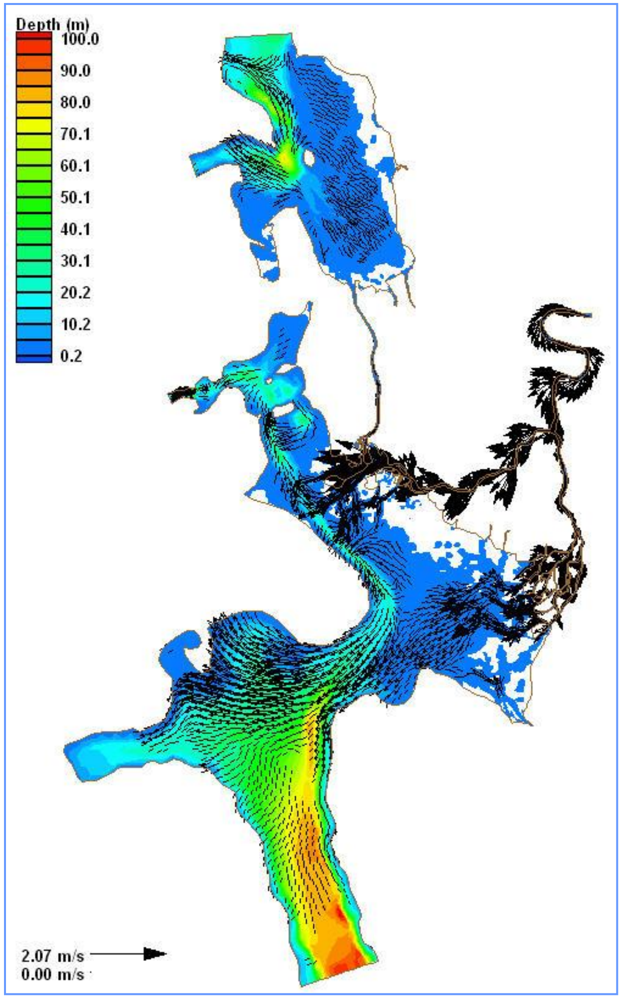
3. Sea Level Rise and Restoration Scenarios



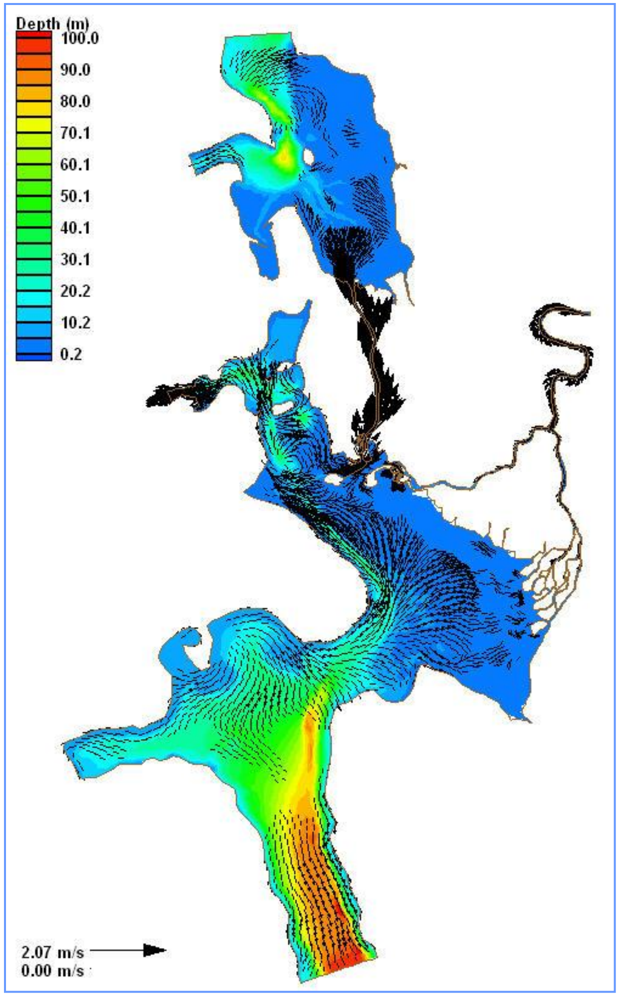
ADCP/CTD Transaction
Tide gage
ADCP/CDT Stations
Model Boundary
T1
T2
T3
T4
T5
T6
M1
M2
M3
M4
M5
M6
P1
Guemes I
Anacortes
LOCAL MAGNETIC DISTURBANCE (see note E)
Joe Leary Slough
Bay View
Samish R
Fidalgo Bay
March Pt
Fidalgo
Whitney
Fredonia
Avon
Mt Vernon
Skagit R
La Conner
Swinomish Channel
Lone Tree Pt
Kiket I
Similk B
L Campbell
Deception Pass
Hoypus Pt
RESTRICTED AREA NO 2 (see note A) 334.1200
RESTRICTED AREA NO 1 (see note A) 334.1200
Dugualla Bay
North Fork
South Fork
Dry Slough
Conway
SKAGIT BAY
Milltown
NOTE
Naval Air Station small arms range operates 7 days a week. Red flashing light and flags are displayed during live fire exercises. Use caution when transiting near the zone.
Oak Harbor
Crescent Hbr
Forbes Pt
Polnell Pt
Brown Pt
RADIO TOWER (KAGT) 1340 kHz
Sugar Loaf
Mt Erie
AERO Rot W & G

Surface Velocity and Water Depth

Low Tide



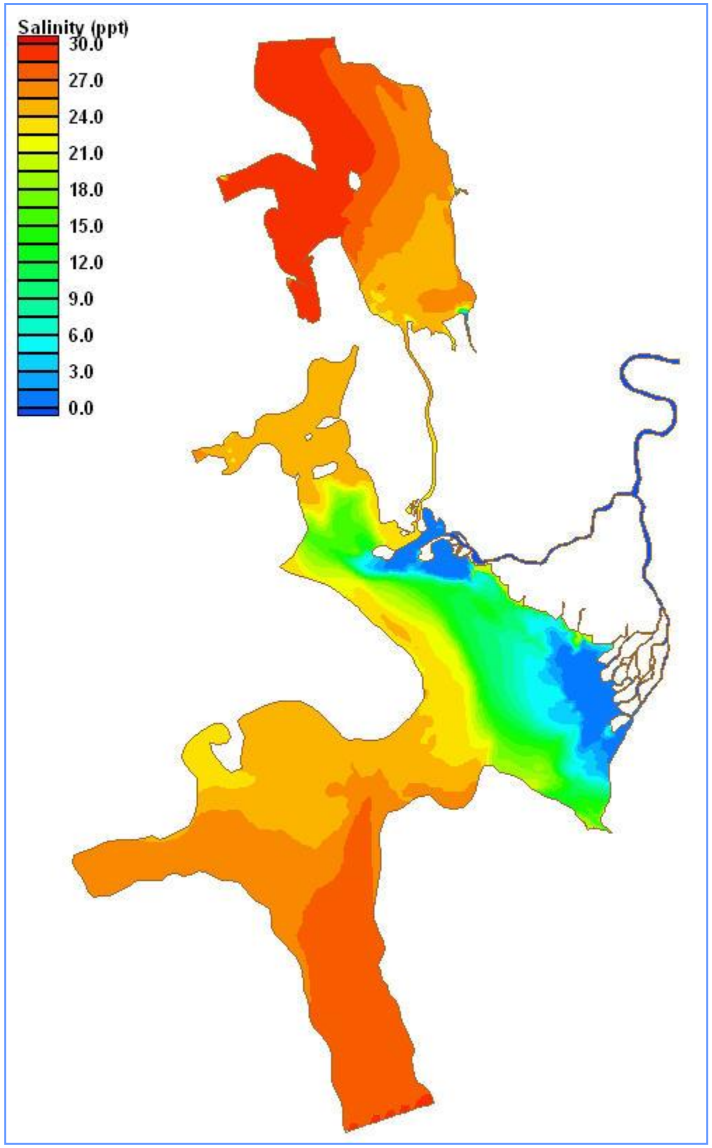
High Tide



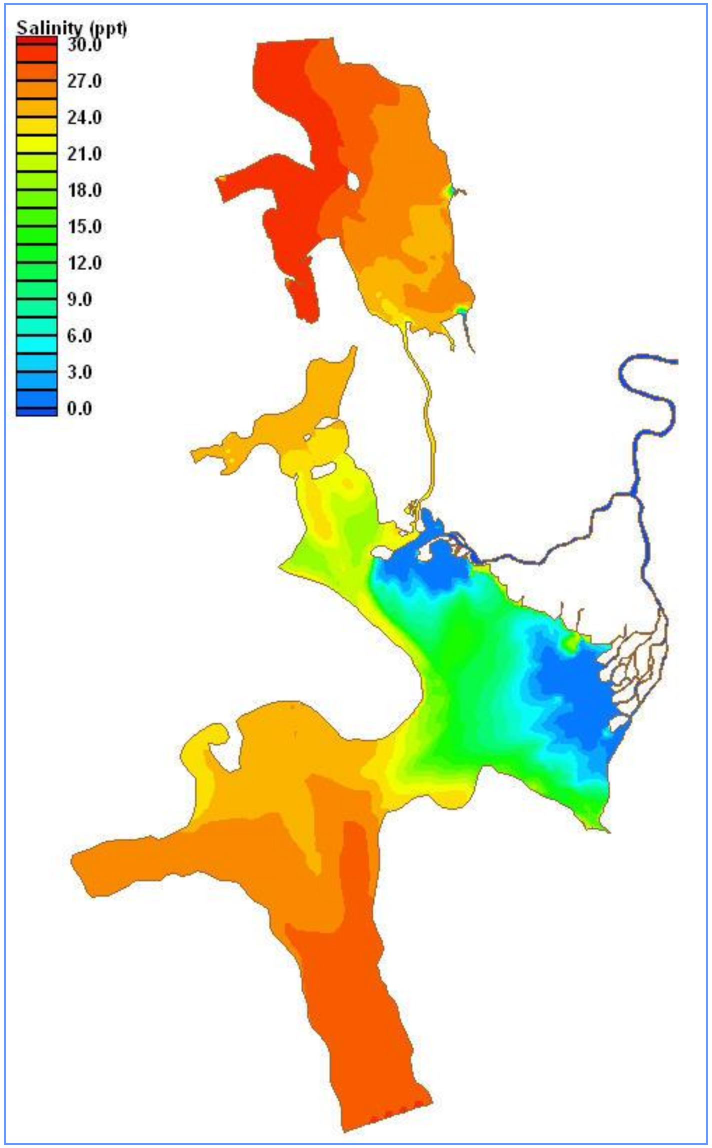
Yang, Z. and T. Khangaonkar. 2009. Modeling tidal circulation and stratification in Skagit River estuary using an unstructured grid ocean model. Ocean Modelling 28: 34 - 49.

Surface Salinity at Flood and Ebb Tides

Flood Tide

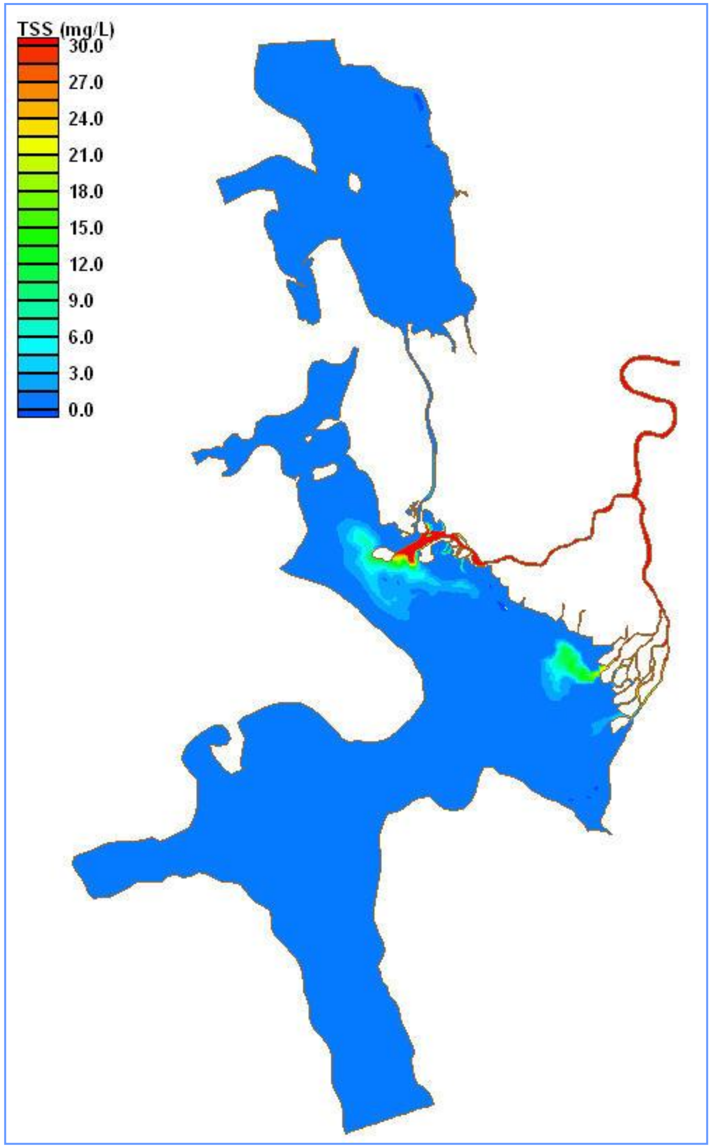


Ebb Tide

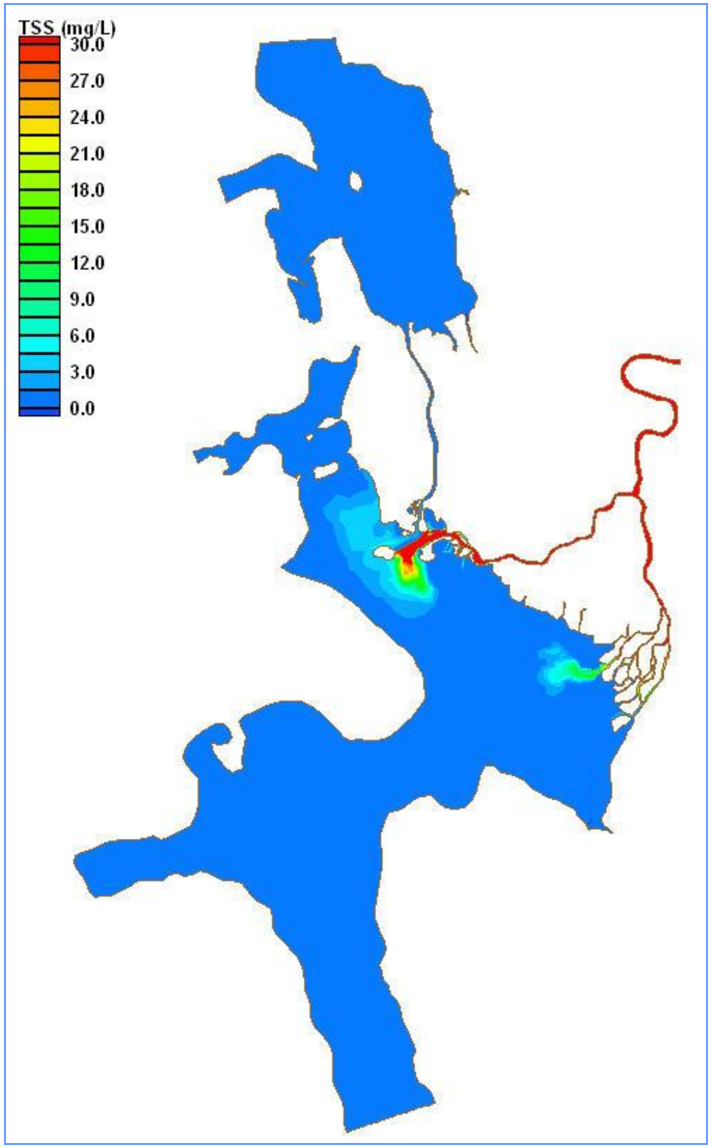


Bottom TSS at Flood and Ebb Tides

Flood Tide

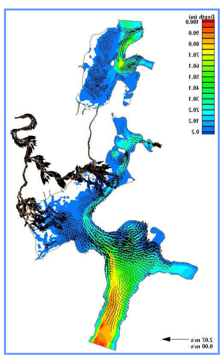


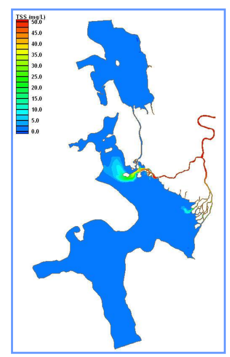
Ebb Tide

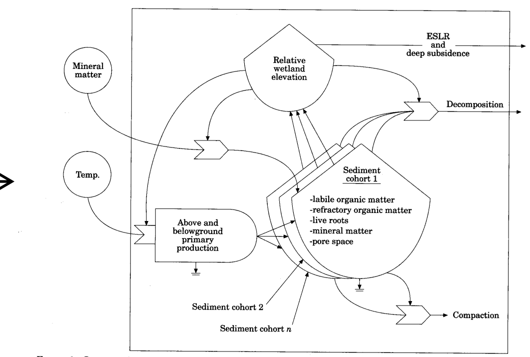


1. Field Data Collection For Model Development, Initialization, Calibration, and Validation

2. Model Development







Hydrodynamic Model

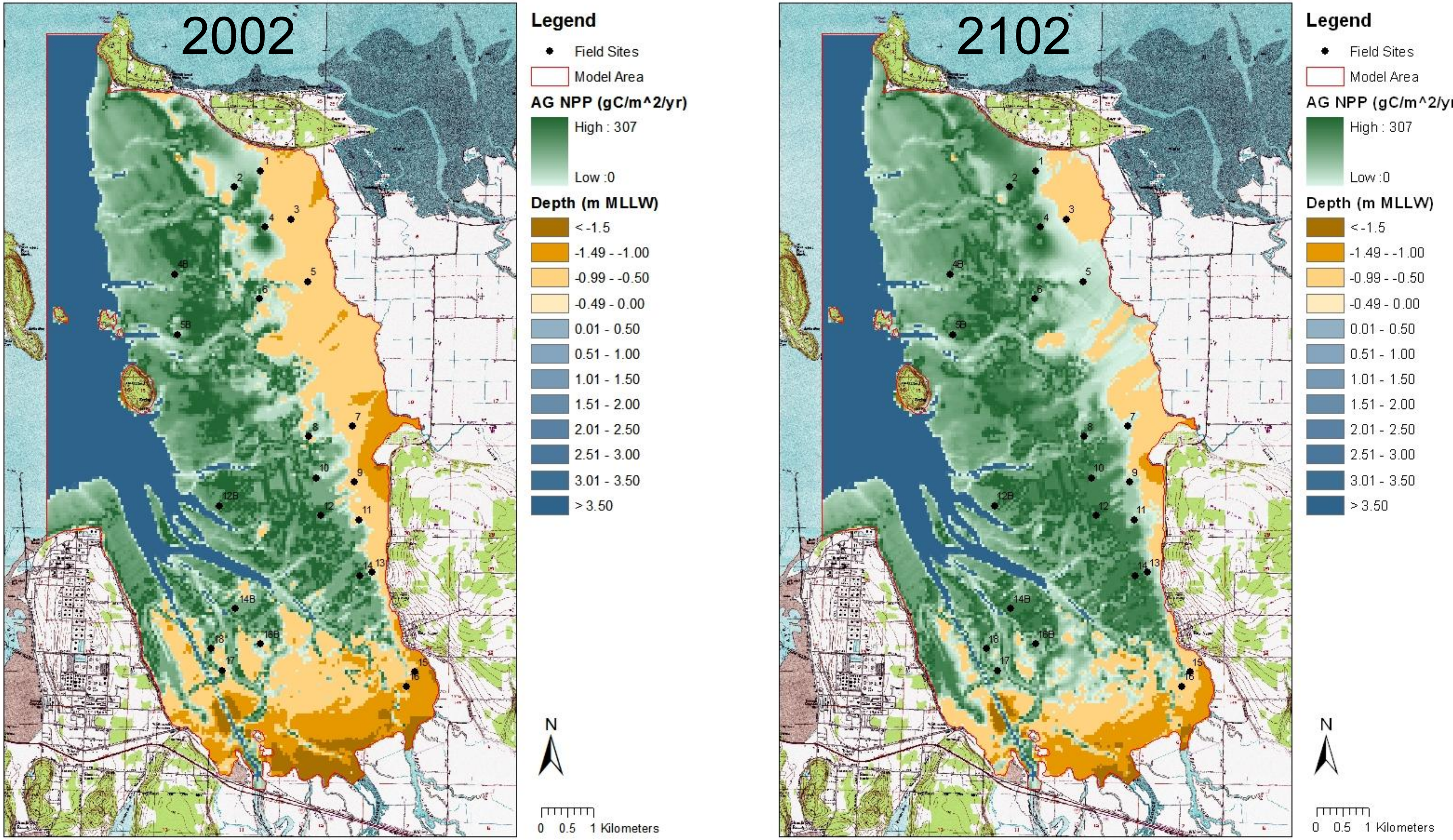
Sediment Transport Model

Relative Elevation and Habitat Model

3. Sea Level Rise and Restoration Scenarios

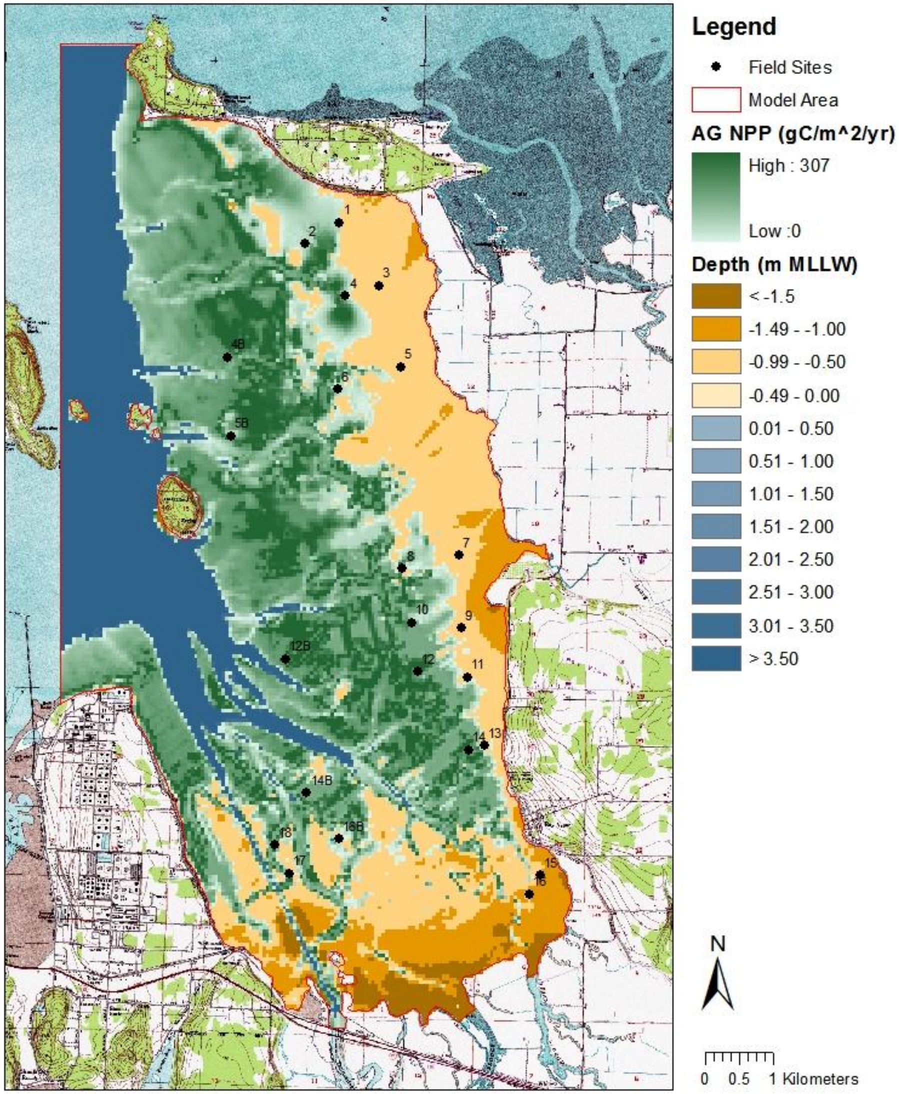
Table 1. Rates of eustatic sea level rise used for each of the seven scenarios.

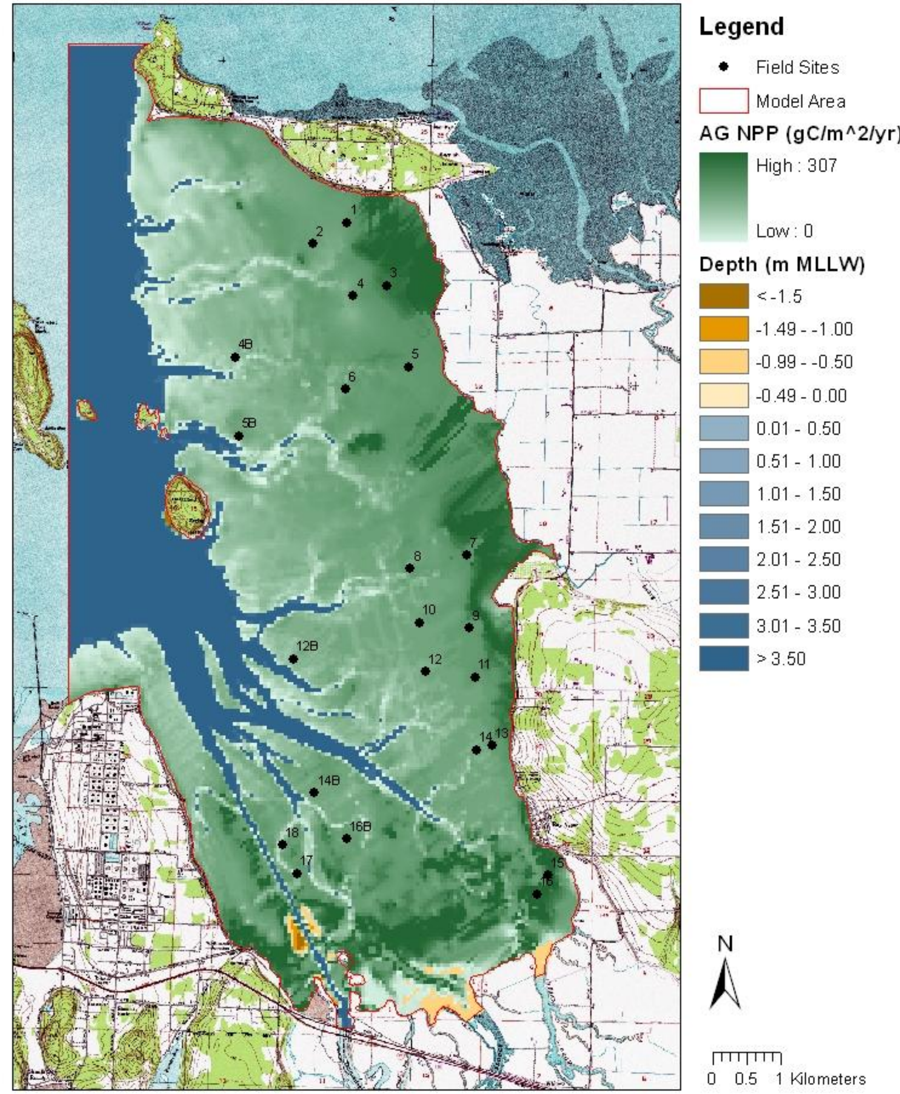
Scenario name	**Description**	**Source**	**ELSR rate (cm/year)**
IPCC-Low	Lower limit of all IPCC AR4 scenarios (from scenario B1)	(Meehl et al. 2007)	0.1714
IPCC-Mid	Average of all IPCC AR4 scenarios	(Meehl et al. 2007)	0.3267
IPCC-High	Upperlimit of all IPCC AR4 scenarios (from scenario A1F1)	(Meehl et al. 2007)	0.5619
IPCC-High+Ice	Upperlimit of all IPCC AR4 scenarios with added central value of scaled-up ice sheet discharge	(Meehl et al. 2007)	0.6381
Rahmstorf-Mid	Central value projected semi-empirically based upon IPCC TAR	(Rahmstorf 2007)	0.8636
Rahmstorf-High	Upperlimit projected semi-empirically based upon IPCC TAR	(Rahmstorf 2007)	1.2727
Biomass-Red	ESLR large enough to cause a reduction in total annual *Z. marina* NPP after 100 years	this study	1.8182



0.56 meter increase in 100 years

Kairis, P. and J.M. Rybczyk. 2010. A Spatially Explicit Relative Elevation Model for Padilla Bay, WA. Ecological Modeling. 221: 1005 -1016.





2002 2102

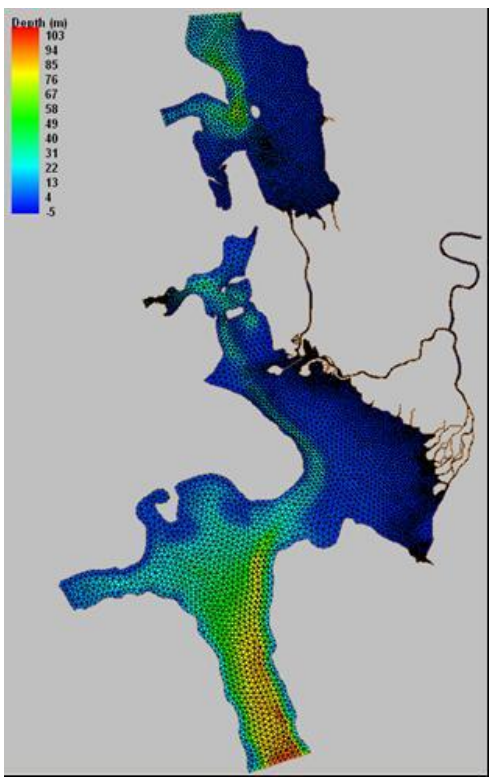
1.27 meter increase in 100 years (Rahmstorf 2007)

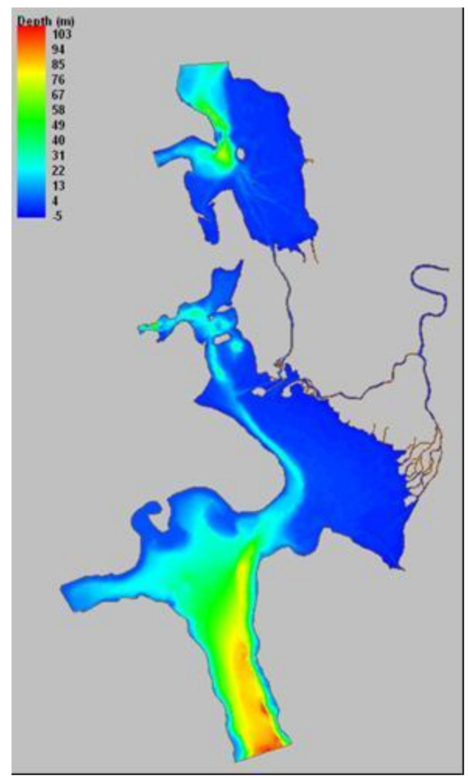
Next Steps

- Refine the sediment delivery and complete the model linkage
- Restoration scenarios for the Skagit Delta
- Outreach

FVCOM Model Grid for Skagit-Padilla Bays

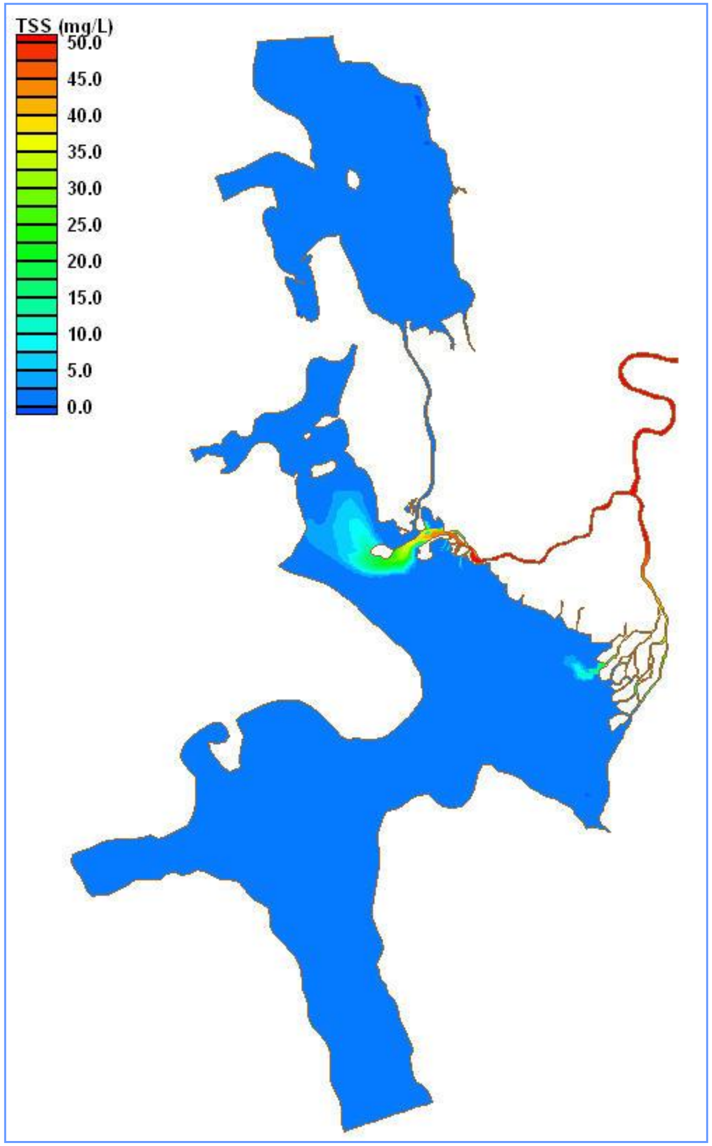
- Expansion of Existing Skagit Bay Model to Padilla Bay and Saratoga Passage
  - Modification of model boundary condition
  - Additional stream flow inputs from Entranco Engineers and Ralph Nelson (1989)



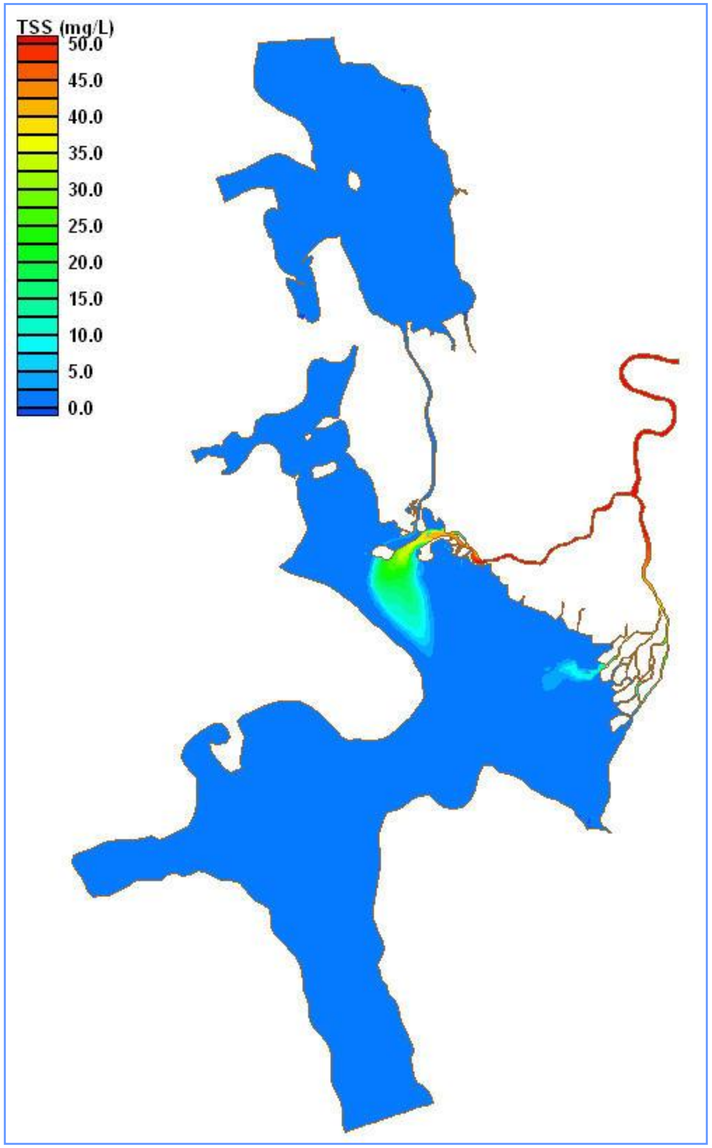


Surface TSS at Flood and Ebb Tides

Flood Tide



Ebb Tide

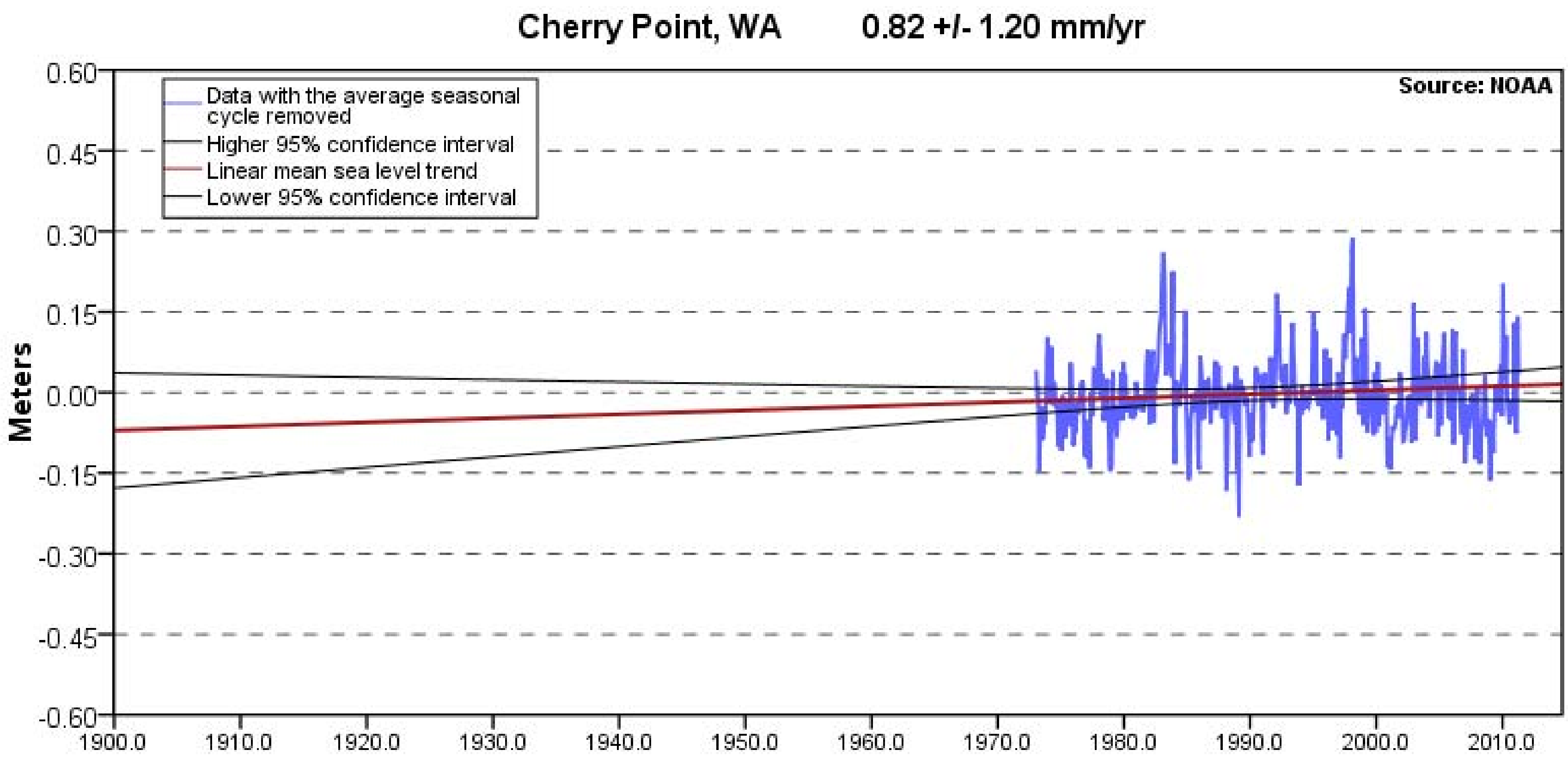


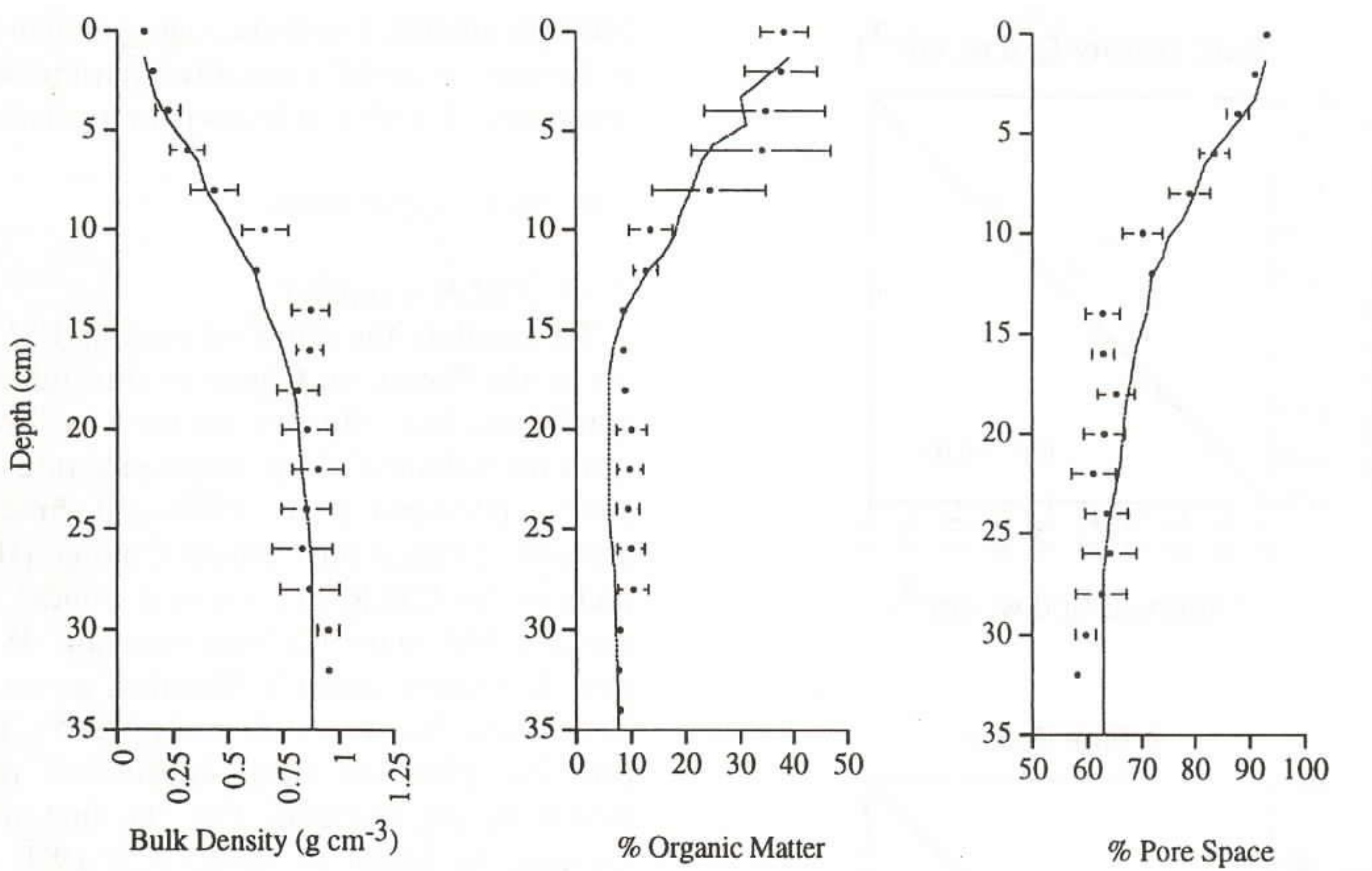
$$\text{Annual Elevation Surplus or Deficit} = \text{Mineral Matter Accretion} + \text{Organic Matter Accumulation} - \text{Shallow Subsidence} \pm \text{Deep Subsidence or Uplift} - \text{Eustatic Sea-Level Rise}$$

	Rate of SLR (mm $year^{-1}$)	
	1961 - 2003	**1993 - 2003**
Actual observed rate of SLR	1.8 ± 0.5	**3.1 ± 0.7**
Estimated contribution from sources		
□thermal expansion	0.42 ± 0.12	**1.6 ± 0.5**
□glaciers and ice caps	0.50 ± 0.18	**0.77 ± 0.22**
□Greenland ice sheet	0.05 ± 0.12	**0.21 ± 0.07**
□Antarctic ice sheet	0.14 ± 0.41	**0.21 ± 0.7**
□sum of estimated contribtions[1]	1.1 ± 0.5	**2.8 ± 0.7**

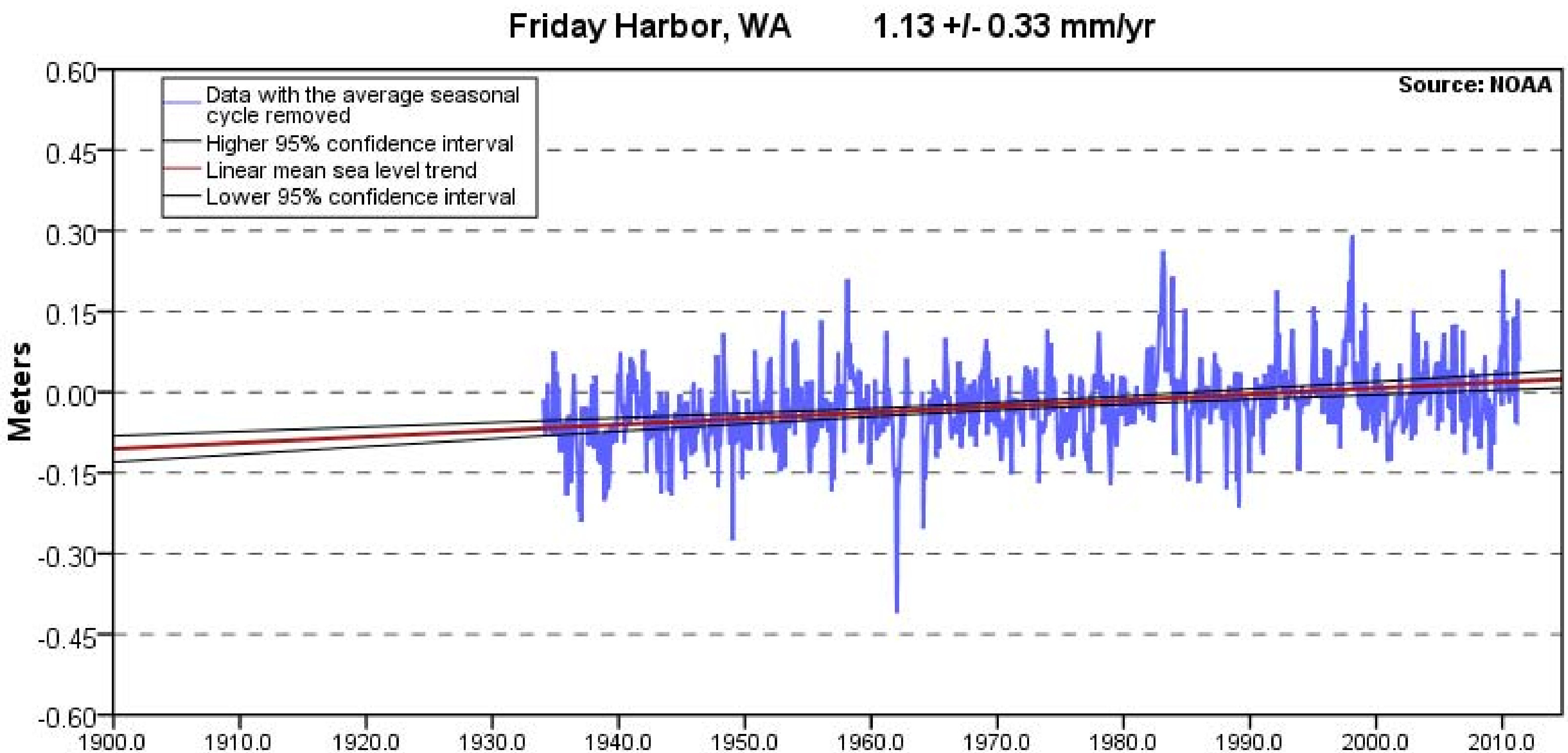
Bathtub model, appropriate for some situations, but wetland exist in a Dynamic equilibrium with sea level rise…accrete at up to 1.5 cm year

Get to high in the tidal frame…too low.

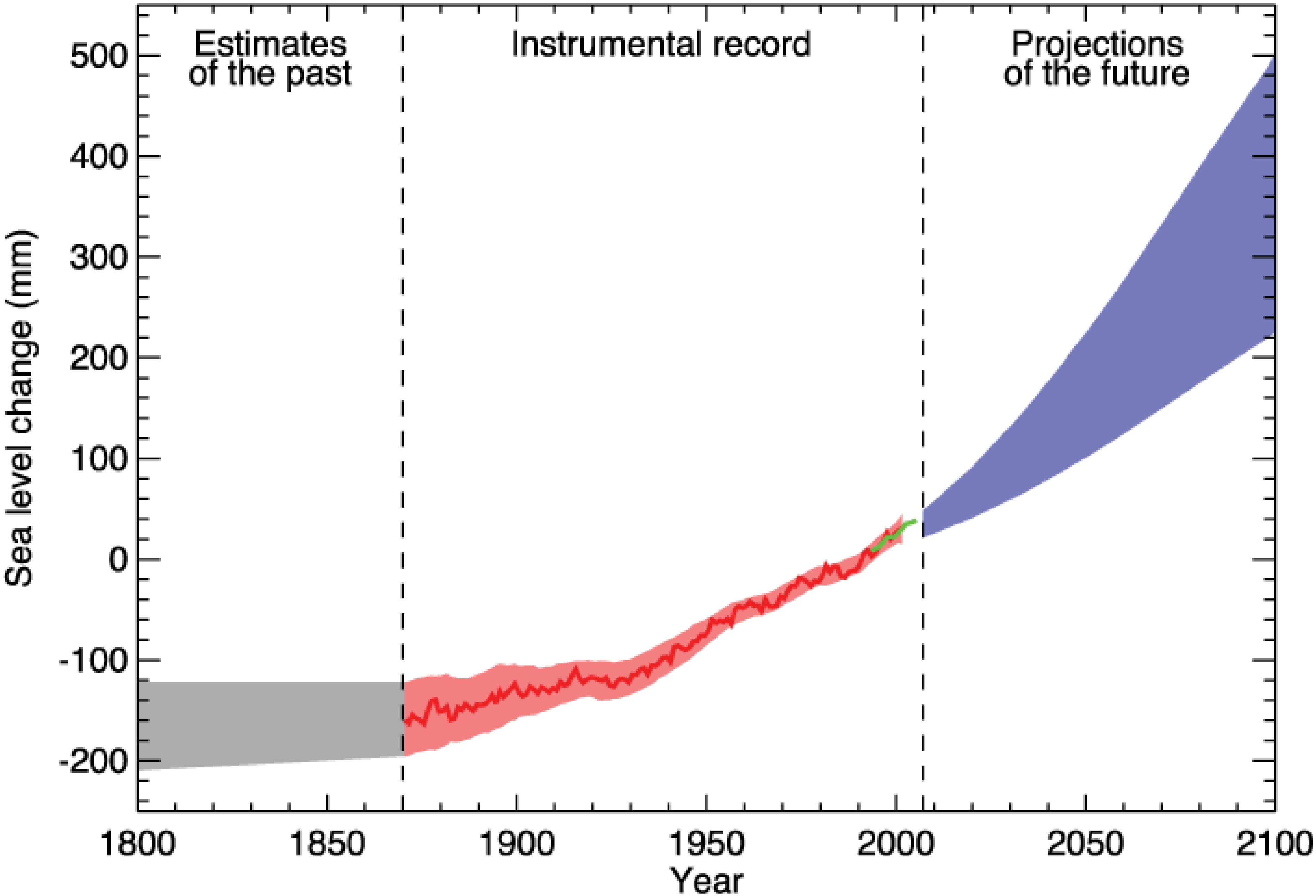

Cherry Point, WA
0.82 +/- 1.20 mm/yr
Data with the average seasonal cycle removed
Higher 95% confidence interval
Linear mean sea level trend
Lower 95% confidence interval
Source: NOAA
Meters
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
1900.0
1910.0
1920.0
1930.0
1940.0
1950.0
1960.0
1970.0
1980.0
1990.0
2000.0
2010.0



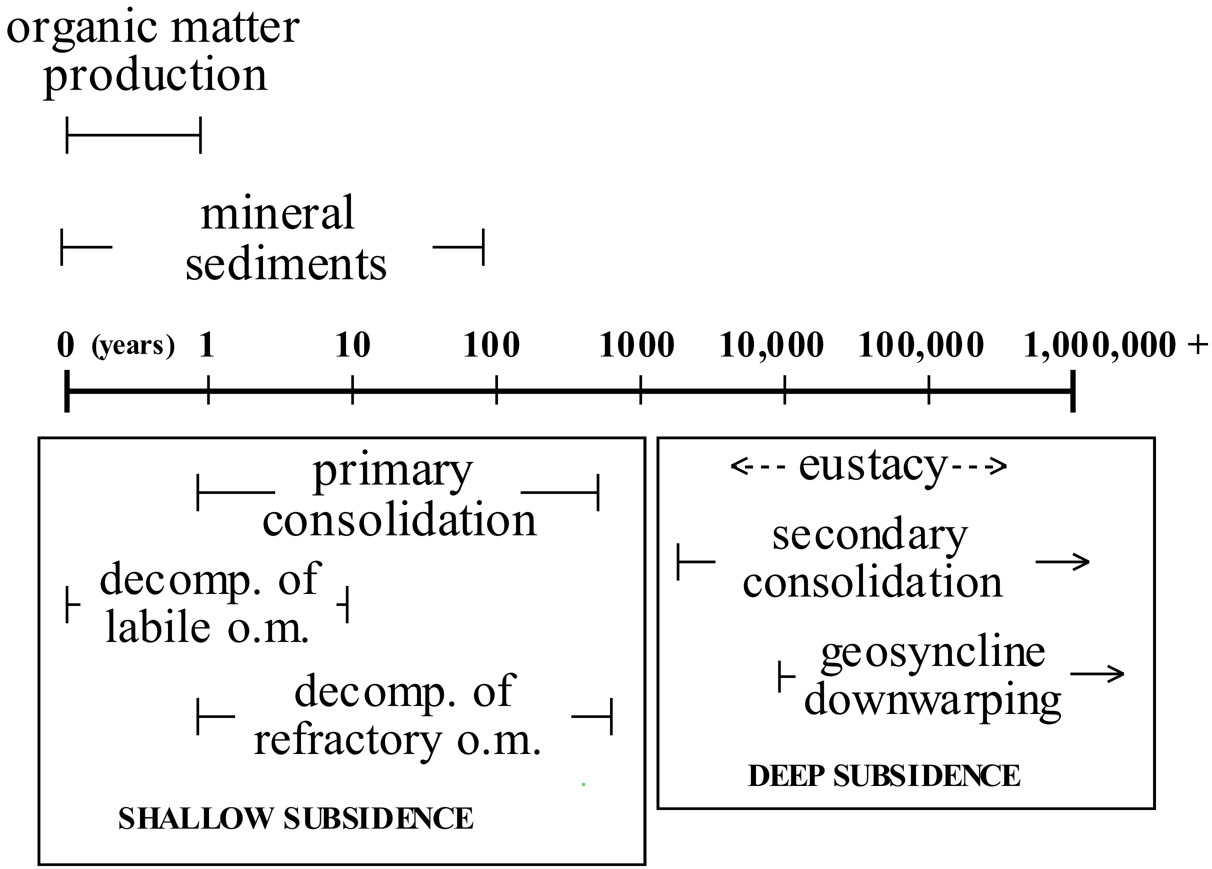
Sediment column integrates all processes



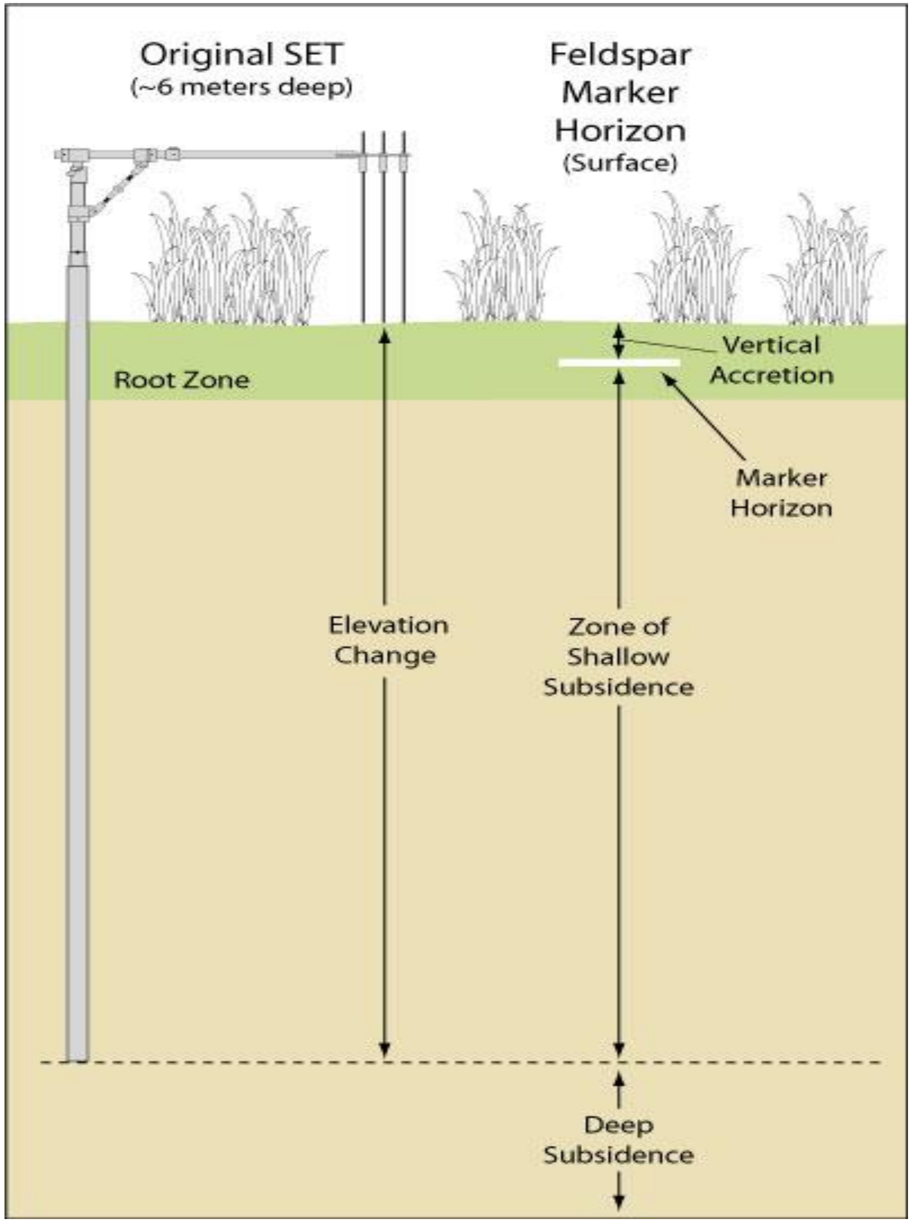
Friday Harbor, WA 1.13 +/- 0.33 mm/yr
Source: NOAA
Data with the average seasonal cycle removed
Higher 95% confidence interval
Linear mean sea level trend
Lower 95% confidence interval
Meters
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
1900.0
1910.0
1920.0
1930.0
1940.0
1950.0
1960.0
1970.0
1980.0
1990.0
2000.0
2010.0

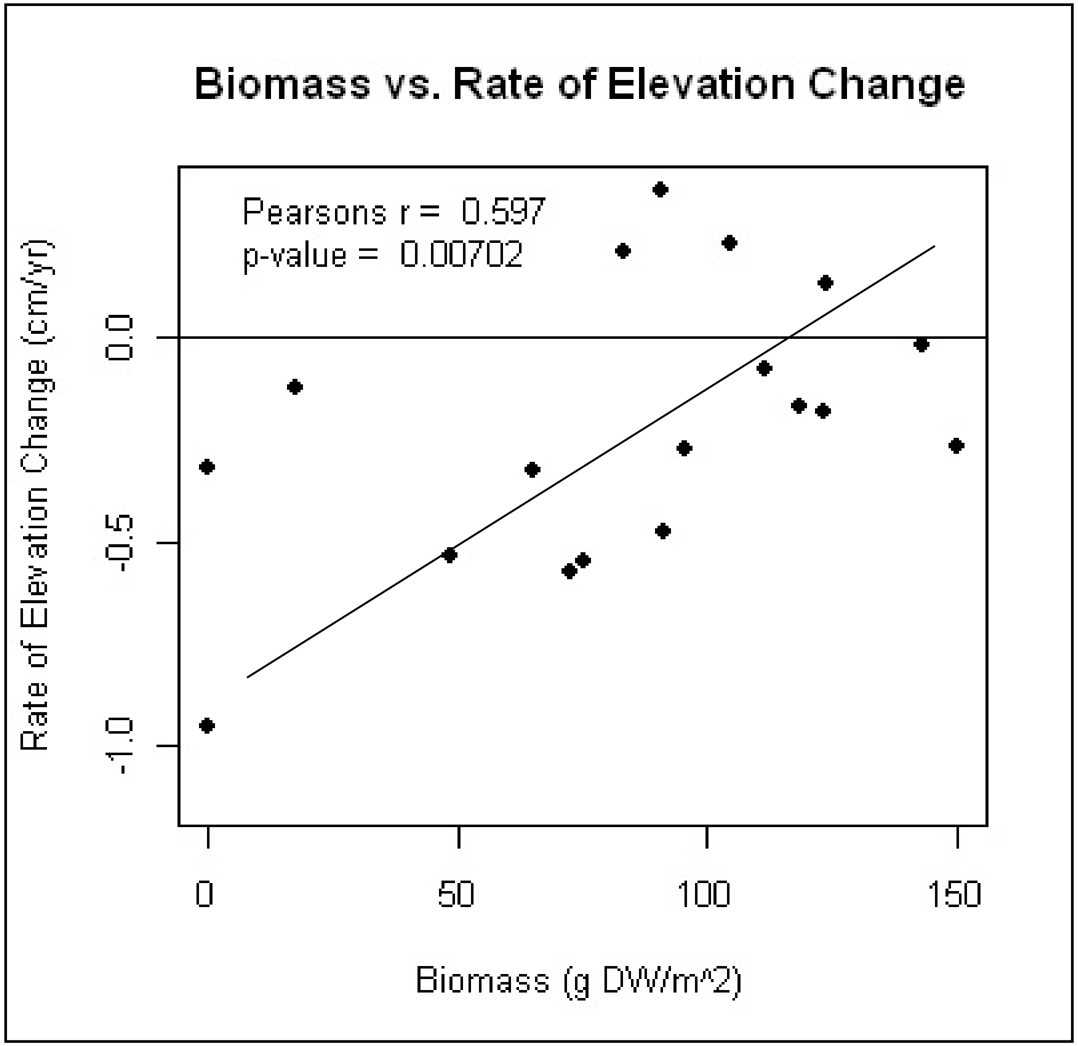


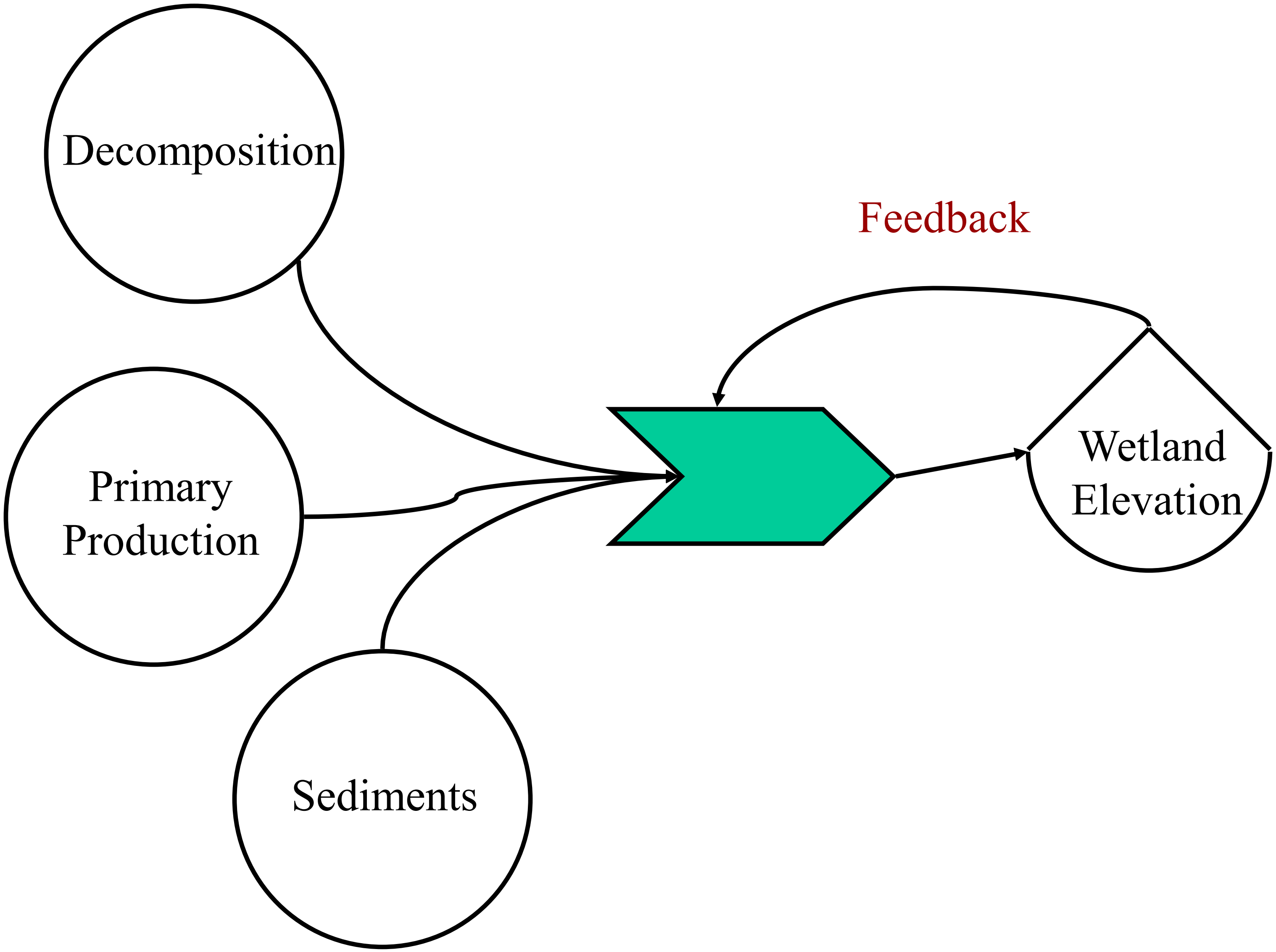
Estimates
of the past
Instrumental record
Projections
of the future
Sea level change (mm)
500
400
300
200
100
0
-100
-200
1800
1850
1900
1950
2000
2050
2100
Year

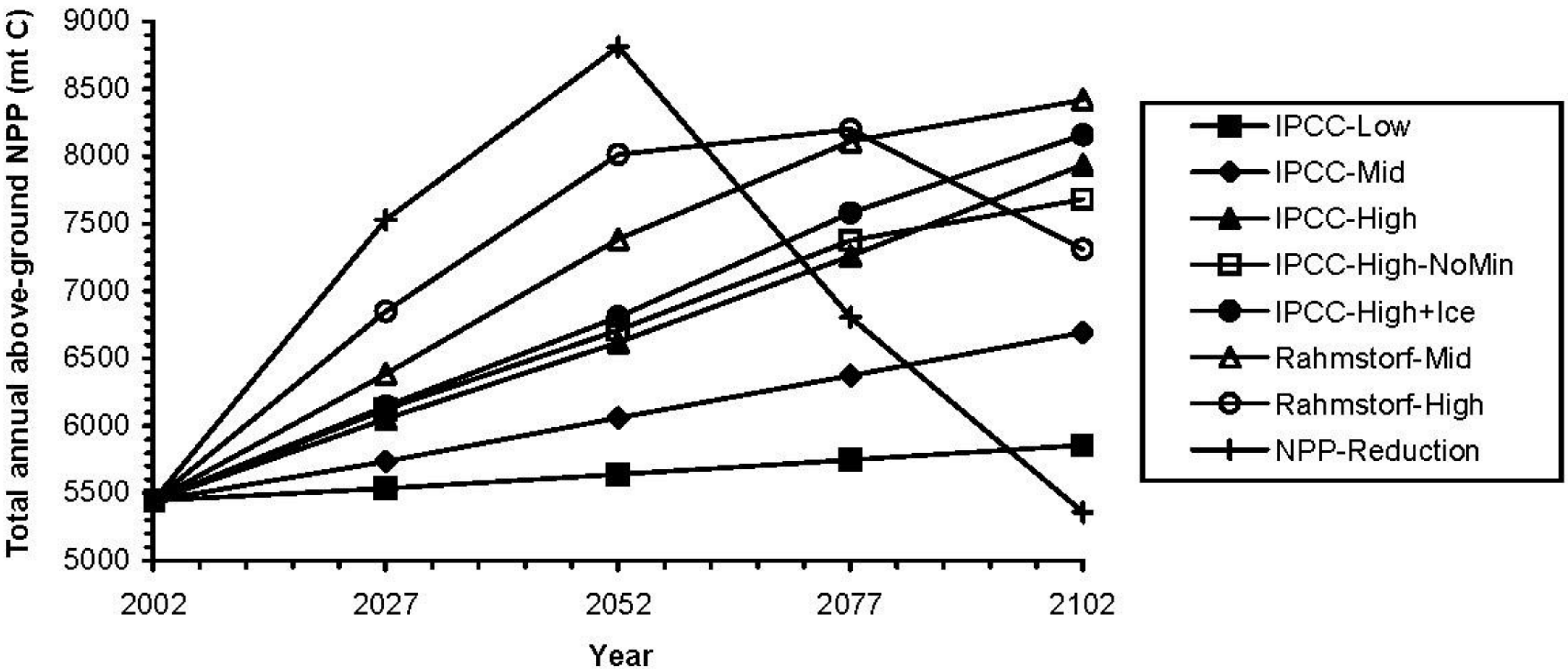


Temporal scale of processes that affect wetland elevation relative to sea level. Processes shown below the timeline decrease relative wetland elevation while those shown above the line increase it.

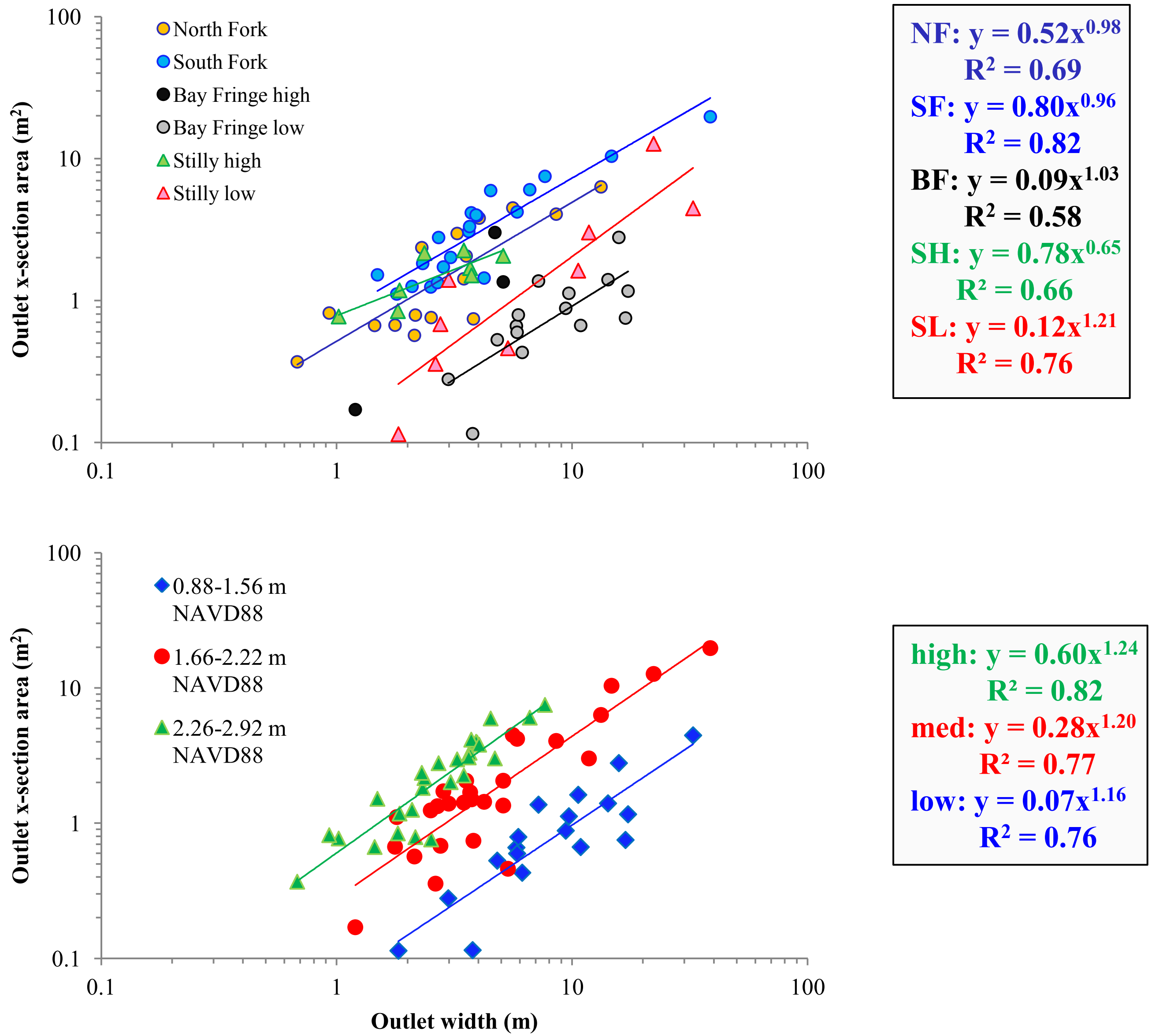

Original SET
(~6 meters deep)
Feldspar
Marker
Horizon
(Surface)
Root Zone
Vertical
Accretion
Marker
Horizon
Elevation
Change
Zone of
Shallow
Subsidence
Deep
Subsidence


Biomass vs. Rate of Elevation Change
Pearsons r = 0.597
p-value = 0.00702
Rate of Elevation Change (cm/yr)
0.0
-0.5
-1.0
0
50
100
150
Biomass (g DW/m^2)


Decomposition
Feedback
Primary Production
Wetland Elevation
Sediments

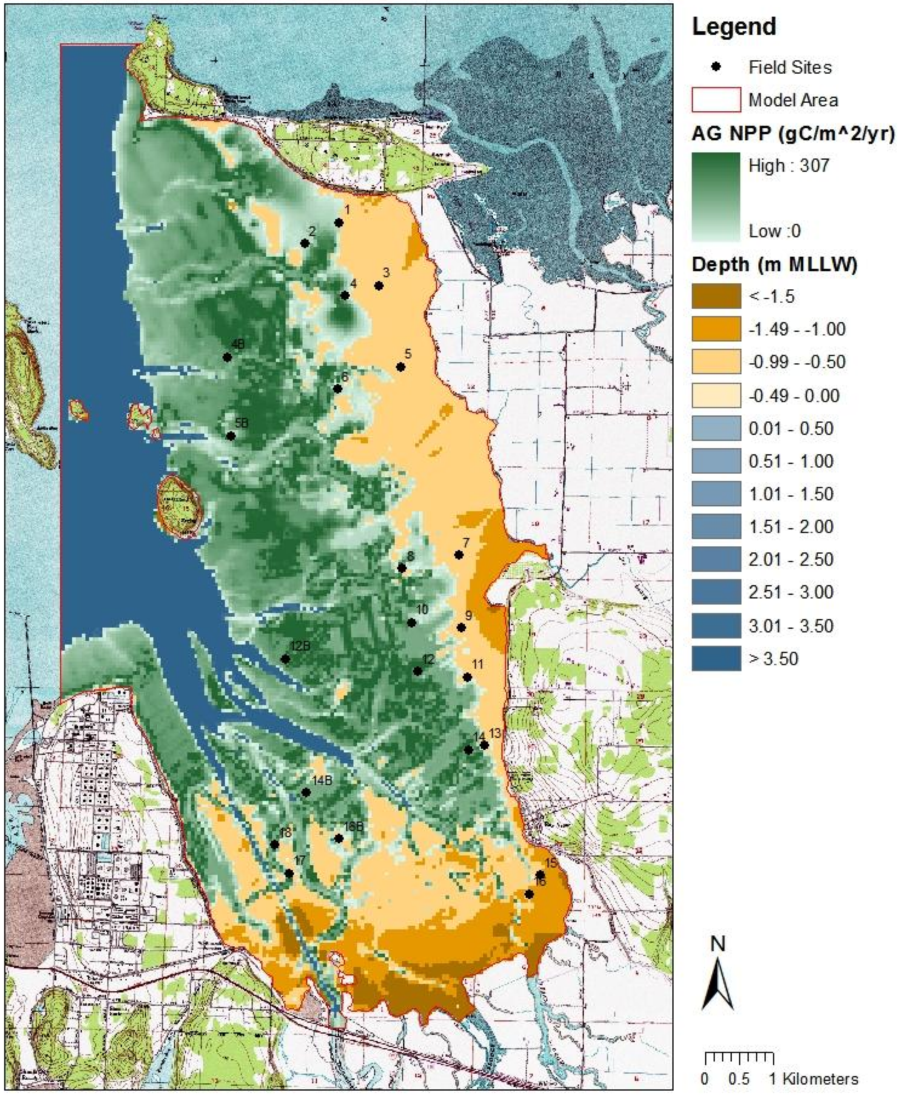


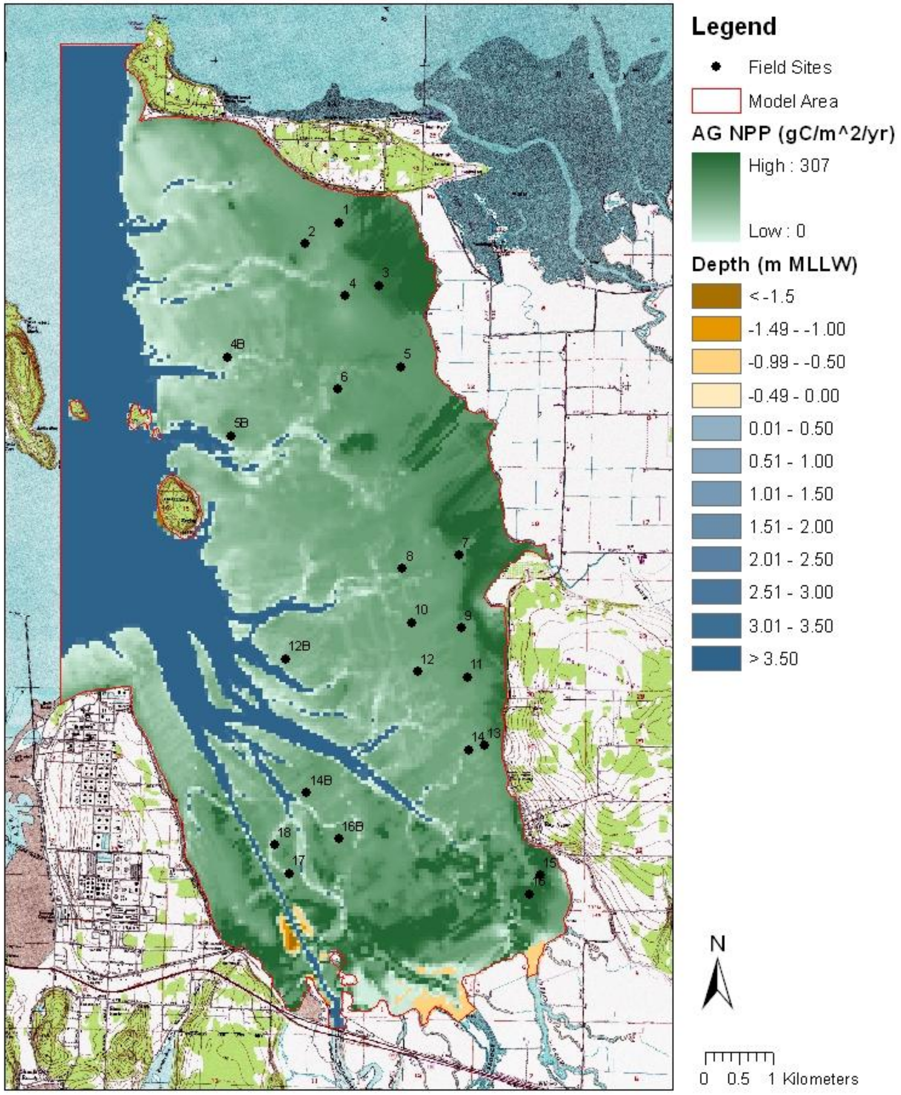
Total annual above-ground NPP (mt C)
9000
8500
8000
7500
7000
6500
6000
5500
5000
2002
2027
2052
2077
2102
Year
IPCC-Low
IPCC-Mid
IPCC-High
IPCC-High-NoMin
IPCC-High+Ice
Rahmstorf-Mid
Rahmstorf-High
NPP-Reduction



North Fork
South Fork
Bay Fringe high
Bay Fringe low
Stilly high
Stilly low
Outlet x-section area (m²)
0.1
1
10
100
NF: y = 0.52x^0.98
R² = 0.69
SF: y = 0.80x^0.96
R² = 0.82
BF: y = 0.09x^1.03
R² = 0.58
SH: y = 0.78x^0.65
R² = 0.66
SL: y = 0.12x^1.21
R² = 0.76
0.88-1.56 m NAVD88
1.66-2.22 m NAVD88
2.26-2.92 m NAVD88
Outlet width (m)
high: y = 0.60x^1.24
R² = 0.82
med: y = 0.28x^1.20
R² = 0.77
low: y = 0.07x^1.16
R² = 0.76

Indicators of marsh erosion from sediment starvation resulting from river distributary blockage by dikes. Marsh pedestals in the Skagit bay-fringe marsh: knee-high (30-40 cm), covered with *Carex lyngbyei* (sedge). Lower elevation matrix is low density *Schoenoplectus americanus* (American three-square). Photo taken in autumn with senescing vegetation.

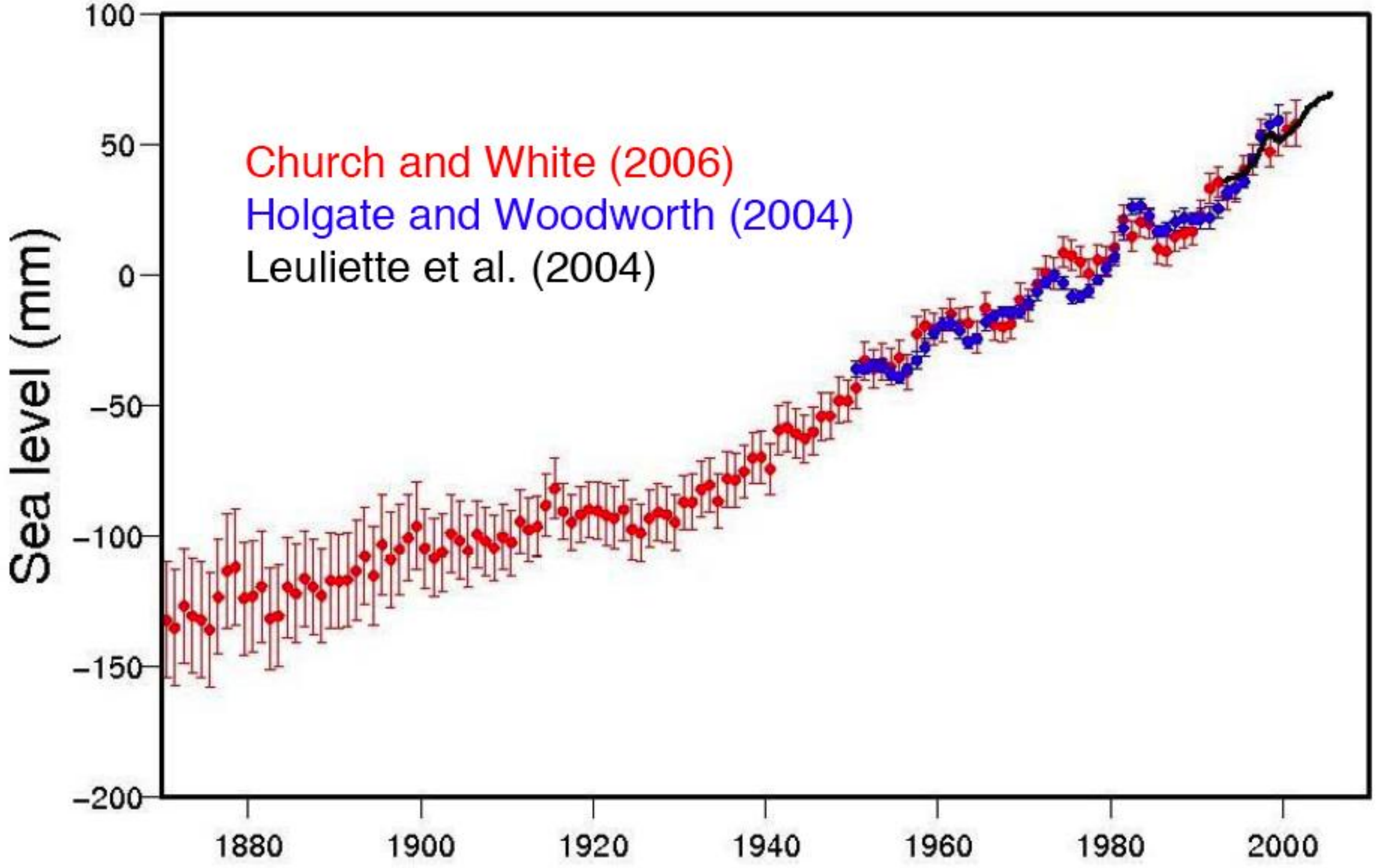




2002 2102

1.27 meter increase in 100 years

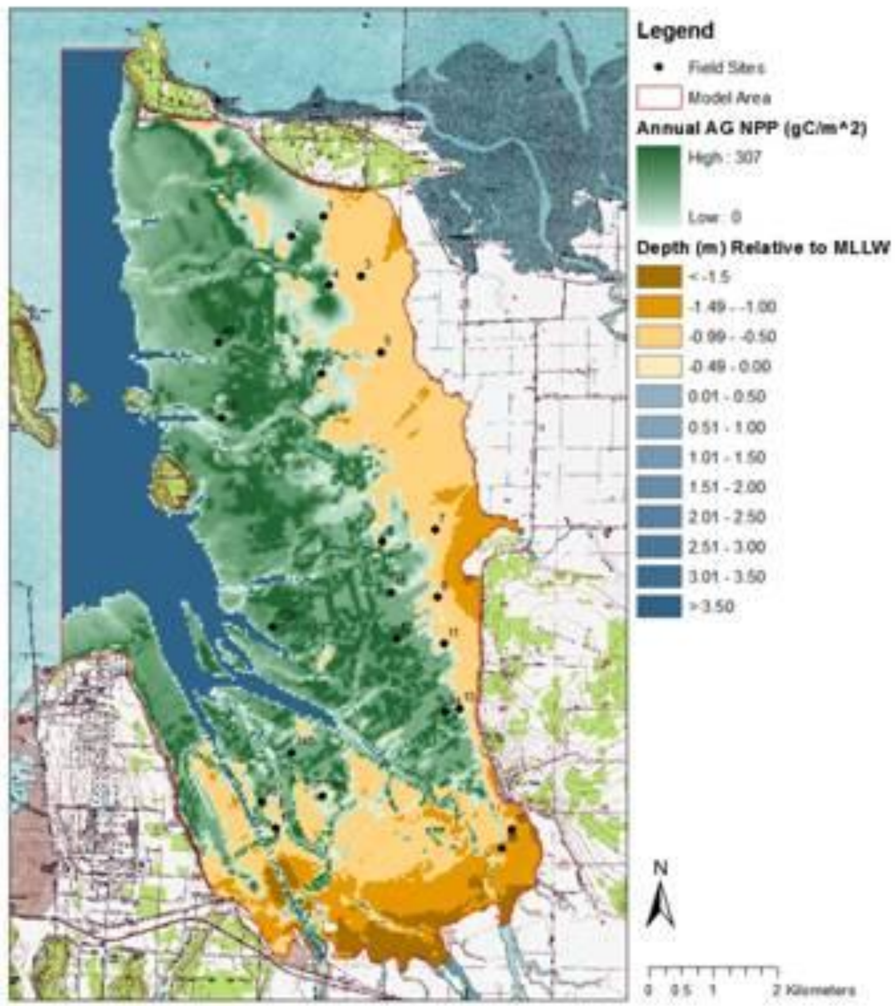
Observed global mean sea level rise

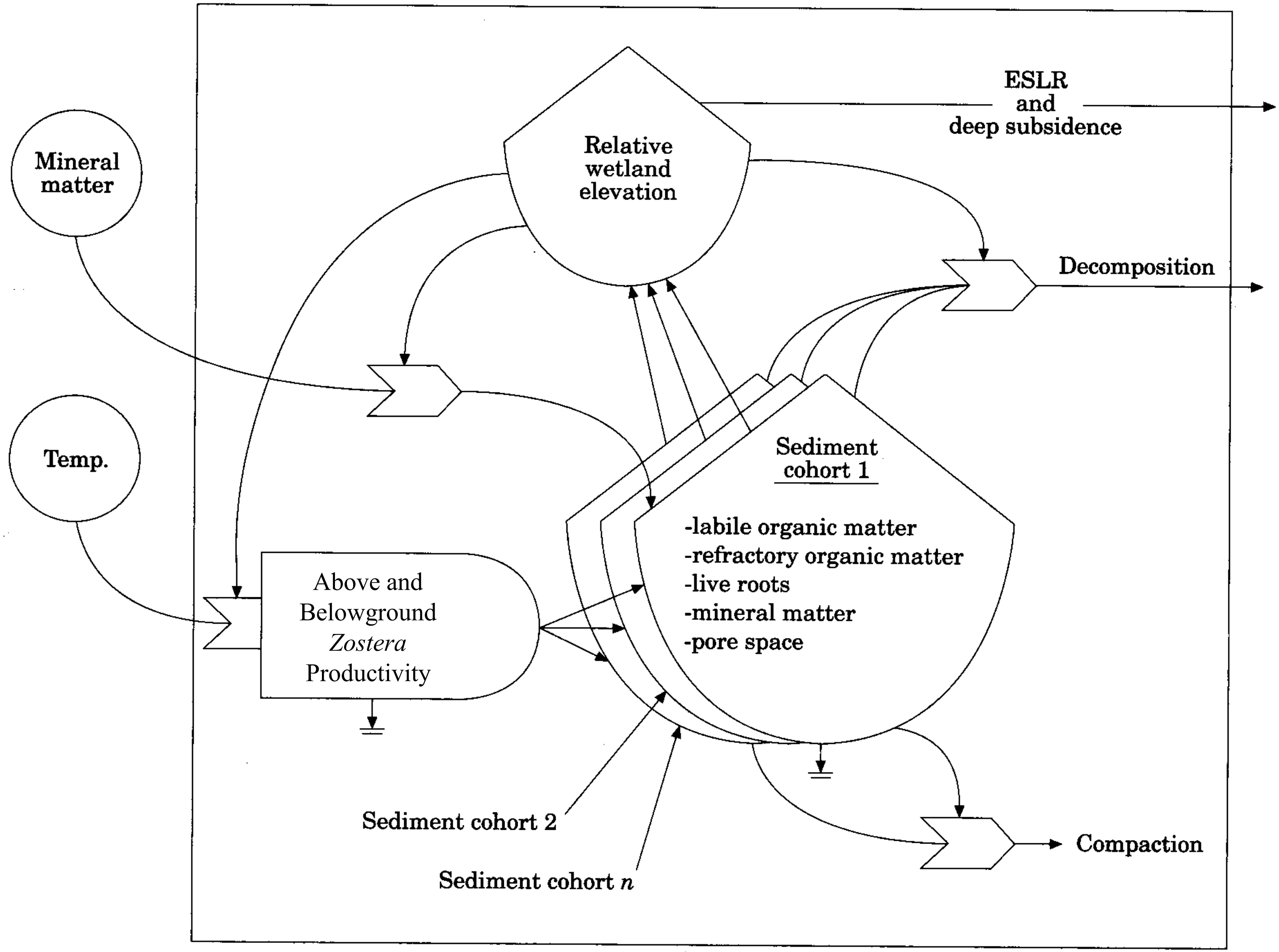


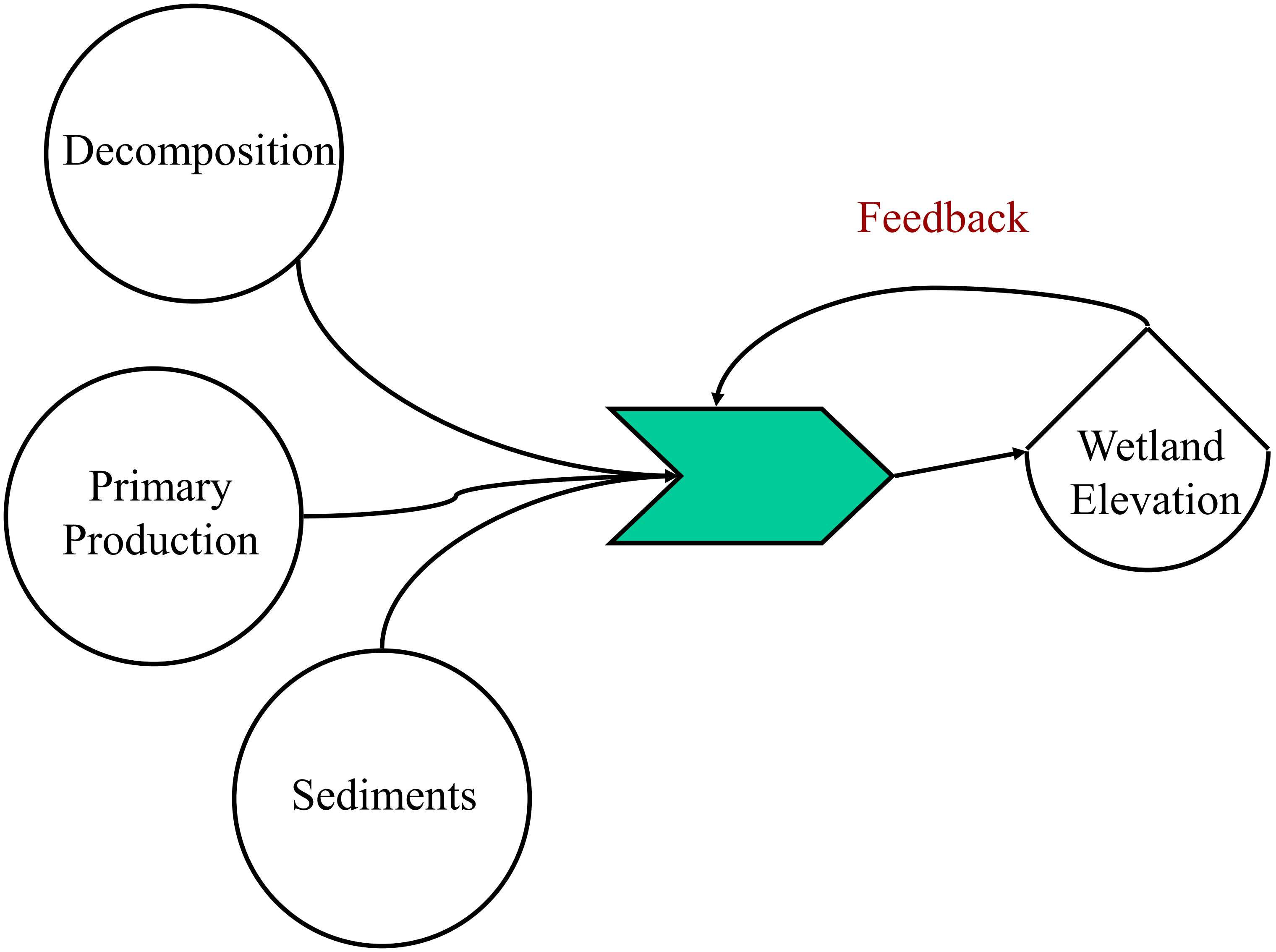
Setup and Testing of Sediment Model

- Assumptions
  - One class sediment
  - Fine suspended sediment only (no bed load)
  - Sediment discharge from Skagit River only
  - Sediment concentration at open boundaries set to zero
  - No bed sediment erosion (for testing purpose)
- Parameterizations
  - TSS concentration at Skagit River = 100 mg/L
  - Sediment settling velocity = 0.05 mm/s
  - Critical shear stress for deposition = 1 x 10^{-5} N/m^2
  - Critical shear stress for erosion = 1 x 10^{5} N/m^2

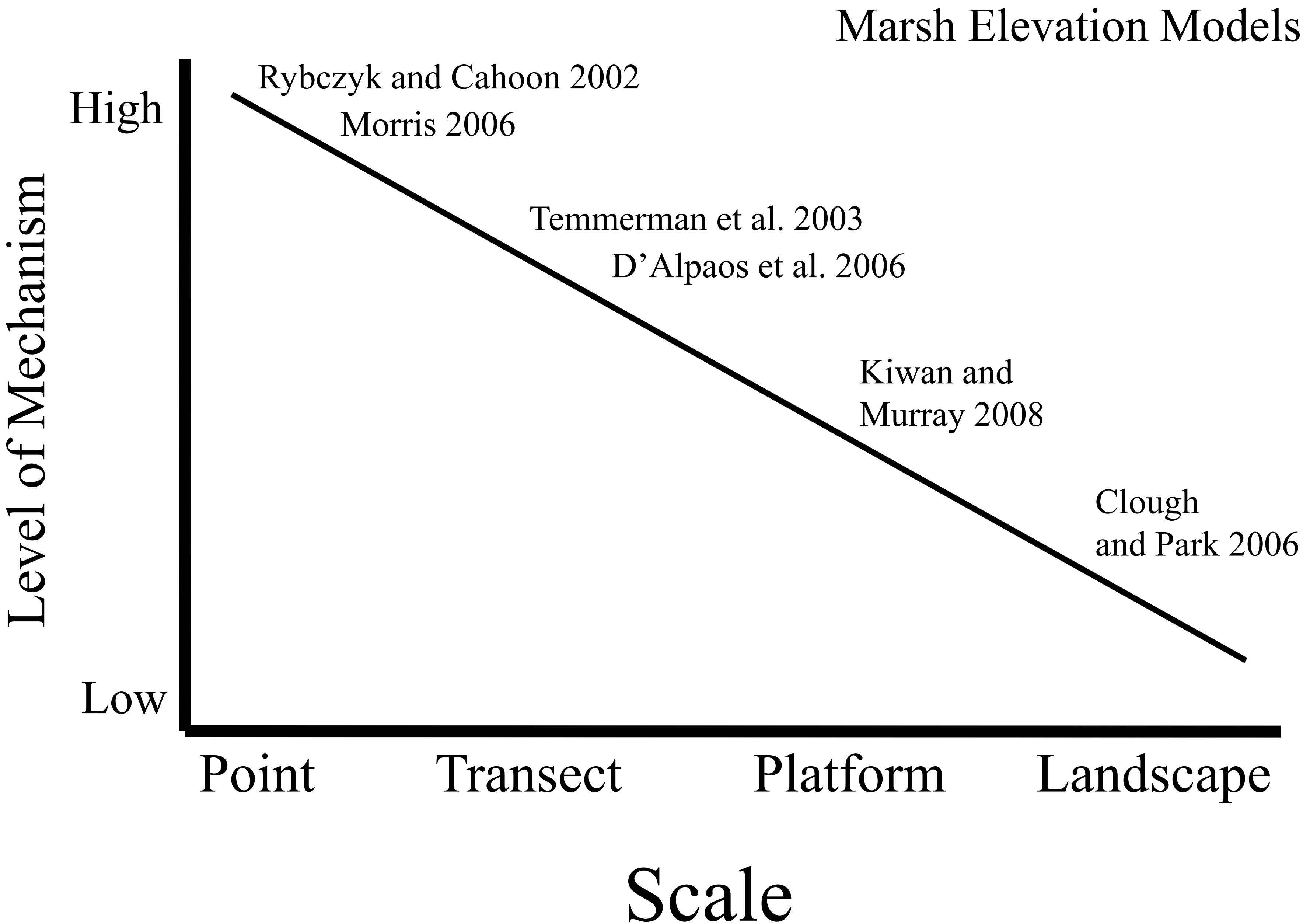
- 3000 ha intertidal eel grass
- - 3.0 - + 0.75 m MLLW




Mineral matter
Temp.
Relative wetland elevation
ESLR and deep subsidence
Decomposition
Above and Belowground *Zostera* Productivity
Sediment cohort 1
-labile organic matter
-refractory organic matter
-live roots
-mineral matter
-pore space
Sediment cohort 2
Sediment cohort *n*
Compaction



Decomposition
Primary Production
Sediments
Feedback
Wetland Elevation



Marsh Elevation Models
High
Low
Level of Mechanism
Rybczyk and Cahoon 2002
Morris 2006
Temmerman et al. 2003
D'Alpaos et al. 2006
Kiwan and
Murray 2008
Clough
and Park 2006
Point
Transcect
Platform
Landscape
Scale