"Cheapeake" comes from native Algonquin who called the bay Chesepiook, meaning "great shellfish bay". In the report on his 1608 exploratory voyage, Captain John Smith reported that oysters were so abundant that they "lay as thick as stones", and the reefs they formed were so large and numerous that they were hazardous to navigation. There were more sturgeon (now rarely seen in the Bay) "than could be devoured by dog or man" and "of fish we were best acquainted with stugeon, grampus, porpoise, seals, stingrays ... mullets, white salmon [rockfish], trouts, soles, perch of three sorts", along with a variety of large shellfish. [Painting by John White in 1585 of Algonquin fishing in Pamlico Sound, North Carolina] **PhySci 110 Lab week 8, 2003**

Phy Sci 110, Spring 2003 Lab Week 8 **May 20-21, 2003**

Environmental History of the Chesapeake Bay:

Using Sedimentary Cores to Test for Stages and Drivers of Ecosystem Decline

Introduction

The changing character of the Chesapeake Bay over the last several decades is evident to even casual visitors. Recreational swimming and sport-fishing for large bluefish & seabass (rockfish; both predators) were popular activities in the 1940's, with fisherman regularly catching specimens 3-5 feet in length. However, by the 1960s and 70s swimming became impossible by mid-summer due to huge blooms of stinging jellyfish, and fishermen were lucky to catch rockfish >1 foot in length; most catches were of species that had formerly been considered bait or "trash" fish (e.g. eels, menhaden). The famous blue crab (predator/scavenger) remained strong – it is described by managers as the last viable fishery in the Bay -- but levels of take have remained steady over the last 30 years only by tripling the number of traps; watermen have shifted their attention to crabs as other formerly commercial fisheries have collapsed. Moreover, fish-killing "red tides" and warnings not to eat local seafood became more common, and in 1997 foul-smelling "blooms" of the fish-killing algae Pfiesteria piscicida began to occur.

Oysters, for which the Bay had been famous since Capt. John Smith's voyage in 1608, were even earlier victims. After a peak harvest in 1884, commercial landings declined 4-fold to ~1930, when the local oyster-industry effectively collapsed (Fig 1). The native oyster has been further devastated in the last ~15 years by two parasitic diseases, MSX and Dermo, which cause wasting (inability to gain weight) and mortality. MSX was accidentally introduced in 1950 via an alien (=non-native) species of oyster that was being trialed to replace the native oyster. To revive the oyster industry, Maryland & Virginia environmental managers are now considering introducing a new alien oyster species from southeastern Asia that has natural resistance to MSX and Dermo diseases, but there is great concern about the inadvertent importation of further disease.

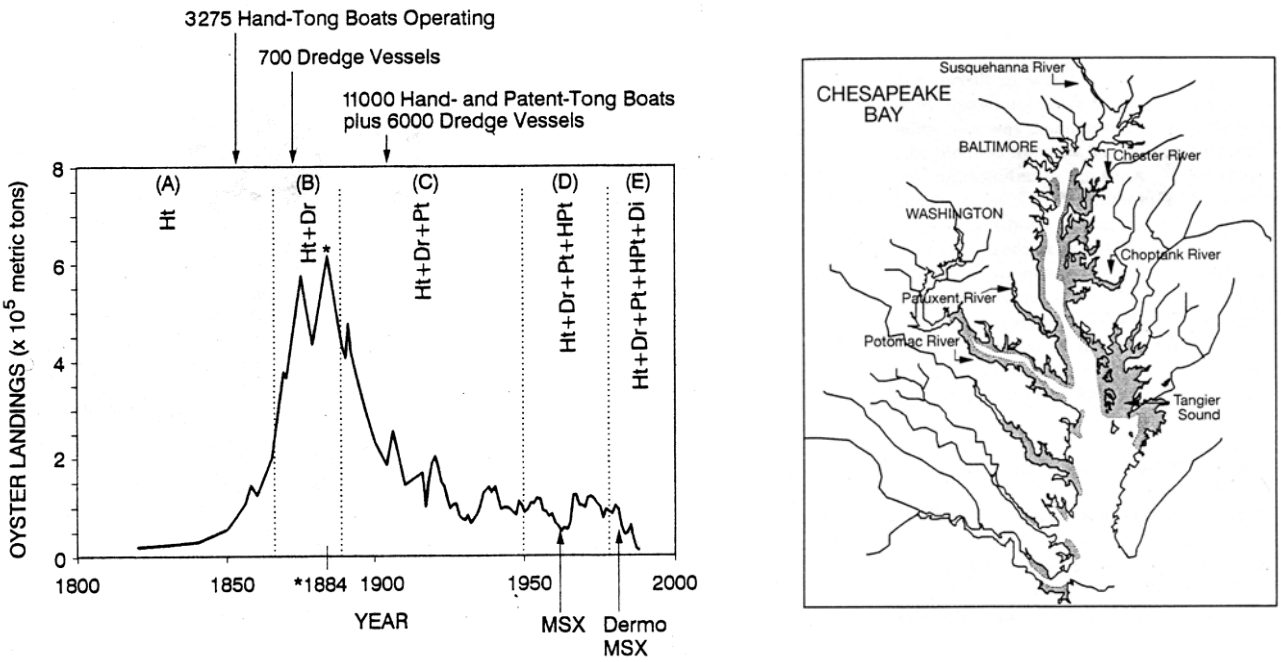


Fig. 1. Time-series of Maryland oyster landings (source: Md Dept Natural Resources), and corresponding evolution of harvesting gear and effort. Shaded area on map shows occurrence of oyster reefs at the turn of the last century (from Yates 1913). Figures reprinted from Rothschild et al. 1994.

This basic history of declining environmental, recreational and commercial quality is common to many eastern U.S. estuaries. Because of the proximity of these estuaries to major population centers (Boston, NYC, Wilmington, Baltimore, DC, Richmond, etc) – in fact, it was the original biological richness and gentle shores of the estuaries that attracted both native and European populations -- their continuing decline in environmental quality has acquired great social, political & economic significance.

The big issues are:

1. What factor or factors have driven this change? That is, who or what is to blame? The potential culprits are:
    a. present-day state is within the range of natural variation in the system → that is, the **decline is a natural trend**
    b. present-day state is an outcome of **anthropogenic climate change**, i.e. "global warming" with its consequences for both water temperatures AND precipitation (droughts, raininess). Estuarine change is thus a consequence of human activity, but the link is indirect via climate-change.
    c. present-day state is an outcome of **anthropogenic nutrient loading of the water**. That is, the ecosystem was degraded by fertilization of primary producers at the base of the food-chain, due to run-off from croplands, domestic animal waste, and/or human waste → change is an anthropogenic "bottom-up" effect
    d. present-day state is an outcome of **human overfishing** of predators and herbivores (mammals, fish, sea-turtles) at the top of the food-chain, and especially overfishing of oysters, which build habitats for other organisms (reefs) and maintain water quality by filtering it for food → change is an anthropogenic "top-down" effect
2. How linked are the changes in environmental quality – that is, has the decline cascaded from a single event or factor, or have multiple factors acted together or in sequence?
3. How, if at all, can declines be reversed? Are some aspects of decline – or some estuaries -- more "fixable" than others?
4. What is "natural" for the Bay? And what should be the ultimate target condition for remediation? That is, do we need to return the Bay all the way to pre-contact conditions, or are there intermediate states that would make reasonable ecological sense and be economically productive? What historical past state should we aim for?
5. How rapidly would the system respond were we to attempt remediation -- that is, how long before we would begin to see an improvement or reach the target condition?
6. Is this response time realistic, politically or otherwise?
7. How realistic are the likely costs of remediation, in terms of changing practices/habits at an individual level, need for new legislation or bureaucracy, and direct investment of private and public funds?
8. What are the economic, social, and health costs (tradeoffs) of NOT remediating Bay condition?

Questions 6-8 are political – the answers depend on how the local/regional/national leadership and population prioritize estuarine health (and the various economic, human health, and recreational assets associated with it), and the effectiveness of individuals and leaders in imagining and enacting change. Political will and individual sacrifice are required for most moves, for example to shift from open-water fishing to aquaculture, from having entirely open public waters to having local biological reserves or experimental areas of "no take", or to change fertilizer use and run-off policies for farmers throughout a large drainage system (with many areas far from the Bay itself).

Good political decisions depend on having reliable answers to the first 5 questions, which are scientific. These 5 questions are answerable using 2 basic approaches:

I. Analysis of environmental and ecological information captured by <u>sedimentary cores</u> -- geohistorical information on the relative and absolute timing of environmental changes leading up to the present day is critical to developing hypotheses about what might have driven any particular change, or how one change might lead to another in a domino effect. Cores also provide unique and critical "baseline information" on estuarine conditions before human occupation and at various stages during decline.

II. Lab experiments using enclosed "microcosms" and "mesocosms", where ecologists and biogeochemists can test the effect of single agents at a time. For example, what is the magnitude of effect of various levels of lead (or nitrogen or phosphorus) on populations of bacteria (or algae or metazoans)? Field experiments are also used – for example, what is the effect on a community of removing all filter-feeding oysters, or removing algae-grazers, or introducing a new algae-grazer to a test area of seafloor? Experiments are direct means of determining whether a suspected agent can actually cause an observed effect.

Unfortunately, field manipulations are not always possible, ethical, or safe, and field and lab experiments both usually provide information on short-term responses only, because funds are rarely available to run them for more than a few months or years or at more than a local scale. Both sedimentary core (geohistorical) and experimental approaches are thus needed.

The aim of this week's exercise is to give you some insights into the kinds of environmental information that can be extracted from sedimentary cores, using the Chesapeake Bay as a study area. The data used in this lab comes from several sources, including the doctoral dissertation of Andy Zimmerman, who was a College student in Geophysical Sciences here at the U of C (B.A. 1987). Data for this lab are based on cores collected from the northern part of the Bay (mostly offshore of Calvert County Maryland; Fig. 2).

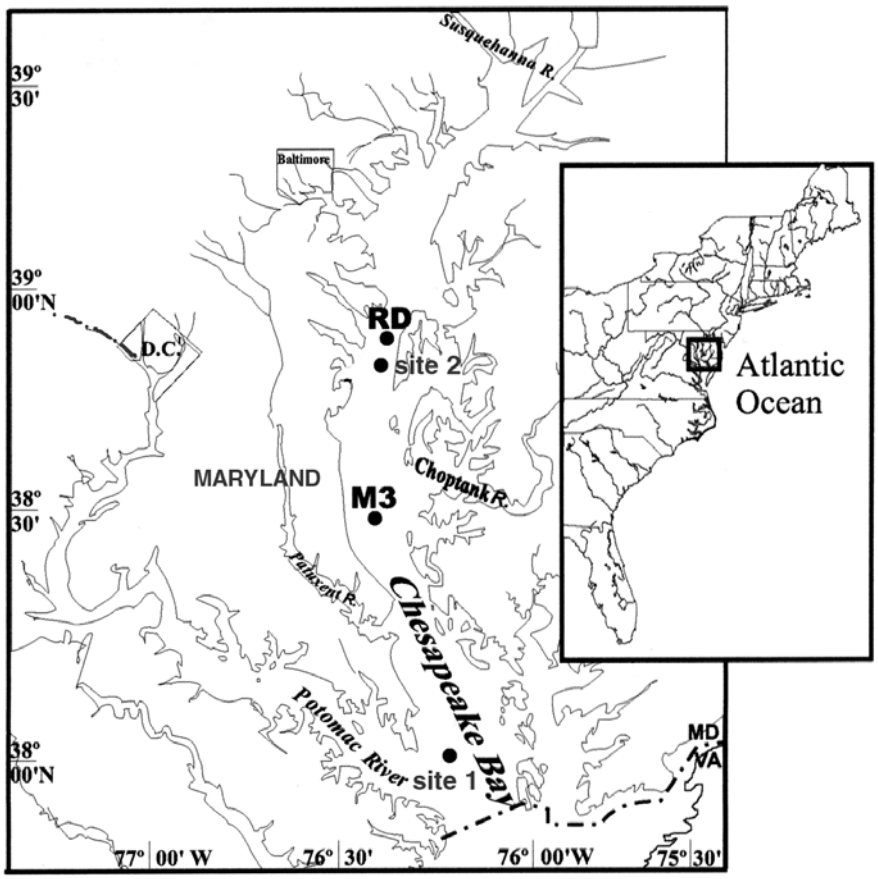


Fig. 2. Map of northern Chesapeake Bay, adapted from Zimmerman (2000), showing location of his cores M3 and RD. Cores analyzed by Cooper & Bush (1993) were collected in same area as Zimmerman Core M3. Cores analyzed by Colman & Bratton (2003) are from Site 1 and Site 2.

Key terms and concepts

Cores are taken from the center of an estuary, where sediment accumulation rates are usually highest and thus time-resolution is the greatest (maximal thickness of sediment deposited per year). Lengths of 3 or 4”-diameter pipe are lowered or driven into the seafloor. Back in the lab, the sediment (usually mud) is extruded from the pipe. This provides a cylindrical sample of 1 to 20 meters length, depending on the equipment used and the penetrability of the local sedimentary record.

Samples (usually from every 1- or 2-centimeter interval down-core) are analyzed for composition by different specialists. Sometimes multiple specialists work on the same core (this is ideal), but often they work on different but closely spaced cores – a single core might not provide sufficient sample to test for all the attributes of interest, or material might not have been saved from earlier studies for later workers to re-examine when new techniques become available. To compensate for possible local incompleteness (gaps) in cores, and to test for consistency in environmental history throughout an estuary, each worker usually repeats their down-core analysis on cores from several different subregions. The larger the number of cores that yield the same history (the same sequence and magnitudes of changes), the greater our confidence that we have accurately captured the true history. This also permits us to identify regional variation in a system (upstream versus downstream; shallow-water margins versus deeper offshore).

Proxy data are used to reconstruct most environmental conditions. For example, paleo-water temperatures cannot be measured directly from a core (you can’t get ancient water temperature by plunging a thermometer into old mud),but oxygen-isotope ratios carried in carbonate shells within the mud are known to indicate temperature at the time of shell formation (tested experimentally and observed in present-day waters). Oxygen-isotope ratios thus provide proxy (“stand-in”) data on water temperature. Similarly, we use sterol abundance in a sedimentary sample as a proxy for the original abundance of eucaryotes in the community at that time, etc. The larger the number of different kinds of proxy data that agree, the greater our confidence that we have a reliable characterization of that environmental variable.

Absolute chronology for a sedimentary core is generated several ways, but primarily using radiocarbon (14C) dating since most estuaries have only developed within the last ~10,000 years and thus are well within the reach of this method. [Most estuaries around the world formed by flooding of old river valleys during the final phase of sealevel rise from the Last Glacial Maximum.] C-14 dates based on shells (microfossils, clams) or large chunks of organic matter are best for this purpose; dates based on generalized organic matter (OM) are generally less reliable. Young sediments can also be dated using the naturally radiogenic isotope 210Pb (lead-210 method), which has a half-life of ~22 years and rains out from the atmosphere in to sediments worldwide. Human-generated pollutants are also useful. For example, Cesium 137, which is produced by atomic bomb blasts, shows up in sediment layers that are 1954 or younger (fallout from Hiroshima/Nagasaki), and attains peak levels within sedimentary cores in 1963, which was the year of maximum atmospheric fall-out from above-ground bomb testing before the nuclear test-ban was enacted. Finally, pollen can be extremely useful in establishing absolute chronology down-core. Pollen from the genus Ambrosia (Latin name for ragweed) increases during land-clearance for agriculture; it will reach a maximum abundance when land-clearance is maximum, and an absolute date for this for a local area can be determined by studying written records (time of land grants to colonists, state reports on acres under cultivation).

Temporal Resolution – i.e., time value per sample. In the M3 core used by Zimmerman (2000), each 2-cm increment in the top of the core records 1.1 years of elapsed time. That is, moving down-core from sample to sample, we can reconstruct environment history with annual resolving power – the equivalent of someone taking an average sample once a year → this is very good! This time-resolution can be achieved for Bay history back to ~1915. For the segment of the core recording the years from 1915 to 1790, the resolving power is slightly lower (3.5 years per sample) because of lower sediment accumulation rates, and for history pre-1790, the resolving power is 6.5 years per 2-cm sample. Because scientific monitoring of the Bay was non-existent during pre-colonial and colonial periods, and only sporadic even in the 20th century, the continuous sampling provided by sedimentary cores is very good in both absolute and relative terms.

A Brief Economic History of the Chesapeake Bay Region

Pre-1600 – hunting/gathering of wild foods by native peoples (based on archeological middens; spearing, hooking and trapping of fish, turtles, marine mammals; hand-collection of oysters, clams); small agricultural plots cultivated by hand (seeds into holes produced by sticks, fertilized by fish scraps)

1608 – exploratory voyage by Capt John Smith: abundant oyster reefs grew right up to the surface of the water and were a "hazard to navigation"; waters clear with abundant benthic seagrasses and the green sea-turtles etc that fed on them.

1650-1750 – initial land clearance; first land grants for Maryland bay-shore counties in 1634 to 1654; hand-removal of trees & stumps; plowing of soil for tobacco & corn using draft animals; hand-harvesting of shellfish for local use

1750 – 1850 – intensification of land clearance to maximum acreage in ~1850

1870's – first intensive use of factory-processed organic fertilizers, such as phosphate imported from mines in South Carolina and bird guano from Pacific islands, rather than using manures and other organic materials produced locally; Baltimore was the center of the processed-fertilizer industry, with the number of factories quadrupling between 1860 and 1880. [However, rates of use were low compared to 1940 onward; see Fig. 3]

1870 – invention and immediate adoption of the mechanical oyster dredge, a motorized conveyor belt that chewed at the tops of oyster reefs and retrieved dead and live oysters, which were then sorted on deck; this increased dramatically the ease of harvesting oysters and permitted harvesting from deeper parts of the Bay. Commercial harvesting for export increased rapidly, leading to peak production in 1884 (Fig. 1).

1880's – introduction of dynamite to blow up stumps, consequent increase in land clearance

1884 – peak harvest of oysters and start of sharp decline in take despite~20x greater effort in terms of licensed oyster boats. Decline attributed to overfishing and to physical destruction (by dredging) of the oyster reefs themselves, which are banks of interlocking live-oysters and their dead shell material. Rising several meters up off the seafloor, these reefs provide colonization sites for subsequent generations of oyster larvae in natural systems.

1920's – further increase in land clearance with mechanization of plowing & harrowing; first commercially available synthetic fertilizers made from inorganic raw materials

1930's -- commercial oyster industry finally collapsed (Fig. 1); low yields ever since, despite efforts to reseed beds and using all possible harvesting methods including divers (Di in Fig. 1]

1930's-40's – widespread abandonment of farms with economic depression of the "Dirty Thirties"; begin reforestation of agricultural lands; U.S. Civilian Conservation Corps and USDAgriculature efforts to combat soil erosion & improve soil husbandry

1950's – first widespread use of commercial synthetic fertilizers, manufactured from inorganic raw materials (N and P); fertilizer use is double that of the 1930's and earlier decades, and multiplies through subsequent decades [see Fig. 3]

1950 - initiation of commercial poultry operations on the Eastern Shore of the Bay, which increases exponentially to present-day [see Fig. 3]; use of intensely nitrogen-rich chicken litter to fertilize eastern shore crop lands

1950 – start of post-war population increase in U.S. and Maryland; increasing urbanization, increasing point-source input of nutrients (sewage and other waste)

late 1950's -1960's –begin intense suburb, mall, and highway construction, including first segments of interstate system

1971 – establishment of US Environmental Protection Agency to "establish and enforce environmental protection standards"; enactment over the next decade of federal and state laws regarding air and water pollution by industry, farms, municipalities and individuals via toxins, nutrients, and solid waste

1970s -- introduction of commercially available low-phosphorus detergents, improved sewage treatment plants, etc; banning of lead additives in gasoline

1980's – labor-intensive tobacco farming becomes uneconomic, resulting in conversion of agricultural land on western shore of Bay to other crops, forest, and, increasingly, commuter exurbs and vacation homes

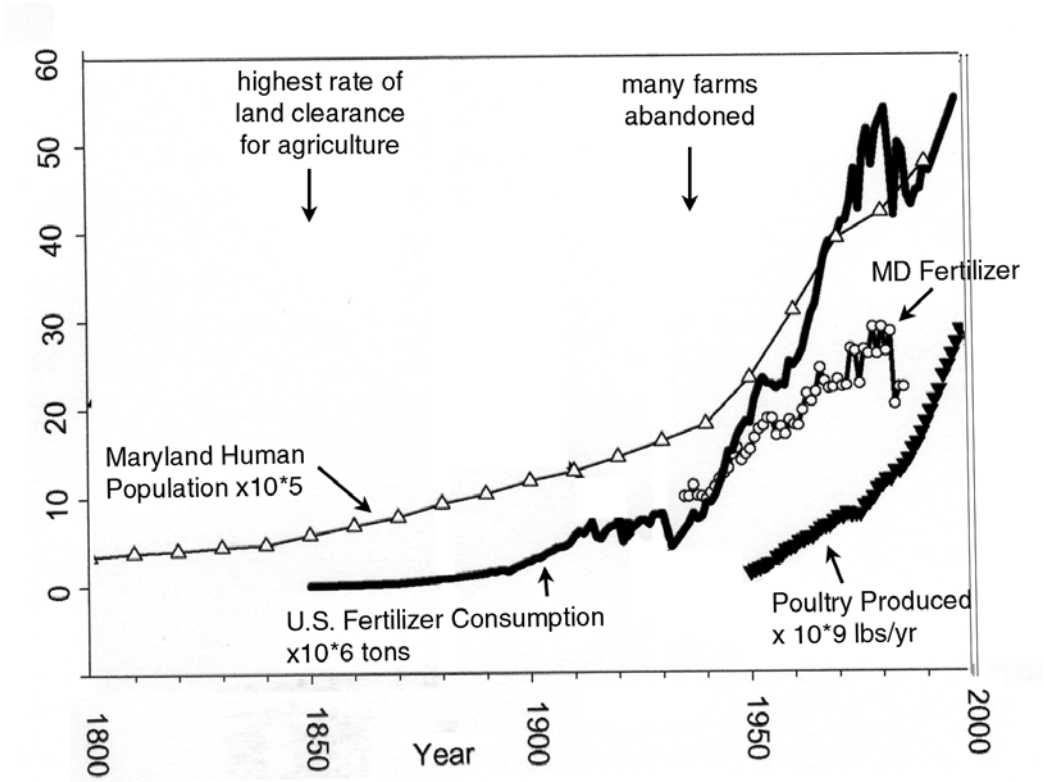
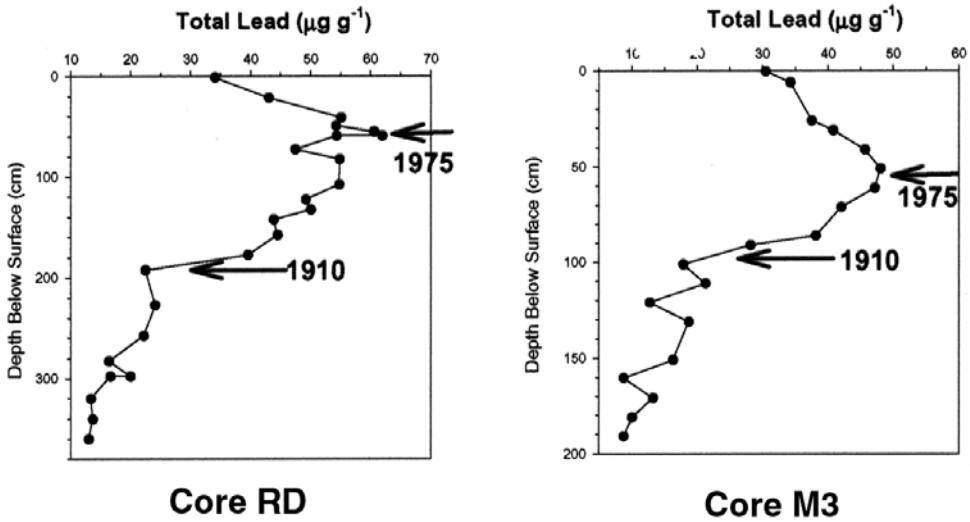


Figure 3. Some sources and magnitudes of nutrient input to the Bay over time (adapted from Zimmerman 2000). Land clearance for agriculture or for construction leads to runoff of solid sediment, plus runoff of soluble nutrients associated with those soils. All of these could be factors in "bottom-up" change in the Bay ecosystem.

Sedimentary core evidence for growth of industry and urbanization, based on total lead levels

Lead additives to gasoline (to keep engines from "knocking") were standard until outlawed in 1975 because of the danger of lead to human health, especially that of children. Estuarine sediments capture lead 2 ways: lead aerosols, put into the atmosphere by internal combustion engines, rain down on land and sea; those on land also get washed to sea via runoff. The 2 cores below from Zimmerman (2000) reveal the progressive industrialization of Baltimore up to 1910, the invention and popularization of automobiles starting in 1910, and the ban on lead-additives in 1975. The cores provide excellent (encouraging) evidence of the positive net effects of the additive-ban on lead levels in the environment, despite continuing growth in the number of cars since 1975. <u>The cores are also a good example of how sediments can capture history.</u>



Materials for this Lab – Core data from 3 independent studies of Chesapeake Bay

1. Cooper and Brush 1993 = sedimentary core data for the last 2500 years of Bay history. Have low time-resolution in upper part of core (last century), but total extends back to 200 B.C., so excellent for pre-colonial history of the ecosystem.
2. Colman & Bratton 2003 = core-data for a few measures of environmental condition back to A.D. 400.
3. Zimmerman 2000 & Zimmerman & Canuel 2000 = oldest samples are from A.D. 1680, which is post-European contact for this region, but has excellent time-resolution from there to present, including geochemical biomarker information that is more sophisticated than available to Cooper and Brush 1993.

Sources of Information

Cooper SR & GS Brush, 1993. A 2500-year history of anoxia and eutrophication in Chesapeake Bay. Estuaries 16: 617-626.

Colman, SM, & JF Bratton, 2003. Anthropogenically induced changes in sediment and biogenic silica fluxes in Chesapeake Bay. Geology 31(1): 71-74.

Cronin, T, et al., 2000. Climatic variability in the eastern United States over the past millenium from Chesapeake Bay sediments. Geology 28: 3-6.

Jackson, J.B.C., M.X. Kirby, and 16 alphabetic authors, 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293: 629-638.

Rothschild, BJ, JS Ault, P Goulletquer, & M Héral, 1994. Decline of the Cheapeake Bay oyster population: a century of habitat destruction and overfishing. Marine Ecology Progress Series 111: 29-39.

Zimmerman AR 2000. Organic matter composition of sediments and the history of eutrophication and anoxia in the mesohaline Chesapeake Bay. PhD dissertation, Virginia Institute of Marine Sciences, College of William and Mary.

Zimmerman AR, & Canuel EA 2000. A geochemical record of eutrophication and anoxia in Chesapeake Bay sediments: anthropogenic influence on organic matter composition. Marine Chemistry 69: 117-137.

Zimmerman AR, & Canuel EA 2002. Sediment geochemical records of eutrophication in the mesohaline Chesapeake Bay Limnology & Oceanography 47 (4): 1084-1093

http://www.chesapeakebay.net/jsmith.htm [early exploration of the Bay]

http://www.mdsg.umd.edu/MarineNotes/Summer95/side3.html [state of blue crab fishery]

http://www.volvooceanadventure.org/article.php/au_4_prs_99969.html [Bay shellfisheries]

http://www.ftldesign.com/cgaux1311/fish.htm [general overfishing]

http://water.usgs.gov/wid/html/chesbay.html [general fertilizers in Bay]

http://www.inform.umd.edu/manurenet/water.htm [agricultural impacts]

http://www.ext.vt.edu/departments/envirohort/articles/misc/chspkby.html [residential impacts]

http://www.mde.state.md.us/Programs/WaterPrograms/SedimentandStormwater/chesapeake.asp [stormwater management]

http://www.dnr.state.md.us/bay/sav/ [seagrass and underwater vegetation restoration plan]

Acknowledgments: Many thanks to Andy Zimmerman (Penn State) for helpful comments and making available his dissertation, and to JBC Jackson et al. for inspiration

Procedure

Part A. Using the original data plots of various authors, identify the general trends, magnitudes of change, and times of change in environmental history for the following variables. Summarize your results on the worksheets provided.

1. Sediment input
2. Rate & fate of primary production, and elevated nutrient input (eutrophication)
3. Water turbidity
4. Composition and diversity of the biological community
5. Bottom-water anoxia (oxygen depletion/stagnation)

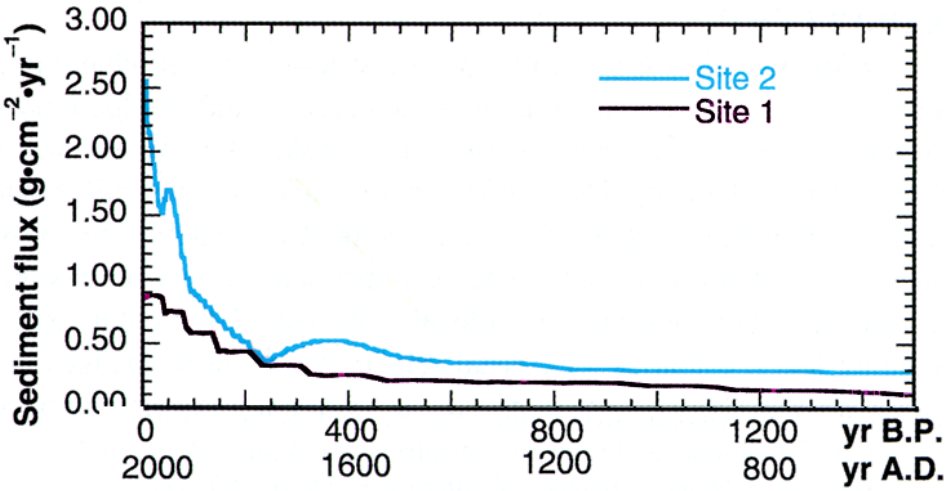
Part B. Synthesis of multiple kinds of evidence to identify cause and effect

Variable 1. Sediment input

Proxy data: Sediment input can be inferred from sediment accumulation rate, which is calculated from the measured thickness of core between dated horizons. It indicates the magnitude of water runoff (versus percolation of rain down into soils) and the severity of land (soil) erosion in the drainage basin: the larger the area subject to erosion (because of land disturbance), and/or the higher the rate of rain run-off (because no vegetation to hold rain), then the higher the rate of delivery of solid earth materials to the Bay. This results in high sedimentation rates in the Bay, which is a natural sediment trap (it's the first standing body of water that rivers and streams encounter).

Consequences: High sedimentation rates (often expressed as a "flux" of grams of sediment per seafloor area per unit time) are stressful to commercially important benthic organisms (e.g. oysters), and cause undesirable "silting-up" of shorelines and harbors. Solid sediments also deliver soil nutrients to the Bay, and if derived from urbanized areas, deliver any pollutants and toxins that had accumulated in the soil.

Available info: data on sediment flux (grams sediment per square-cm per year) from 2 cores (site 1 & site 2), generated by Colman & Bratton 2003:



What is the initial state of this variable, relative to its later history?

_____

(e.g., starts lower, higher, same as later)

At what point in time was the Bay in the worst condition, in terms of this variable?

_____ _____

date @ site 1 how different is this from pre-contact time (e.g., 10x higher, 2x lower)?

_____ _____

date @ site 2 how different is this from pre-contact time (e.g., 10x higher, 2x lower)?

At what point in time did this environmental variable first begin to change?

_____	_____
date @site 1	kind of change (began to rise, fall, ?)
_____	_____
date @site 2	kind of change (began to rise, fall, ?)

Are there any other points along the history when the variable made a distinct change for the worse? YES/ NO

_____	_____
date @ site 1	change (rate of change steepens; steps up to a new plateau; etc)
_____	_____
date @ site 2	change (rate of change steepens; steps up to a new plateau; etc)

ADDITIONAL QUESTIONS:

1. Zimmerman (2000) reports a continuous increase in sediment flux over the last 300 years:
   0.24 g/cm*2/yr from ~A.D. 1700 to 1850
   0.36 g/cm*2/yr from 1850 to ~1975
   0.47 g/cm*2/yr from 1975 to 1996 (date of coring)

→ Is this trend consistent with what is observed in the two Colman & Bratton cores above? YES/ NO

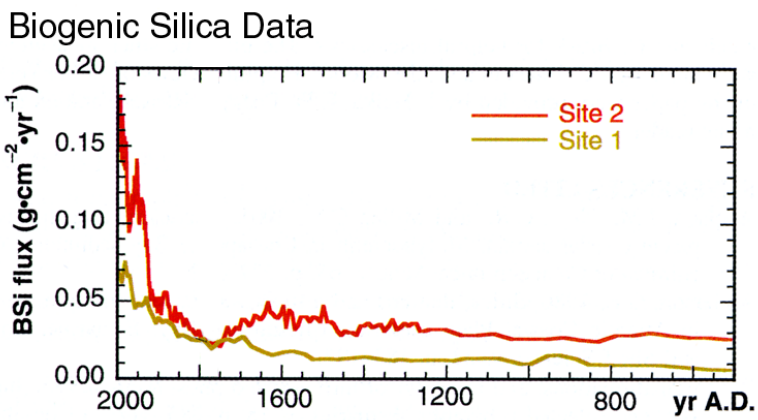
2. Given that rates of land-clearance for agriculture have been declining since 1850, that widespread reforestation began in the early 20th century, and that conservation efforts have been enacted for remaining land under cultivation, what might be causing the continuing rise in rates of sediment accumulation? For inspiration, consider the "Brief Economic History" on page 5 and associated figures.

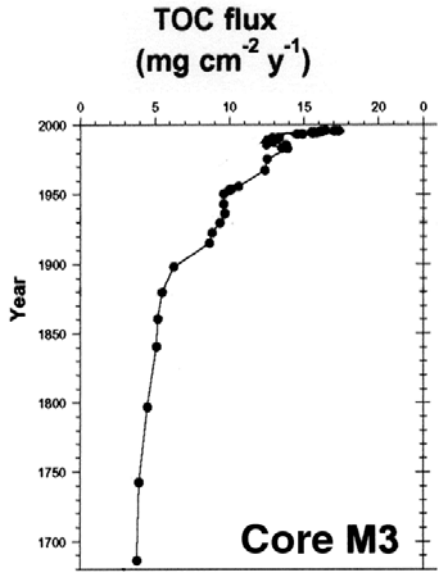
Variable 2. Rate of primary production, and eutrophication (high nutrient supply)

Proxy data. At the base of all food chains are primary producers, which generate food for herbivores and other higher organisms. In marine and estuarine systems, these primary producers include benthic algae and seagrasses but also phytoplankton (floating photosynthetic unicellular eucaryotes & procaryotes). When nutrient levels are low, primary productivity is limited, and almost all of the organic matter produced will be quickly consumed and recycled into the tissues of animals. As nutrient supply increases, primary productivity increases and can reach levels that outstrip the ability of herbivores to consume it. This results in an increased supply of raw (undigested) organic matter to the seafloor. An imbalance between primary productivity and animal consumption can be inferred from the Total Organic Carbon (TOC) buried in the sediment (excess primary production gets buried; calculated as a flux, i.e. grams per square centimeter of seafloor per year). A good proxy for nutrient levels themselves is the flux of "biogenic Silica" (BSi), which comprises the siliceous exoskeletons of microscopic diatoms. Diatoms are superb competitors against other phytoplankton under high-nutrient conditions, and their population "blooms" dramatically increase the delivery of biogenic silica to the seafloor.

Consequences. The decomposition of organic matter removes oxygen from surrounding water. Therefore, regions where organic matter input is high are prone to oxygen depletion, especially in bottom waters adjacent to the organic-matter-rich seafloor. Low to zero oxygen (hypoxia, anoxia) causes morbidity and mortality of bottom-dwelling animals. This is especially dangerous for benthic animals like oysters that are permanently affixed to the seafloor (and thus cannot flee into shallower oxygen-rich waters), but also affects fish and crabs and the worms and clams they feed upon.

Available info: Flux of biogenic Silica (BSi, mg/cm2/yr) at two sites with cores going back to A.D. 400, generated by Colman and Bratton (2003). Flux of Total Organic Carbon (TOC) for core M3 generated by Zimmerman (2000). NOTE: Because the Zimmerman core extends only to 1700, which is post-contact, use the oldest sample as the benchmark to judge subsequent change.





What is the initial state of this variable, relative to its later history?

BSi _____

(e.g., starts lower, higher, same as later)

TOC _____

(e.g., starts lower, higher, same as later)

At what point in time was the Bay in the worst condition, in terms of this variable?

BSi _____ _____
Date @ site 1 how different is this from pre-contact time (e.g., 10x higher, 2x lower)?

BSi _____ _____
Date @ site 2 how different is this from pre-contact time (e.g., 10x higher, 2x lower)?

TOC _____ _____
Date @ M3 how different is this from pre-contact time (e.g., 10x higher, 2x lower)?

At what point in time did this environmental variable first begin to change?

BSi _____ _____
Date @site 1 kind of change (began to rise, fall, ?)

BSi _____ _____
Date @ site 2 kind of change (began to rise, fall, ?)

TOC _____ _____
Date @ M3 kind of change (began to rise, fall, ?)

Are there any other points along the history when the variable made a distinct change for the worse? YES/ NO

_____ _____ _____
variable date change (rate of change steepens; steps up to a new plateau; etc)

_____ _____ _____
variable date change (rate of change steepens; steps up to a new plateau; etc)

_____ _____ _____
variable date change (rate of change steepens; steps up to a new plateau; etc)

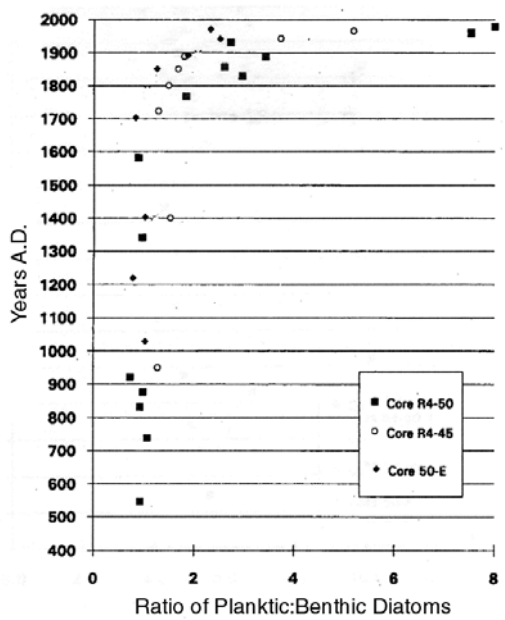
_____ _____ _____
variable date change (rate of change steepens; steps up to a new plateau; etc)

Variable 3. Water turbidity

Proxy data: Diatoms (microscopic unicellular algae) are important components of phytoplankton (photosynthetic organisms floating in the upper water column), and secrete a silica shell (exoskeleton) that can be preserved in sediments. If the water is sufficiently clear for light to penetrate to the seafloor, "benthic" (seafloor-dwelling) diatoms will also be present in the local community. Thus the ratio of planktonic (usually round in shape) to benthic diatoms (usually oblong) in a fossil assemblage is a good indicator of original water clarity: if water is turbid, benthic diatoms will be few, and thus the ratio of planktic to benthic diatoms will be high.

Consequences: If prolonged, water turbidity causes the die-off of subaquatic vegetation (seagrasses) by reducing light-penetration to the seafloor. Seagrasses provide food for estuarine herbivores (various sea-turtles, manatees, many fish & snails), and provide important nurseries for egg-laying and juvenile development of many fish, crabs, and prey-species for those organisms. Although waters can be turbid immediately after a storm due to temporarily suspended solid sediments, water turbidity is usually due to high quantities of unconsumed phytoplankton and their debris. Turbidity thus alarms ecologists that the metazoan community of phytoplankton consumers (various herbivores, planktivores, and filter-feeders) may be in poor health. Turbid waters are also unattractive for swimming and resort development.

Available info: Planktic:benthic diatom ratios for 3 closely spaced cores, generated by Cooper & Brush (1993):



What is the initial state of this variable, relative to its later history?

_____

(e.g., starts lower, higher, same as later)

At what point in time was the Bay in the worst condition, in terms of this variable?

_____ _____

date how different is this from pre-contact time (e.g., 10x higher, 2x lower)?

At what point in time did this environmental variable first begin to change?

_____ _____

date kind of change (began to rise, fall, ?)

Are there any other points along the history when the variable made a distinct change for the worse? YES/ NO

_____ _____

date change (rate of change steepens; steps up to a new plateau; etc)

_____ _____

date change (rate of change steepens; steps up to a new plateau; etc)

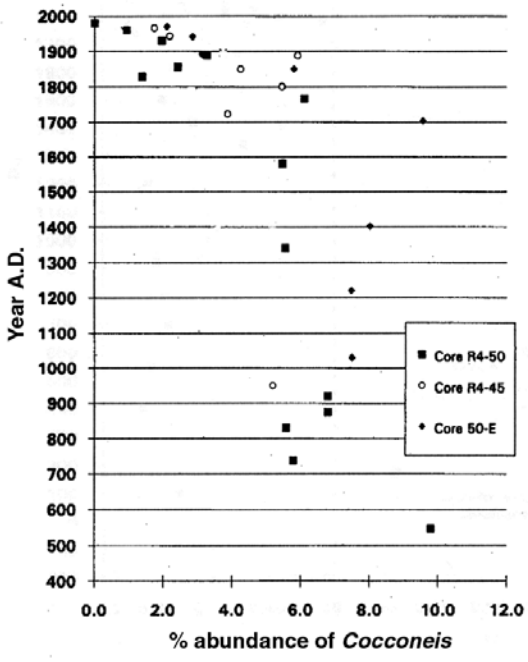
ADDITIONAL QUESTION:

Cooper and Brush (1993; Figure below) also provide data on the down-core abundance of the diatom genus *Cocconeis*, which lives attached to seafloor vegetation – it is present ONLY in the presence of large, multicellular green plants in the benthic community, and its abundance varies with the abundance of those plants.

Date when *Cocconei*s abundance first begins to decline _____

Time when *Cocconeis* reaches lowest abundance _____

Is this history of water turbidity inferred from *Cocconeis* consistent with that based on planktic:benthic ratios? YES / NO



Variable 4. Composition and diversity of the biological community

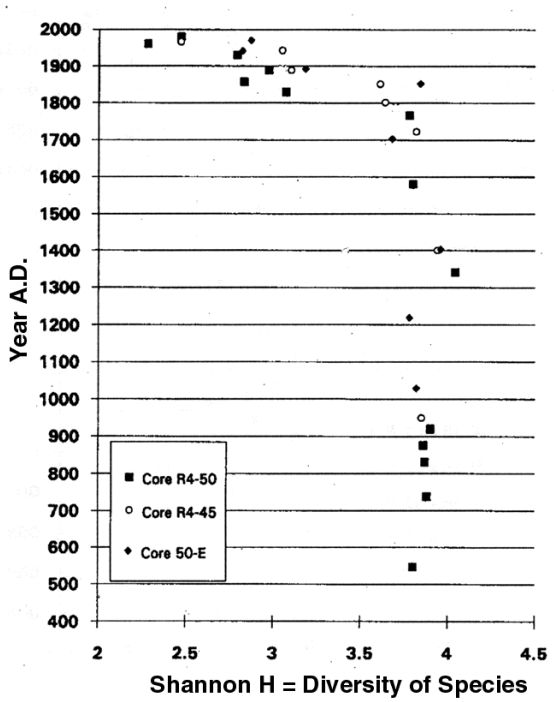
Proxy data: The status of the biological community can be tracked using many different proxies.

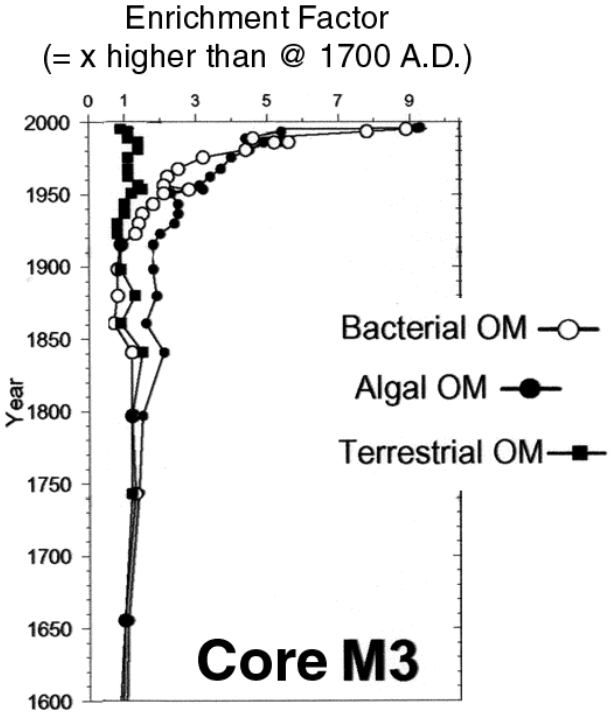
a. Ecologists commonly use information on the number of species present and their relative abundance (that is, how individuals are distributed among species) to quantify the diversity of local communities. Shannon's H' is one widely used index for this – when it's value is high, diversity is high and the community is considered to be "healthy" and also in a state of relative equilibrium. When the Shannon diversity index is low, the community is generally under some degree of stress and instability, for example from eutrophication or pollution (toxins).

b. Biogeochemists are now able to extract organism-specific compounds (biomarkers) in organic matter that permit them to identify the original producer. For example, plankton in general (phytoplankton plus zooplankton) have a signature distinctive to that of algae and bacteria that live on or in seafloor sediments. Also, organic matter that was produced by planktonic algae includes distinctive eucaryotic sterols, whereas organic matter produced by cyanobacteria contains distinctive procaryotic fatty acids, and organic matter washed in from adjacent land (trees, grass) contains distinct leaf waxes from land-plant cuticle. Thus one can determine whether an increased flux of Total Organic Carbon is due to a shift in land-runoff, a shift within the estuary from benthic to planktic production (affecting turbidity), or, among the plankton, a shift from algal blooms to high bacterial populations within the water column.

Consequences. Many metazoans can eat a variety of foods, but there are limits to their flexibility, and not all food materials are equal in terms of food value. Cyanobacteria, for example, are much smaller than diatoms and other eucaryotic phytoplankton, and thus are more difficult for mollusks to filter out of the water; moreover, many bacteria are toxic either to the herbivore/filter-feeder or to the predator on that animal. Thus, a shift from algal to bacterial populations in the phytoplankton is a bad sign for metazoans, which will suffer reduced growth rates if not death. A similar difficulty is presented to herbivores if the bottom vegetation changes from seagrasses to multicellular algae: these 2 plant types have different nutritive value and support different organisms, with many species being specialists on seagrass (sea turtles, many kinds of snails & fish). Metazoan communities thus tend to decline as seagrasses are replaced by macro-algae during eutrophication, eventually collapsing if replacement by algae is complete. Algae-eaters in turn go into decline when, as eutrophication becomes even more severe, bacterial populations begin to grow and replace algae.

Available info: Shannon's H' values for diatom communities generated by Cooper & Brush (1993). For core M3, Zimmerman (2000) documents how the different components of Organic Matter have changed over time, expressed as an enrichment factor relative to 1700 A.D. [For example, bacterial Organic Matter is at present 9x higher than it was in 1700]





What is the initial state of this variable, relative to its later history?

Shannon Diversity _____
(e.g., starts lower, higher, same as later)

Bacterial OM _____

Algal OM _____

Terrestrial OM _____
(e.g., starts lower, higher, same as later)

At what point in time was the Bay in the worst condition, in terms of this variable?

Shannon Diversity _____ _____
date how different is this from pre-contact time (e.g., 10x higher, 2x lower)?

Bacterial OM _____ _____
date how different is this from pre-contact time (e.g., 10x higher, 2x lower)?

Algal OM _____ _____
date how different is this from pre-contact time (e.g., 10x higher, 2x lower)?

At what point in time did this environmental variable first begin to change?

Shannon Div. _____ _____
date kind of change (began to rise?)

Bacterial OM _____ _____

Algal OM _____ _____
date kind of change (began to rise?)

Are there any other points along the history when the variable made a distinct change for the worse? YES/ NO

Shannon Div. _____ _____
date change (rate of change steepens; steps up to a new plateau; etc)

Bacterial OM _____ _____
date change (rate of change steepens; steps up to a new plateau; etc)

Algal OM _____ _____
date change (rate of change steepens; steps up to a new plateau; etc)

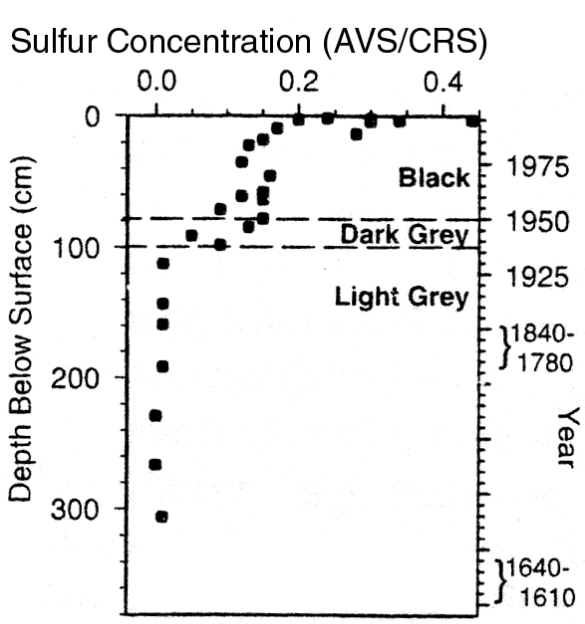
Algal OM _____ _____
date change (rate of change steepens; steps up to a new plateau; etc)

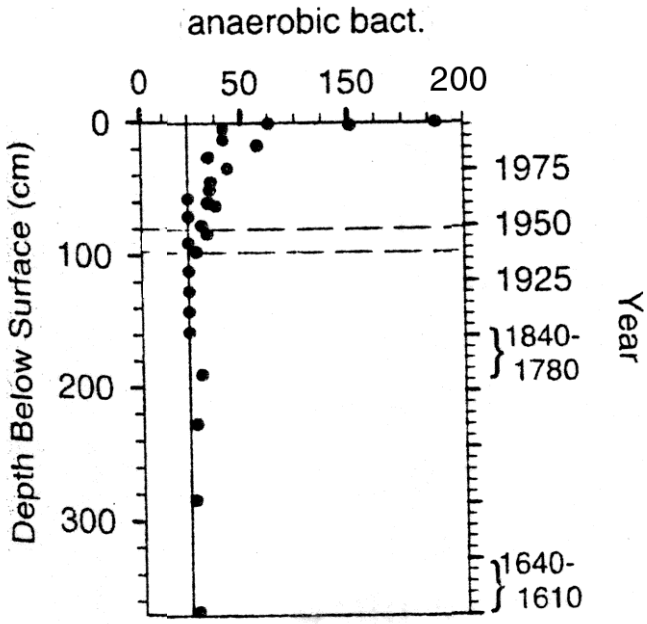
Variable 5. Bottom-water anoxia (oxygen depletion, stagnation)

Proxy data: Seafloors receiving high quantities of organic matter are prone to oxygen depletion because of the demand for oxygen by microbial decomposers. Once oxygen is depleted, organic-matter decomposition proceeds by microbial reduction of sulfate ions (SO4) in seawater, producing various sulfur compounds including the toxic gas hydrogen sulfide. Benthic anoxia can be recognized several ways. Geochemical evidence consists of the abundance of various sulfur compounds, particularly iron sulfide (pyrite), which precipitates in the sediment by the reaction of hydrogen sulfide with available iron in the absence of oxygen. Biomarkers for anaerobic, sulfate-reducing bacteria will also increase in abundance. Because metazoans are killed by these zero-oxygen, hydrogen-sulfide-rich conditions, and thus there are no burrowing organisms to disturb the seafloor, the original laminations of sediments will be preserved in the sedimentary record, and these too become useful proxies for seafloor anoxia.

Consequences: extensive die-off of benthic organisms, rather than simple morbidity and local mortality. If anoxic intervals become frequent, then benthic metazoan communities have little chance to become re-established during intervening aerated periods, and the system becomes dominated by anaerobic procaryotic microbes (like the Archean Era).

Available info: data on reactive sulfur concentrations and anaerobic bacterial biomarkers for core M3, generated by Zimmerman (2000).





What is the initial state of this variable, relative to its later history?

Sulfur _____

SO4 bacteria _____

(e.g., starts low, high, same as later)

At what point in time was the Bay in the worst condition, in terms of this variable?

Sulfur _____ _____

SO4 bacteria _____ _____

date how different is this from pre-contact time (e.g., 10x higher, 2x lower)?

At what point in time did this environmental variable first begin to change?

Sulfur _____ _____

SO4 bacteria _____ _____

date kind of change (began to rise, fall, ?)

Are there any other points along the history when the variable made a distinct change for the worse? YES/ NO

Sulfur _____ _____

date change (rate of change steepens; steps up to a new plateau; etc)

SO4 bacteria _____ _____

date change (rate of change steepens; steps up to a new plateau; etc)

Part B. Synthesis of Multiple Kinds of Evidence to Identify Cause & Effect

By now, you will have discovered that all or virtually all indicators of environmental and ecosystem health are presently at their worst state since pre-contact times. This is really quite surprising, given the reforestation of surrounding land that has occurred since the early 20th century, the increasing awareness of the perils of environmental degradation to human health and economic welfare (especially commercial fisheries and sport-related businesses), and the research and regulation efforts since the "environmental movement" started in the early 1970's. In terms of remediation, it is also somewhat discouraging that most of these declines began well before the 20th century – that is, even modest populations of agrarian colonists began to impact the Bay environment – and that rates of decline have intensified over time, but especially within the last 100 years.

However, before you become depressed(!), realize (a) that the variables we have examined here are some of the most difficult and complicated aspects of an ecosystem to understand and to rectify, and (b) that some impactors on the Bay ecosystem, rather than having been slowed or reversed in the last 30 years of heightened environmental awareness, have actually continued to increase. This is especially true for factors that increase nutrient supply to the Bay (fertilizer use, industrial poultry production, human population size; Figure 3). When we examine other indicators of Bay health, particularly those dominated by a single source or toxin, the picture is more positive. One example is the dramatic decrease in industrial lead levels (figure on page 6) – this decrease since 1975 has occurred despite increasing numbers of cars, and is paralleled by strong decreases in other industrial and urban toxins, which constitute a dramatic improvement for human health. A highly visible ecological improvement has been the strong rebound in populations of osprey, bald eagles, and other predatory birds, which were nearly extinct in this region by the late1960's because of DDT poisoning. The strict regulation of many pesticides that accumulate through food chains, supplemented by introduction of breeding pairs, has had a dramatic effect within a few decades, and some kinds of fish populations have also recovered sufficiently to support these new bird populations and limited sport-fishing. Thus enactment and enforcement of environmental regulations based on scientific research can in fact have impressive results.

The aspects of Bay health explored in this Lab are very clearly research that is still in progress, with policy decisions still largely unmade. To synthesize results from the core-data examined here, use the following table to organize information and sort through some possible cause-and-effect relationships.

Working Hypothesis 1: Although the Bay is in worse shape now than in our parents' or grandparents' time, its condition is still within the range that the Bay has naturally varied across in the past. Policy Implication: the Bay will self-correct (i.e., without active remediation by humans) because it has done so in the past.

Test: to evaluate the sedimentary core evidence, fill in the following table:

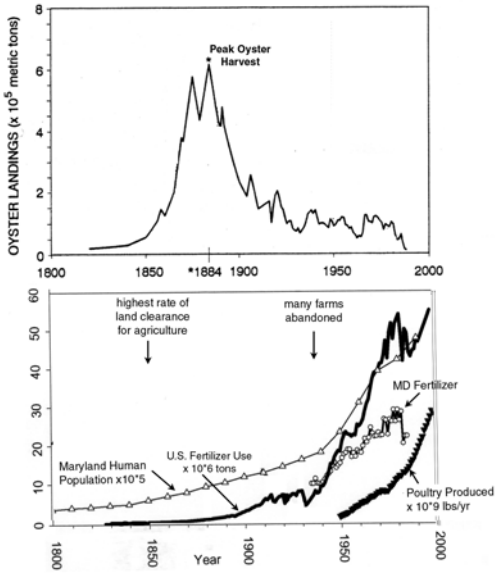
VARIABLE	TRUE	FALSE
Sediment input (proxy = sed accumulation rate)		
Primary productivity (TOC flux)		
Nutrient input (Biogenic Silica flux)		
Water turbidity (planktic:benthic ratio)		
Community Composition & Diversity (Shannon's H, bacterial biomarker, algal biomarker)		
Anoxia (Sulfur, biomarker for anaerobic bacteria)		

→ Based on data from sedimentary cores, is it true for any of the investigated variables that the present level is within the range of past variation?

→ On this basis, would you reject or accept Hypothesis 1, and with what confidence? [Estimate confidence by counting votes – how many checks in the true column and how many in the false column, based on giving each proxy it's own vote.]

Working Hypothesis 2: The miserable state of the oyster industry is due to environmental conditions (high TOC loads, high bacteria counts, frequent anoxia) created by run-off of agricultural fertilizers and poultry waste. Policy Implication: reduce nutrient inputs to the Bay from these sources and the oysters should recover. [one would also have to solve the MSX & Derma oyster disease problems]

Test using economic data:



Government records indicate that oyster harvests started to decline steeply in 1884, despite intensifying effort (Fig.1).
→ Based on data for commercial fertilizer consumption, did fertilizer use increase significantly in 1884 or in the decade or two before 1884? (see Figures 1 & 3 reprinted above) YES / NO When did it begin to rise sharply? _____

→ How about poultry factories: when did this industry start? _____

→ Using these economic data, would you reject or accept Hypothesis 2 that high fertilizer use caused the decline of oysters?

Test using sedimentary data: fill in this table:

Indicator of Water Conditions	1. Did this factor increase notably in 1884 or in the decade before 1884?	2. When did this factor first increase sharply?
TOC flux	YES / NO	Give date
Biogenic Silica (2 sites)		
Water turbidity		
Bacterial & Algal Organic Matter		

→ Based on sedimentary core data, did eutrophication become notably worse in 1884 or in the decade immediately before 1884? YES / NO

→ Using these sedimentary data, would you reject or accept Hypothesis 2 that eutrophication caused the oyster decline?

Important Fact = Filter-feeding organisms in general – and oysters in particular – are highly effective at removing plankton from water, and are thus a natural means of maintaining good water quality (keeping water clear for seagrasses, etc).

Working Hypothesis 3: The severe reduction in oyster stocks from 1884 onward – whether this was caused by overfishing or by eutrophication or some combination of these 2 factors -- had a negative feedback on the Bay system. As oysters became less numerous, the rate of water-filtering would have decreased, allowing higher numbers of plankton to persist in the water column and then become buried as undigested organic matter in the sediment → that is, water turbidity and sediment TOC would have increased. Oysters were eventually removed to a point where organic matter input exceeded the availability of oxygen to decompose it, turning bottom waters anoxic and sulfur-rich. It then became difficult for oysters to become reestablished, leaving the fishery in a depressed level. Policy Implication: Physically rebuild the reefs and permit oyster populations to recover, and they will restore much of the original water quality of the Bay.

Test: If the reduction of oyster beds were important drivers, then eutrophication should start to intensify as the oysters decline, and BEFORE fertilizer input becomes intense. Re-examine the information in the data table for hypothesis 2 above:

→ Column 2 in Table above: how many indicators of water quality begin to increase steeply between the ~1884 and 1930 [i.e. during the decline in oyster populations but before fertilization from land intensified in the 1940s onward]? _____

→ go back and look at the data graphs for Anoxia (Sulfur & anaerobic bacteria; p. 16):

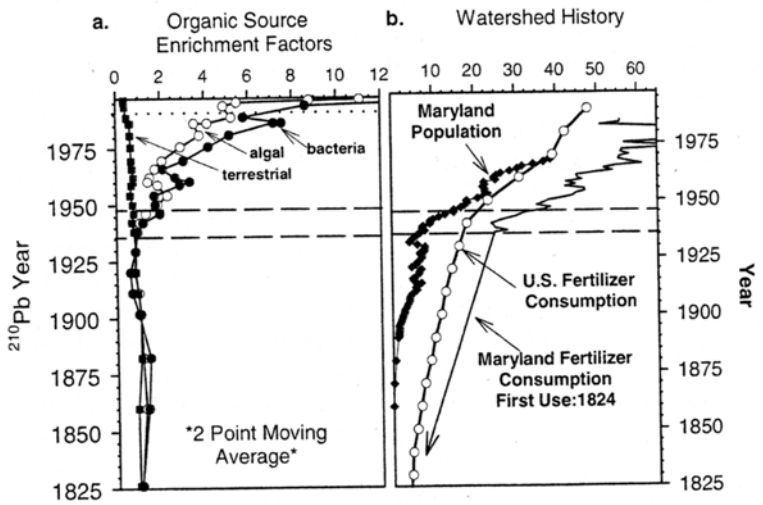
e. did anoxia begin after the oysters started to decline (after 1884)? YES / NO
f. did anoxia begin before fertilizer use intensified (before 1940s)? YES / NO

→ Would you accept or reject Hypothesis 3 that the loss of oysters caused (or permitted) a decline in water quality, and with what confidence?

******** ********** *********

Working Hypothesis 4: The shift in the 1940s/1950 to modern agriculture with its intense use of fertilizers caused a dramatic increase in nutrient supply to the Bay, and this caused a comparable unprecedented rate of increase in eutrophication. This was compounded by concurrent development of the poultry industry and growth in human population, with both contributing additional nutrient load to coastal waters. Policy Implication: reduce fertilizer and waste runoff and the Bay should revert to a healthier state.

Compare trends in this plot from Zimmerman & Canuel 2000 (note that data extend back only to 1825]:
→ Is the timing of the sharp increases in algae and bacteria, relative to the sharp increase in fertilizer consumption, reasonable for fertilizer to the be a causative factor since the 1930s? YES / NO



Pulling it together: A cause-effect environmental history of the Chesapeake Bay

→ Have these changes been driven by natural processes and variability, or by human factors?

_____

→ But which of the many human factors has been key?

Working Scenario: The Bay has experienced a series of different stressors and has declined in successive stages.

Stage 1 [colonial contact to late 1800's)– mild eutrophication due to nutrient input from newly cleared land and early fertilization of land (up until late 1800's). This might have had some negative effects on oyster populations, but oyster-fishery yields continued to rise until 1884, and so the effect was not too severe, even though rates of land clearance continued to rise (to a peak in 1850). Waters remained reasonably clear and healthy, with a relatively small rain of organics to the seafloor and little of this being bacterial in origin.

Stage 2 (late 1800s to ~1930) – continued harvesting of oysters through the late 1800's, but net yield began to decline from 1884 onward despite increasing harvesting effort. This indicates that populations were being fished out: commercial take was at a higher rate than oyster populations could renew themselves, and mechanical dredging was destroying the reef structure, reducing recolonization success. Indicators of declining environmental health start to increase more steeply. By the 1930s the oyster industry collapsed and organic matter loading was sufficient to cause anoxia in bottom waters of medium depth (it began to occur earlier in deeper parts of the Bay).

Stage 3 (1940s onward)– begin modern post-Depression, post-WWII period of growth in US population and development of modern agricultural methods. Results in ever-increasing quantities of nutrients entering the Bay from intense fertilizer use, chicken factories, and urbanization (concentrated waste sources). These nutrients entered a water body with relatively sparse populations of benthic filter feeders because of earlier overfishing, and thus the Bay was a system with little self-cleaning ability. Indicators of eutrophication increase in phase with these new nutrient loads; in fact, based on sedimentary cores, levels of TOC flux etc today are the worst in the history of the Bay, and over the last 10-20 years have been rising at the steepest rates in documented Bay history. Mortality associated with toxic algal blooms and invasion by oyster diseases accompanied this intensifying eutrophication.

→ What are the policy implications of this history? Write a paragraph about the options available to stabilize or reverse these changes, including which factors should (or must) be addressed first, and a <u>second</u> paragraph about the economic & political pro's and con's of such decisions. Consider the multiple sectors of the public in the larger drainage area as well as along the Bay shores that would be affected by regulations concerning the Bay: farmers, coastal real-estate developers, seafood harvesters and seafood wholesale/retailers, private land-owners of shoreline, sport-fishermen, etc.