Oysters, biogenic carbonate production and shell management in estuaries: it's a matter of two reference points.

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with thanks to:

Eric Powell (USM), Tom Soniat (UNO), John Klinck (ODU), Jim Wesson (VMRC), Missy Southworth (VIMS), Juli Harding (VIMS & CCU), and colleagues at IMARES, Yerseke, Netherlands: Brenda Walles, Tom Ysebaert and Karin Troost.

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Outline of talk

- Evolutionary biology of bivalves in general and oysters in particular.
- An introduction to the Taphonomically Active Zone (TAZ) where carbonate is added through growth, moves to the shell pool through mortality, possibly lost through burial, and feedback loops at various scales.
- Shell in moderating the sediment water interface: why do we care?
- Carbonate production: quantitative prerequisites and rising sea level.
- What is happening in local (Chesapeake Bay) oyster populations.
- Chesapeake Bay shell and alkalinity budget: a work in progress.
- Work beyond the Bay – the Gulf coast and Netherlands.
- Concluding thoughts on oyster and shell management.

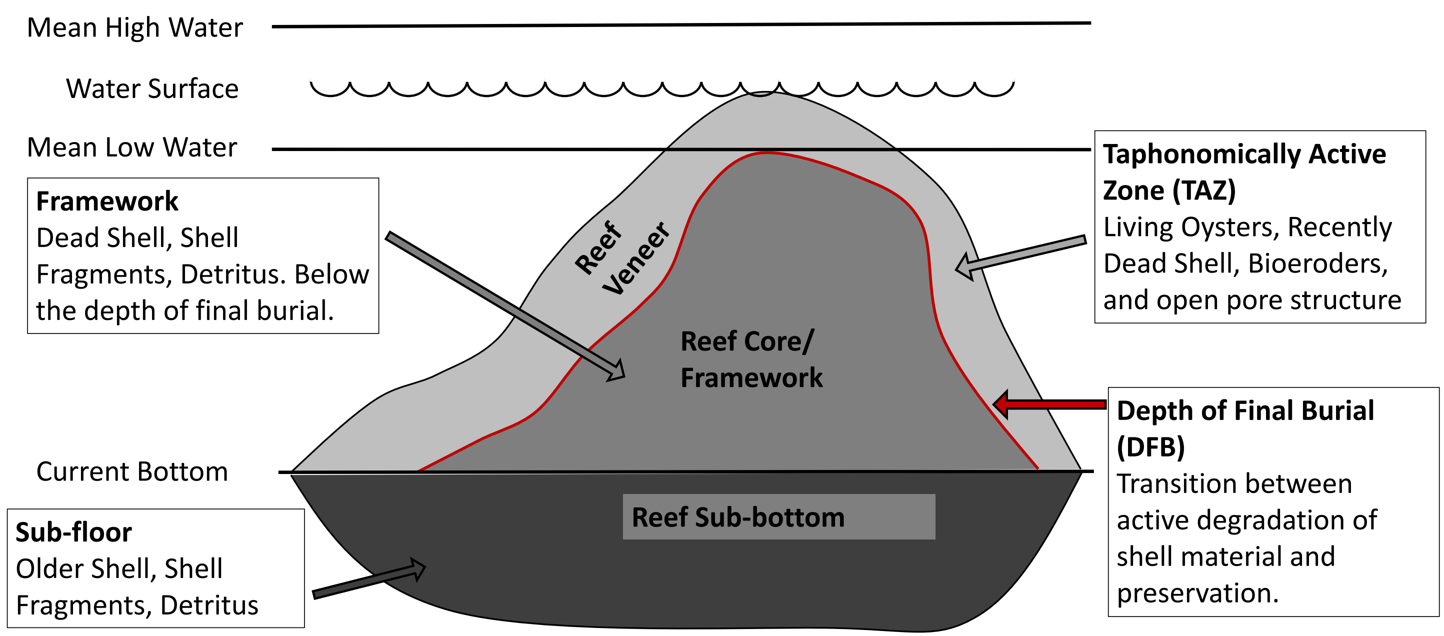
Evolutionary biology of bivalves, and oysters in particular

- The molluscan lineage extends back to the late Cambrian.
- Of the 80,000 or so species of molluscs about 8,000 are bivalves.
- Vast majority conform to typical “clam” form, bury below sediment water interface. They have foot (digging) and siphons (water passage). Burial provides protection from predation and stable habitat.
- Minority adopted differing forms, losing various “body parts”: scallops swim, oysters and mussels generally live above the sediment-water interface. Predation problems? Living intertidally helps – also presents requisite need for these species to ***create their own habitat***. They live gregariously in reefs and are foci for ***biogenic carbonate production***.

Oysters produce lots of carbonate in big "chunks", and some of it stays around for a long time in the form of shells: as an example consider a Pleistocene reef on the shore of the Piankatank River. Note the size of the shells – this is important in terms of both live demographics and persistence of the shell post death .

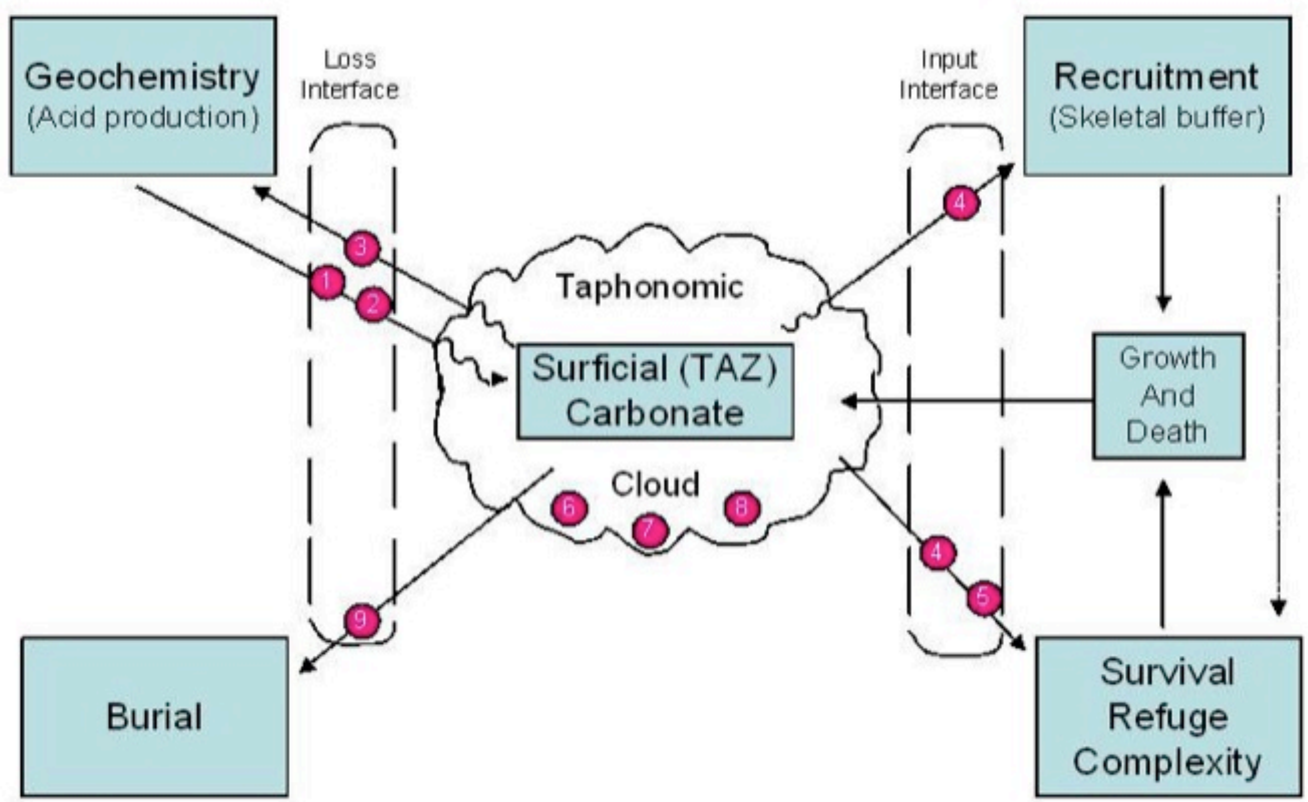
Graphics: Roger Mann, VIMS

How does reef structure work? Carbonate production through growth, contribution to the shell pool through mortality, the role of the Taphonomically Active Zone (TAZ), burial, exhumation, feedback loops, and why do we care?

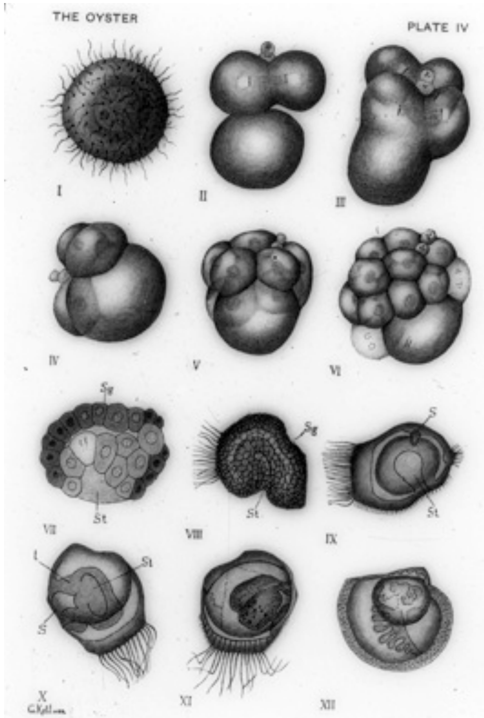


Graphic from Waldbusser, Powell and Mann. (2013) Ecology 94(4): 895-903

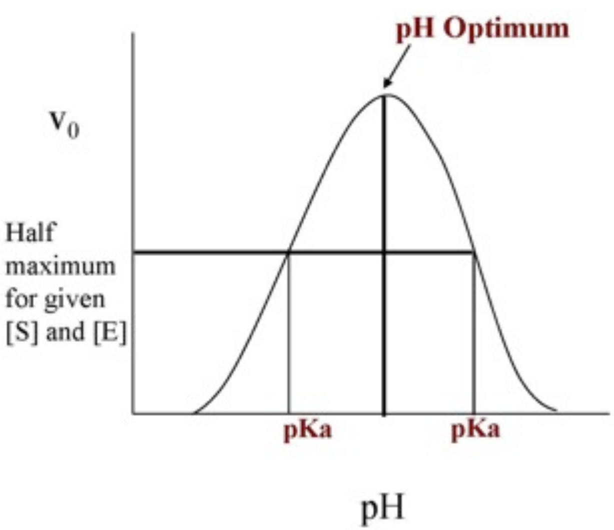
Think about oyster shell as dynamic habitat and chemical moderator rather than just living organism – then proceed to a consideration of the factors controlling the rate of carbonate addition and loss in an estuarine oyster reef system.



Graphic courtesy of Eric Powell, USM



Graphic: W.K. Brooks (1905) The Oyster



Shell in moderating the sediment water interface: why do we care?

- Water column organics fall to the interface where they produce acid that is neutralized by carbonate.
- The literature portrayal: below the interface as a region of carbonate dissolution "attacking" shells of metamorphosed molluscs… but it is much more.
- The typical invertebrate larval egg is between 75 and 300 microns diameter.
- The swimming ciliated form approximates 300-1000 microns at metamorphosis: max size is all about Reynolds numbers and viscosity.
- Its all about surface exchange properties, and enzyme pH optima.
- This implicates all ciliated invertebrate larvae, and thus all estuarine food chains.

Carbonate production: Quantitative prerequisites

recall the sequence:

Recruitment ➔ Growth ➔ **M**ortality ➔ accretion of **S**hell base

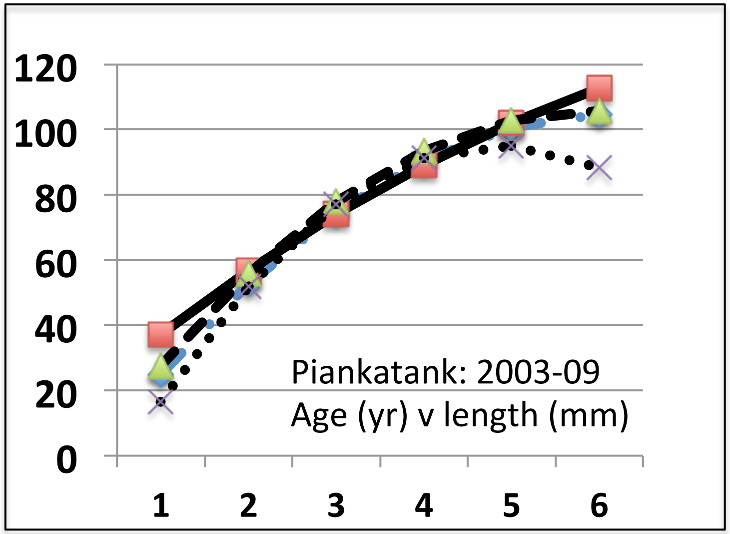
- **Biological reference point #1:** dN/dT $\geq$ 0 or R $\geq$ F + M
- **Biological reference point #2:** Shell: dS/dT $\geq$ 0 where addition to S is by mortality and subtraction from S is by degradation processes.
- What is the requirement for dS/dT to accomplish stability of habitat? **Net** accretion rate is set over evolutionary and geological time frames as the rate of sea level rise. Anything else and intertidal reefs would not form. This rate is non negotiable and ≈ 3.5mm/yr.
- But this is NOT the required shell production rate because shell is lost at about 30% per year (salinity variable).
- So the shell (**gross**) production rate must serve a reef accretion rate of 4.55 mm/y or 4.55 L/m^2/y (10L = 1 cm thick layer). Between 20-50% of this volume is shell, (although in recent publications I have not always corrected for this) ≈ 2.5-6 kg wet shell /m^2/y.

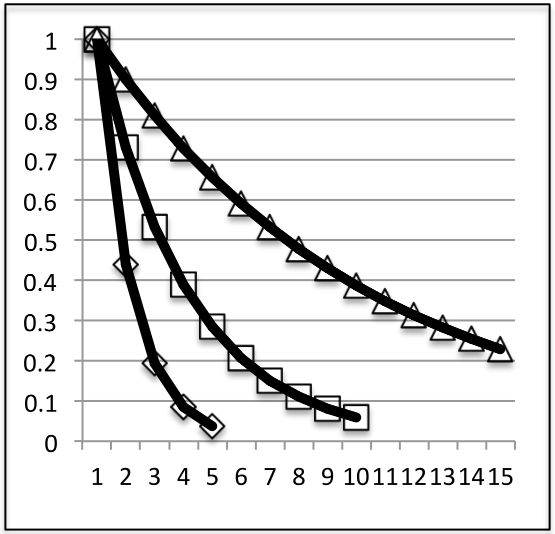
Carbonate production: Quantitative prerequisites (continued)

again, recall the sequence:

Recruitment ➔ Growth ➔ **M**ortality ➔ accretion of **S**hell base

- What demographic will produce 4.55 $L/m^2/y$ of reef accretion?
- We can estimate this if we know rates of **R**ecruitment (from quantitative sampling), Growth (challenges with non isodiametric growth, but these can be overcome) and **M**ortality (the interesting parameter).
- Using extant growth data investigate mortality and recruitment rates in virtual populations that generate the base 4.55 $L/m^2/y$.





Mortality rate options: constant rate or age(size) specific.

- Assume high mortality until a refuge size from crab predation (approximately 45 mm, Eggleston, 1990, JEMBE 143).
- Hoenig (1983, Fish Bull 82) – constant rate based on estimate of longevity.
- Mann et al (2009, ECCS 85) reconstructed both the demographic and the shell budget based on a "Hoenig" approach.

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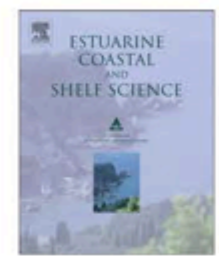

Reconstructing pre-colonial oyster demographics in the Chesapeake Bay, USA

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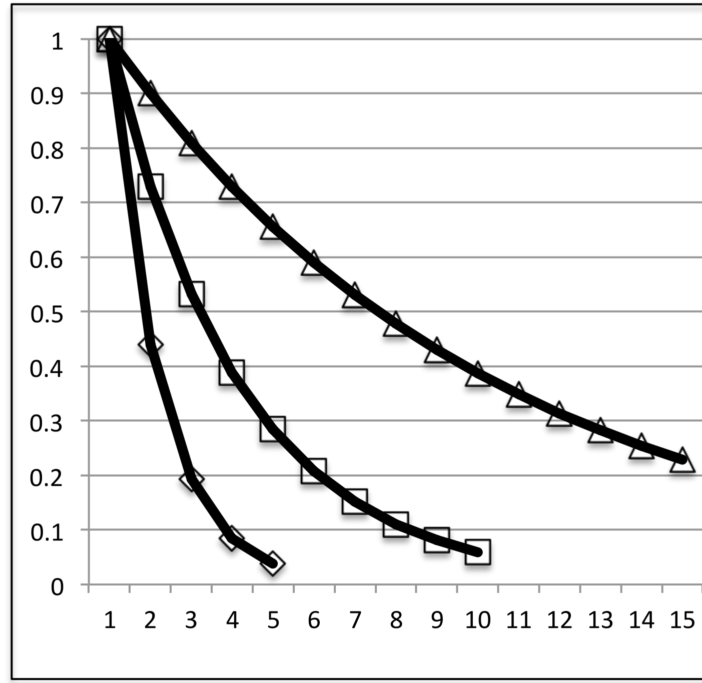
Constant mortality rate option

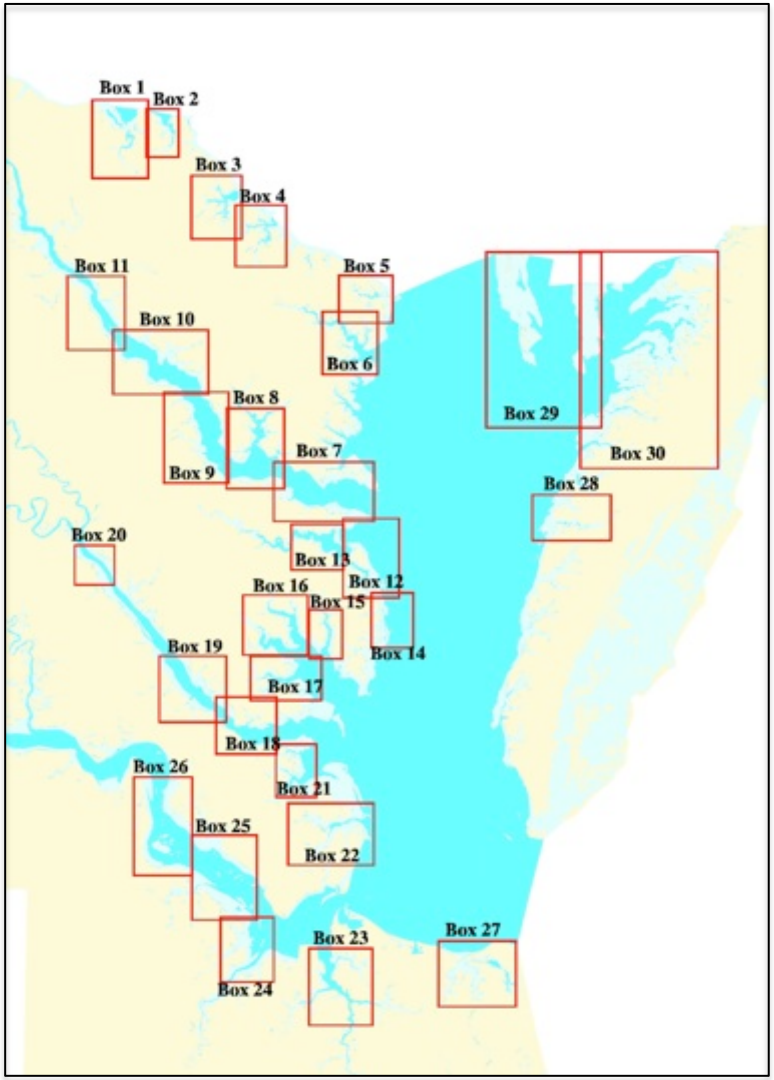
- Need longevity estimates – literature values 5-15 years, although De Broca (1865) at 450 mm SL may be as high as 19 years using growth data from Harding et al (2008 JSR 27).
- Few large individuals in demographic, requires sustained high recruitment to provide mid size (in the graphic) individuals in sufficient abundance to sustain the habitat. Remember the Pleistocene examples.



Mann et al (2009): Scenarios supporting equilibrium accretion rates (**all shell, uncorrected for sediment inclusion**) for defined max age. M: annual mortality rate (0.0 =no mortality, 1.0 =all died). N: density age 1 oysters (n per m^2) required at defined max age and mortality rate.

	Maximum Age (yr)												
	3	4	5	6	7	8	9	10	11	12	14	16	19
M	0.78	0.65	0.56	0.49	0.4	0.35	0.31	0.27	0.24	0.21	0.16	0.125	0.1
N	77	63	52	44	35	29	24	20	17	14.5	11	8	6

Example from Virginia oyster populations?



- Public or "Baylor" oyster grounds <u>in Virginia</u>. NOT 243,000 acres (98,000 hectares) as originally surveyed, probably <10,000 (4046 hectares) in Bay.
- Surveyed every year since 1998, some back as far as 1993, by quantitative methods.
- Abundance, demographic, shell resource as both "brown" in the oxic layer (TAZ) and black (buried).
- Disease status.
- ***<u>MD DNR does a parallel survey.</u>***
- ***<u>2011 onwards - single bay wide stock assessment.</u>***
- ***<u>We are working towards shell budgets bay wide.</u>***

Graphic: http://www.vims.edu/research/units/labgroups/molluscan_ecology/restoration/va_restoration_atlas/index.php

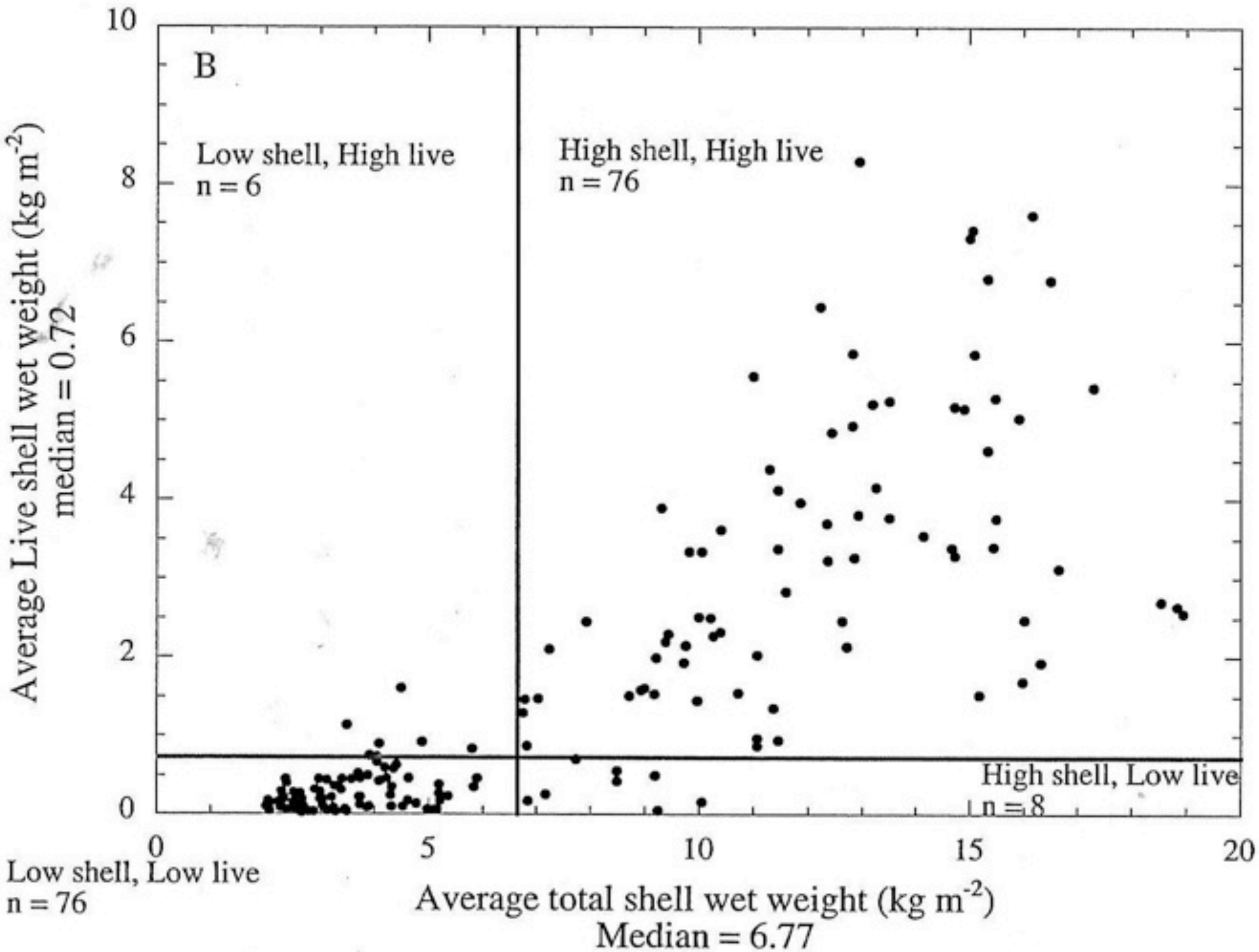
VA fall 2011, 1600 stations, 175 reefs, 8883 acres, 3594 hectares

- *By number: 2.03×10^9 = 2.08×10^8 YOY + 1.67×10^9 age 1 + 1.62×10^8 age ≥ 2*
  - *YOY drive the number, it can vary by 10X in successive years, 2011 was a low recruit year.*
- *Dry biomass: 832 metric tonnes = 15 YOY + 654 age 1 + 162 age ≥ 2*
- **Brown shell (TAZ) = 164 million liters, 96,300 metric tonnes (sp. gr. = 0.6)**.
- **"Grand mean" = 4.56L m^{-2} shell or a uniform layer ≈ 0.5 cm thick dependent on open space in shell matrix** (care - this is a "pictorial number", - all grand means have scale problems).
- James River dominates the summary:
  - 76.5% of area, *90% by number, 91% of biomass,* 71% of brown shell.
  - *Within James, seven reefs, 125 hectares total, 5.01×10^8 oysters.*
  - *= 28% by number in 4.6% of the area within the river.*
  - *= 21.7% by number in 3.5% of the entire Virginia survey area.*
  - **TAZ brown shell = 16.6 – 29.6 L m^{-2} ≈ 4-6x that of "grand mean".**
  - Accreting populations are characterized by high shell and high biomass.

What does the demographic and mortality look like on these productive reefs (25-30% of population in 4.6% of total reef area)? Follow the diagonal…

	year											
	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Y-O-Y	***79***	167	167	161	***539***	391	170	64	112	138	896	446
1	95	***56***	109	114	46	***51***	136	162	64	77	78	110
2	57	33	***37***	49	15	10	***28***	78	88	56	42	37
3	10	7	10	***10***	5	2	6	***11***	25	18	11	13
4	1	0	1	0	***1***	0	1	1	***3***	4	4	3
sum	242	263	323	336	604	454	342	316	293	292	1031	609

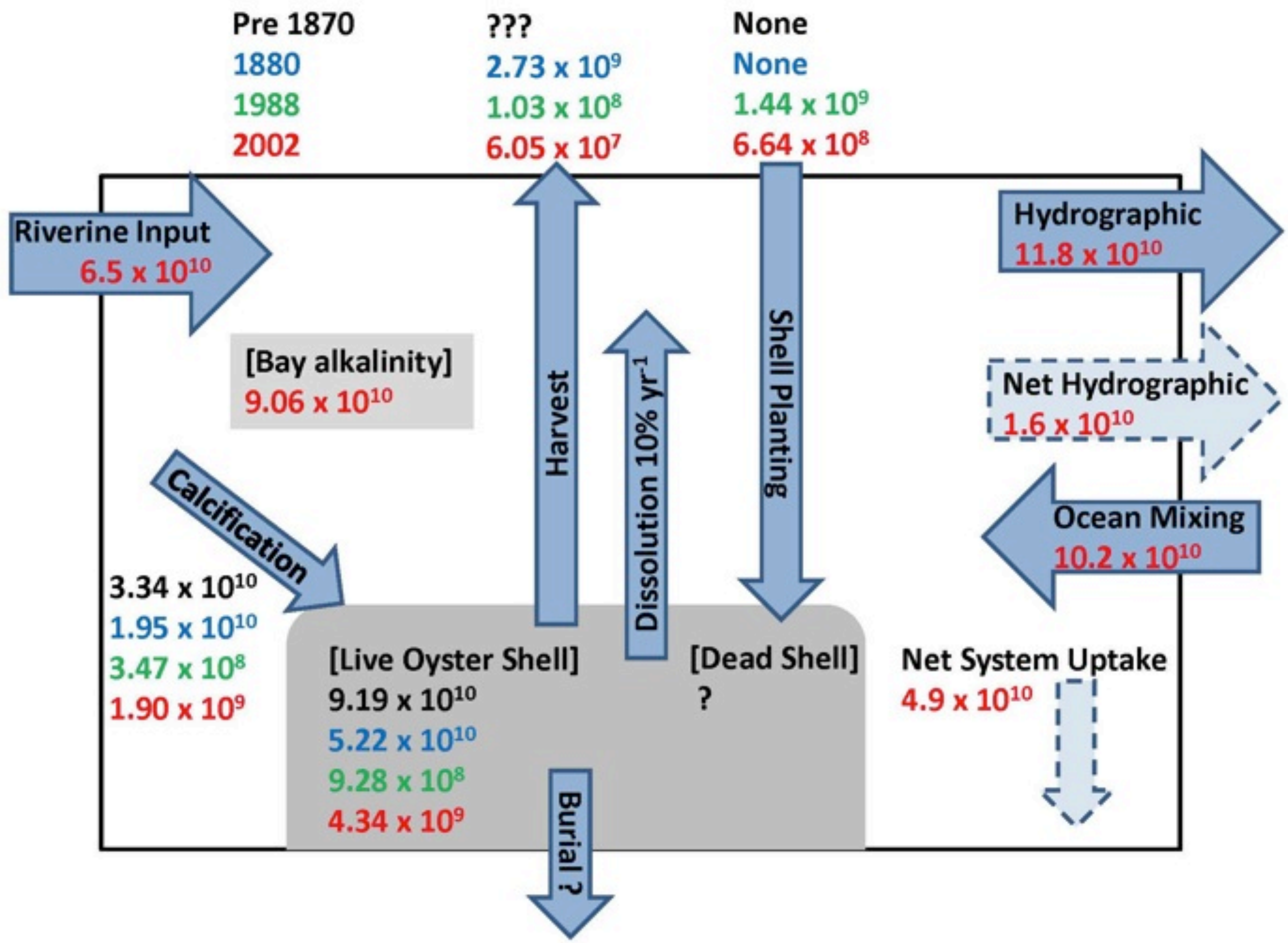
- Moon Rock in James River. Truncated age structure. Few reach >100mm SL.
- The shell budget is driven by age classes 2-3.
- A book-keeping approach can be applied - this reef accretes > 4.55 $L/m^2/y$.
- High recruit and high mortality **<u>unlike</u>** what you see in MD.



A plot of all the surveyed reefs in the James over a multi-year period produces this – reefs congregate as (high shell+high live) accreting and stable reefs, or (low shell+low live) reefs that fall below accretion baselines and exist as patches. Reefs do not move from one category to the other - this is a restoration challenge.

Graphic from Mann et al (2009), J. Shellfish Research, 28(2): 1-30

Chesapeake Bay Shell/Alkalinity Budget



So shell is important – what is the situation like across the bay as a whole?
All unit in Moles or mole equivalents (Waldbusser, Powell and Mann (2013) Ecology).
We use land-ocean interaction coastal zone (LOICZ) box model of Webb and Smith (1999).
Note the reduction in alkalinity "reserve" in 140 years.

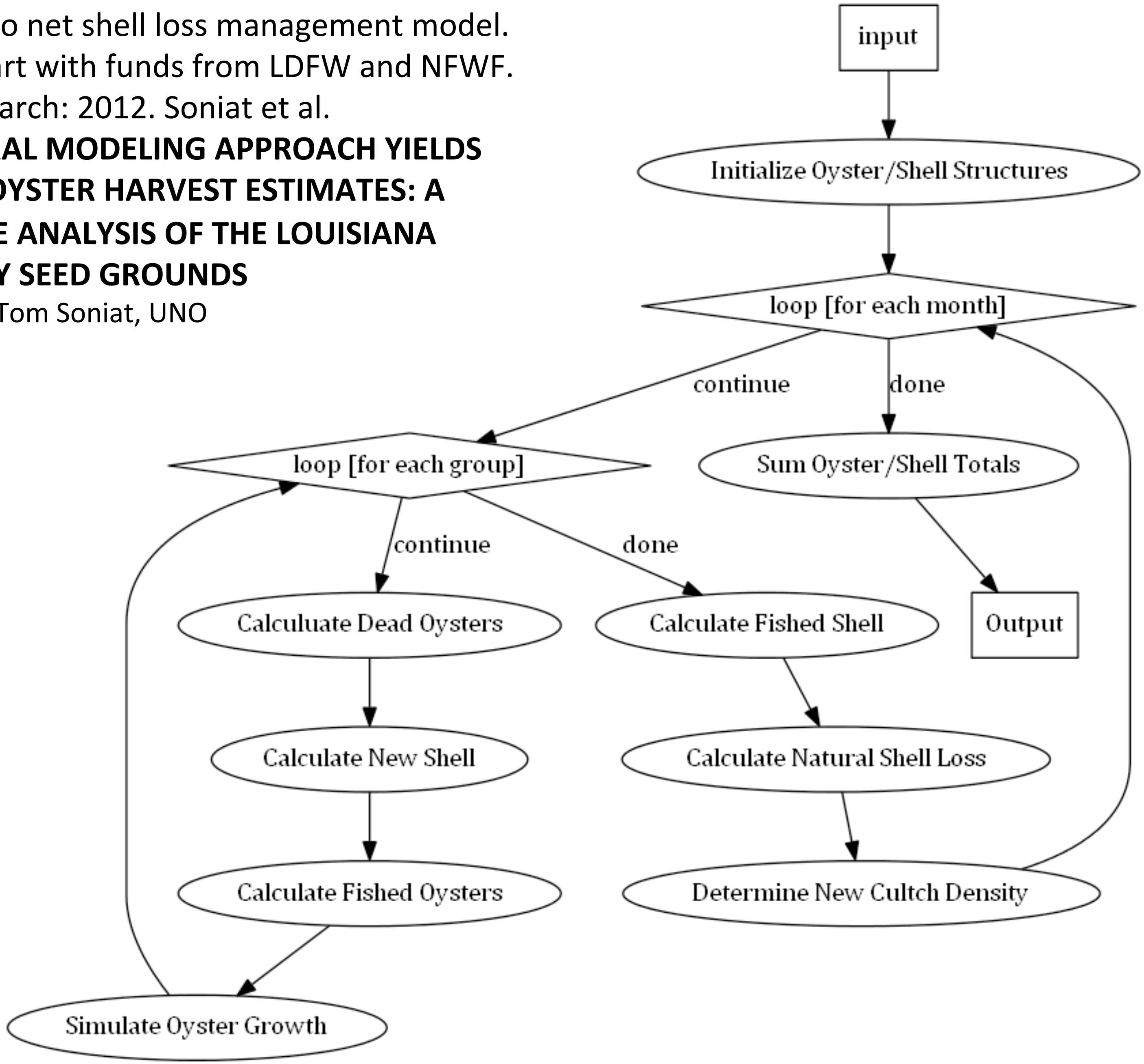
Summary so far….

- We need to consider TWO reference points
  - Biological reference point #1: $dN/dT \geq 0$ or $R \geq F + M$
  - Biological reference point #2: Shell: $dS/dT \geq 0$ where addition to S is by mortality and subtraction from S is by degradation processes.
- Maintaining shell substructure and all the services it provides is critical. It is about recruitment, growth and mortality – we cannot simply remove adult product and expect the base to persist.
- We can manage for this option by calculating what proportion of the population is required to sustain the shell input – rotation works here (Harding et al, 2010. J. Shellfish Res. 29(4):867-888) – more later.
- To emphasize the point about recruitment and longevity I offers examples of (a) where no net shell loss is a management directive in Louisiana, and (b) where reefs clearly are accreting – an invading oyster population in the Oosterschelde in the Netherlands.

The **Louisiana** no net shell loss management model.
Supported in part with funds from LDFW and NFWF.
J. Shellfish Research: 2012. Soniat et al.

A SHELL-NEUTRAL MODELING APPROACH YIELDS SUSTAINABLE OYSTER HARVEST ESTIMATES: A RETROSPECTIVE ANALYSIS OF THE LOUISIANA STATE PRIMARY SEED GROUNDS

Graphic courtesy Tom Soniat, UNO



Data entry and model access: www.oystersentinel.org

Netherlands collaborative studies.
IMARES, Yerseke.

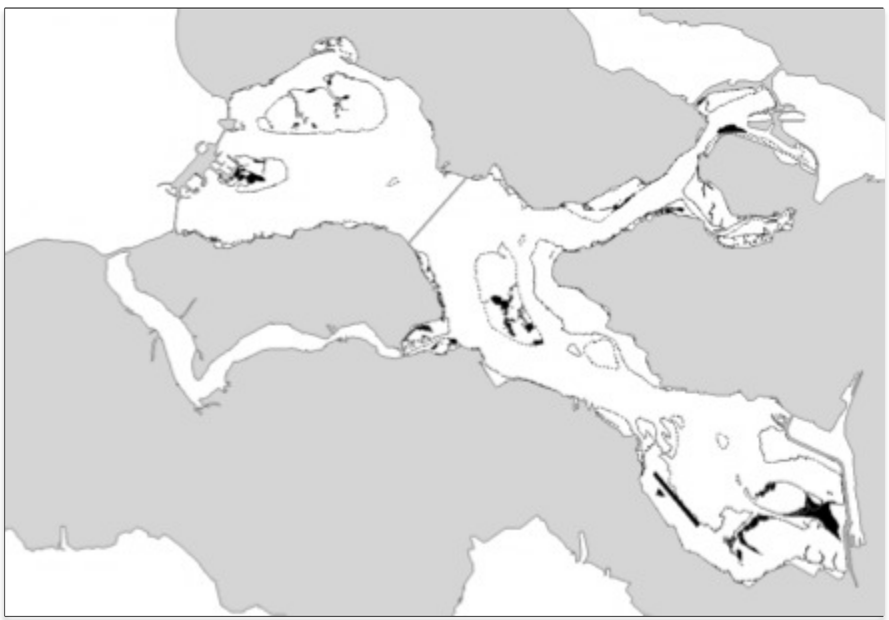
To reinforce the points I have made about recruitment and longevity contributing to a positive accretion rate I offer an example of an invading population of oysters: *Crassostrea gigas* in the Oosterschelde in the Netherlands. Originating from a 1964 introduction and proceeding with modest recruitment but excellent growth and longevity in the absence of an apex predator.

Invading populations of *Crassostrea gigas* in the Oosterschelde, the Netherlands: unexploited, essentially free of disease, and arguably lacking an apex predator when they reach refuge size

Image: Roger Mann 2011

The Oosterschelde estuary: dominated by human induced erosion after constructing a storm surge barrier (1987): **0.50-1 km^2** tidal flat area loss each year. *Crassostrea gigas* arrived in 1964, setting the time baseline.

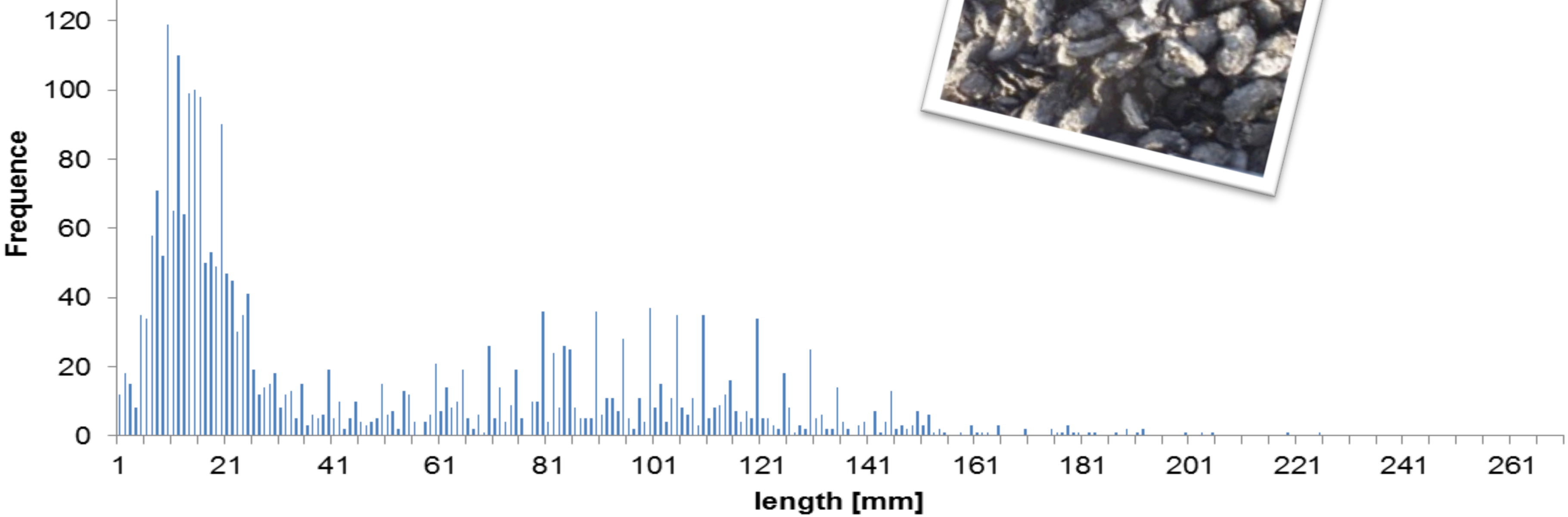
351 km^2 tidal basin , *118 km^2 tidal flats*
Tidal range of 3.25 m, salinity 30 psu, deep gullies and shallow water areas, artificial rocky shores (dikes), and a huge storm surge barrier



Graphics: Tom Ysebaert, IMARES

Data collection: October-November 2011

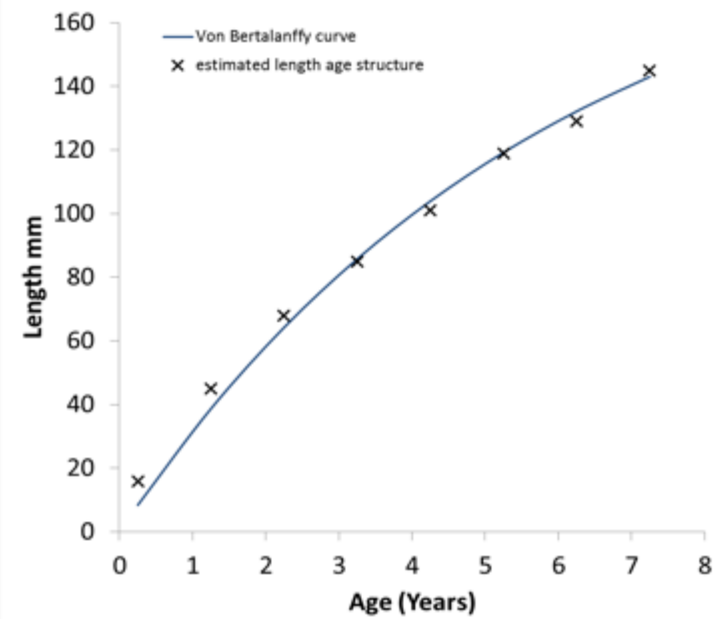
10 randomly fixed quadrats/reef
Measure SL (mm) oysters (n=2640)
Subsample for further analysis: weight, volume, etc., conversion functions. We use these in a later calculation…..



Graphics: Brenda Walles, IMARES, Netherlands

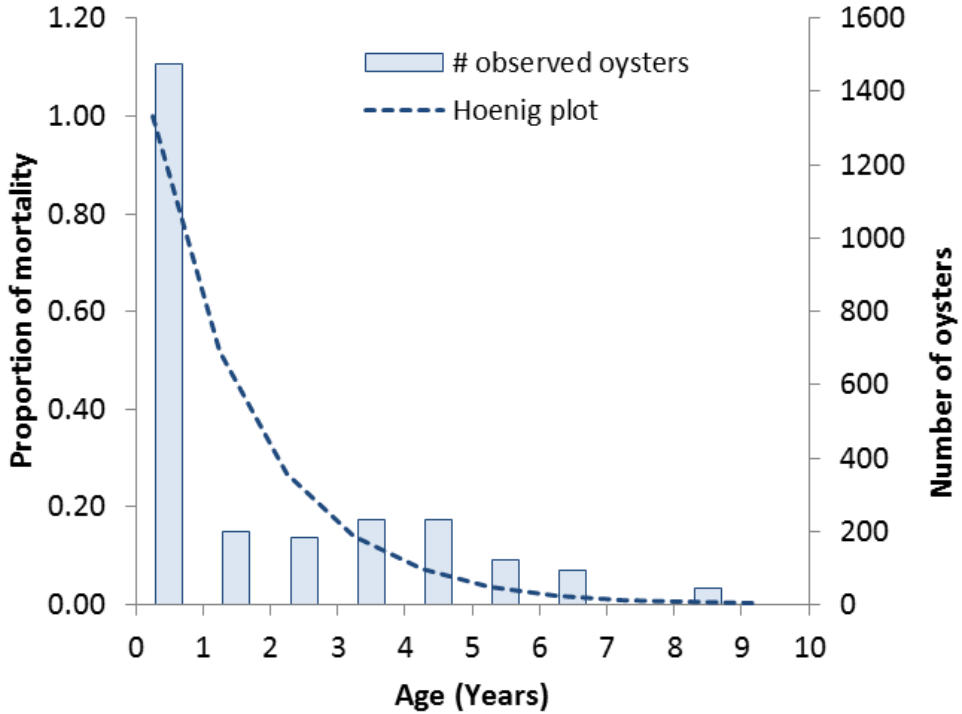
Estimate age structure as a series of Gaussian distributions (Bhattacharya 1967), then fit a von Bertalanffy. Confirm by annual growth rings (B. Walles, unpublished, dissertation).

age	mean length mm
0.25	16
1.25	45
2.25	68
3.25	85
4.25	101
5.25	119
6.25	129
7.25	145
L_∞	**202**



Graphics: Brenda Walles, IMARES, Netherlands

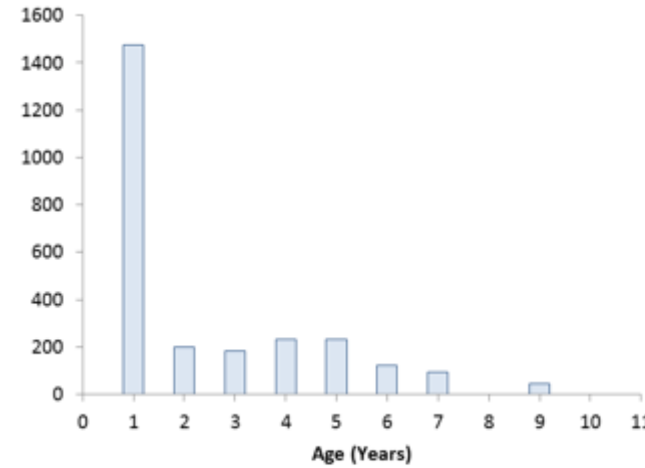
What if.. (1) we recast the length demographic as age – will it give constant or age dependent mortality?.. And (2) can estimate shell addition to reef base structure from such a mortality structure?



The demographic suggests age (size) specific mortality with two phases: High mortality <45 mm (<1.33y) and Low mortality >45 mm (.1.33y).

Graphics: Brenda Walles, IMARES, Netherlands

Consider the following: If the age dependent mortality is correct, and we make a virtual population that has survival demographic that approximates the multi-year class age demographic of the observed population, then will the estimated reef accretion match that observed in the field?



To estimate shell addition…..

Mortality rate ('virtual population")

Use length: weight: volume conversions

Weight of the shell per year class ($w = 0.0002\ L^{2.8258}$, $R^2=0.96$)

Proportion shell-mud (0.35)

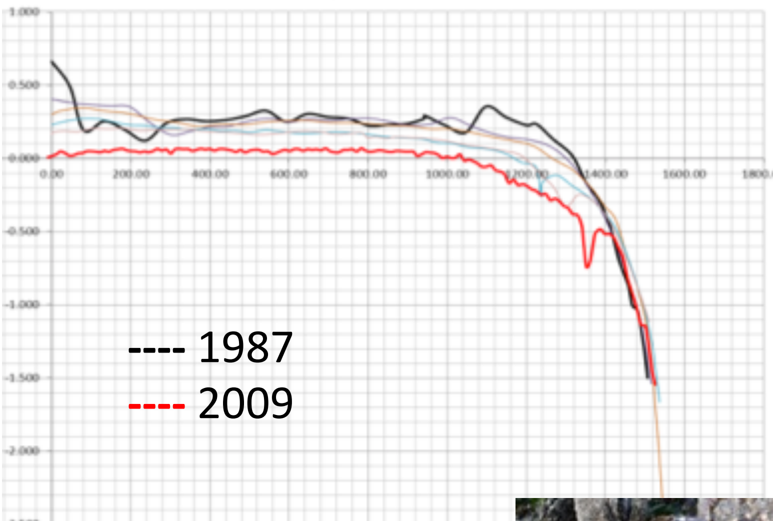
Est. reef accretion **10 – 17 mm**/y (9.5 -16 kg shell /m^2/y)

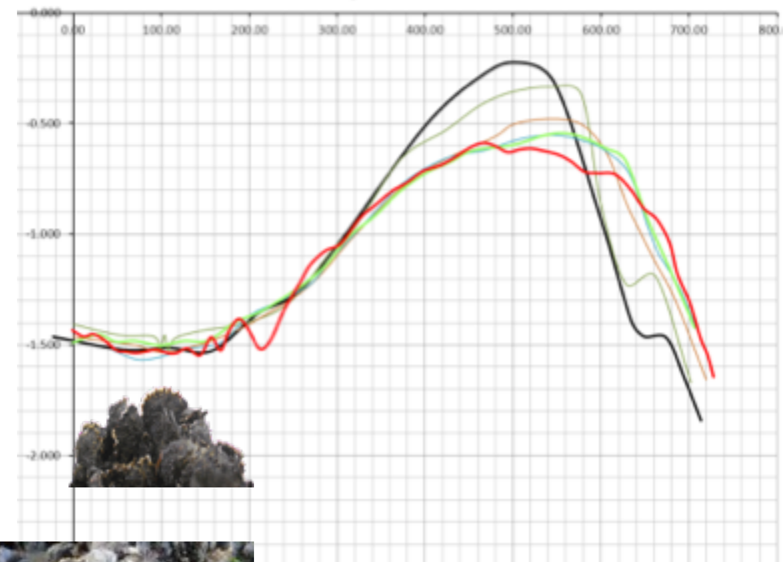
This is in the order of the erosion rate of the tidal flats

In 40 years this is **40 – 65 cm** accretion: dig a hole to test it!

This fits with our observation in the field

C. gigas in the Oosterschelde accrete and maintain persistent reef structures. Left graphic- loss in elevation of intertidal flat 1987-2009 in the absence of reefs. Right graphic – Reefs maintain elevated structure with expanding footprint in same time frame despite surrounding loss of intertidal flat elevation. Oysters use an age dependent mortality rate with survival to large individuals that subsequently make significant contributions to the base reef structure.





Graphics: Tom Ysebaert, IMARES, Netherlands, and Roger Mann, VIMS

Concluding thoughts

- Bivalve molluscs produce vast quantities of biogenic carbonate in estuaries and coastal embayments world wide.
- A limited number accrete habitat (reefs) above the sediment water interface.
- "Evolved" accretion rates minimally track sea level rise, but can be impressively higher in exceptional circumstances.
- Shell degrades at rates set by physical, chemical and biological processes.
- This is balanced by recruitment, growth and mortality to maintain structures.
- Age structure in the populations is critical in maintaining shell addition to the underlying pool and stable reef structure. Stable structure is enhanced by feedback regulation.
- Shells are essential to alkalinity budgets in estuaries – but the "reservoir" has decreased in Chesapeake Bay in "recent" history.
- ***Restoration is about two reference points, not one, or it will fail – this is not a point of debate.***
- This is a work in progress with elements in the Chesapeake Bay (the bi-state assessment), the Gulf of Mexico (in Louisiana, discussions in Mississippi), Netherlands and planned for extension to the continental shelves.