Results of Prior Research

Dr. Hank Shugart, University of Virginia

Grant: DEB-9411974 (Division of Environmental Biology)

Title: Long-term Ecological Research on Disturbance, Succession, and Ecosystem State Change at the Virginia Coast Reserve: LTER III; Project Period: 11/1/94-10/31/00; See below, Dr. Hayden.

Dr. Stephen Macko, University of Virginia

Grant: EAR-9417836

Title: A Molecular Isotope Perspective on the Processes of Organic Matter Preservation in Fossils; Project Period: 2/95-1/99; Principal Investigator: Stephen Macko

Affiliated Investigators/Collaborators: Dr. M.H. Engel, University of Oklahoma

Research: The results of these experiments provided new insights into biosynthetic processes, using modern analogs and ancient materials, of diagenesis and of preservation. Several new methodologies resulted from this project, including a gas chromatography/combustion isotope ratio mass spectrometry (GC/C/IRMS) method for determining the stable carbon isotope compositions of individual carbohydrates and a GC/C/IRMS method for determining the ^{15}N stable isotope compositions of individual amino acid enantiomers in complex mixtures at nanomole levels. The latter technology was used to determine the first stable nitrogen isotope values for extraterrestrial amino acid enantiomers. Nineteen publications resulted from this grant, including: Engel, M.H. and Macko, S.A. 1997a; Engel, M.H. and Macko, S.A.; 1997b; Engel, M.H. and Macko, S.A. 1997c; Macko, S.A. *et al*. 1997; Macko, S.A. *et al*. 1998; Macko, S.A. and Engel, M.H. 1999; Macko, S.A. *et al*. 1999a; Macko, S.A. *et al*. 1999b; Macko, S.A. *et al*. 1999c; Engel, M.H. and Macko S.A. 1999; Engel, M.H. and Macko, S.A. 2001.

Grant: DEB-9411974 (Division of Environmental Biology); Title: Long-term Ecological Research on Disturbance, Succession, and Ecosystem State Change at the Virginia Coast Reserve: LTER III; Project Period: 11/1/94-10/31/00; See below, Dr. Bruce Hayden, for details.

Dr. Bruce Hayden, University of Virginia

Grant: DEB-9411974 (Division of Environmental Biology); Title: Long-term Ecological Research on Disturbance, Succession, and Ecosystem State Change at the Virginia Coast Reserve: LTER III; Project Period: 11/1/94-10/31/00; Principal Investigator: Bruce P. Hayden (Univ. of Virginia)

Affiliated Investigators/collaborators included Shugart, Macko, Porter

This research focused on ecosystem change as exhibited by disturbance, succession, and state change in a coastal barrier island, lagoon and mainland complex. It focused on three major areas: environmental history, faunal biogeography, and storm-driven ecosystem disturbances. Constructing the history of the site proceeded at two major levels. Oertel and his students studied changes the site had undergone since the Pleistocene using foraminifera (Culver *et al*. 1996; Woo *et al*. 1997), pollen (Woo *et al*. 1998), stratigraphic analyses (Foyle and Oertel, 1997) and analysis of landforms (Oertel and Woo, 1994, Oertel and Foyle, 1995). For a more recent period, Shao, Young and others used remote-sensing linked to ground surveys and historical maps to quantify dramatic changes in the distribution of *Myrica cerifera* shrubs on the barrier islands since 1942 (Hayden *et al*. 1995; Young *et al*. 1995a,b; Shao *et al*. 1998). Changes in climatic patterns that generate storms have dramatic impacts on the island system (Davis *et al*. 1995, Davis *et al*. 1997, Hayden 1999a,b). A surprising conclusion was that there were periods where the geographic patterns of shoreline accretion and erosion reversed (Fenster and Dolan, 1994). From January 1994 through January 2000, this research produced 100 journal articles (84 published or in press, 16 in review). PIs contributed 37 book chapters or published proceedings.

Dr. John Porter, University of Virginia

Grant: DEB-9411974 (Division of Environmental Biology)

Title: Long-term Ecological Research on Disturbance, Succession, and Ecosystem State Change at the Virginia Coast Reserve: LTER III; Project Period: 11/1/94-10/31/00; See above, Dr. Hayden.

Dr. Grace Brush, Johns Hopkins University

Grant: DEB-9411974; Title: Long Term Ecological Research on Human Settlements as Ecosystems: Metropolitan Baltimore from 1797-2100, Principal Investigator: Dr. Steward Pickett, Institute of Ecosystem Studies; subcontract from Institute of Ecosystem Studies: Project Period: 11/97-12/04. Research: The study under this subcontract studies vegetation gradients along a rural to urban gradient; uses pollen analyses to reconstruct vegetation; uses historical documents to reconstruct land use; uses trace metals, particularly chromium, to trace sediment accumulation in the riparian area; and uses sediment cores in the Chesapeake Bay to estimate the effect of human activities in an urbanized watershed on the estuary. Published results include Brush and Zipperer (submitted to Ecology); Groffman *et al* (submitted to Frontiers in Ecology and the Environment)

Grant BES-0119903; Title: Instrumentation to Measure the Emission and Transport of Biological Aerosols into the Atmosphere from Microns to Kilometers (Biocomplexity Project), one of five P.Is, Project Period 9/1/01-8/31/06. Research: The development of instrumentation to measure wind transport of biological aerosols, from their initial release to atmospheric entrainment and transport downwind. The particular application considered is pollen transport.

Introduction

Coupled natural-human ecosystems now tessellate the terrestrial surface of the Earth. There is little land that is not to some degree a consequence of its human inhabitants. Indeed, given the unique capacity of our technological society to alter both the atmosphere and ocean, even remote and unpopulated landscapes are to some degree altered by human activity. But does this human activity affect the stability of the natural-human system? Its resistance to change? Or resilience (the likelihood of returning to its original state after being disturbed)? While humans often assume intuitively that the answer to these questions must be in the affirmative, this project will assess the question quantitatively and qualitatively through advanced socio-environmental systems analysis.

These questions concerning human pressures on the coupled natural-human system are among the most complex to be asked, yet may be the most critical to address in the 21st Century. Anthropologists, archaeologists, historians, scientists, and even policymakers have struggled for centuries to measure natural-human dynamics and their implications for both social and natural change. The approach to this inquiry generally has been to identify constraints imposed on humans by nature in order to explain the range of adaptive poses assumed by human societies. In the context of this project, however, we endeavor to assess the response of the greater natural-human system to the activities of human societies as well. More specifically, we ask whether (and, if so, how) changes in human demographics, land use, and technological capabilities over time influence the resistance, resilience, and stability of coupled natural-human systems.

For the past 5,000 years, the Eastern Shore of Virginia has experienced a remarkable progression of human-terrestrial-estuarine ecosystem interactions that mimic, as a microcosm, a substantial part of our history as a species. With its complex settlement history, rich documentary resources (both historical and scientific), and location at the mouth of one of the world's largest estuaries, the Eastern Shore offers an ideal site for the study and analysis of the complex dynamics of a regional landscape and its inhabitants. Interfaces between terrestrial and aquatic systems make for a particularly fertile region for the study of the reciprocal relationship between people and their environment because they are: (1) highly dynamic; (2) frequently sites of human settlement due to the abundance of natural resources; and (3) acutely sensitive to global change. Our research team has the benefit of an extensive body of information that characterizes the ecosystem and explain its fundamental physical and ecological processes. Remarkably, we also have access to a vast archive of historical records (dating to 1632) and ethnohistorical records (from prior to 1632) to document land use and resource management practices since before the arrival of European settlers.

While the findings of this study will improve our understanding of past, current, and future natural-human dynamics in the Eastern Shore of Virginia, it will also contribute to our awareness of coupled natural-human ecosystems in a more generalizable way as well as in countless land-water interfaces inhabited throughout the world. Moreover, understanding the mutually interacting influences of human society and the environment upon one another is vital to the stewardship of ecosystems, natural resources, and future generations, both from a policy and scientific perspective.

Statement of Purpose

We are an interdisciplinary research team of historians, archeologists, ecologists, paleoecologists, geochemists, and information systems specialists. Our overarching objective is to characterize, quantify, and model the spectrum of coupled natural-human dynamics on the Eastern Shore of Virginia over the past 500 years as, first, Native Americans and, later, European and African colonists and their descendents, interacted with their environment. We will collect and integrate historical, archaeological, ecological, and geochemical data to create human ecosystem models at varying spatial and temporal scales in order to examine the coupled human-terrestrial-aquatic dynamic, including properties such as stability, resistance to change, and resiliency.

We propose this coordinated, interdisciplinary study to improve our understanding of the dynamics of a coupled natural-human system under different social and environmental pressures and through the course of evolving human societies, both technologically and demographically. Our efforts will culminate in the development of integrated human-ecosystem models, which will be parameterized, calibrated, and validated by historical, archaeological, ecological and geochemical data as described below. The models will simulate natural-human systems during specific historical periods that represent changes in human culture, land use, technology, and demographics: Protohistoric (1550-1610); Colonial (1650-1700); Late Plantation (1800-1850); Commercial/Industrial (1850-1950); and Modern/Conservation (1950-present). We intend to investigate system stability, resiliency, and resistance to change during these time periods using standard quantitative procedures (e.g., Monte Carlo analyses and Lyapunov's non-linear stability criteria as described in the Modeling Activities section below). We will evaluate our hypotheses (see below) and identify the critical characteristics of resistant and resilient human-natural systems via principal component analysis (PCA) of the variables included in our models.

HYPOTHESES - We have developed the following three testable hypotheses in which the term "complex" is defined as "complicated, elaborate, or intricate in structure". For the purpose of hypothesis testing, we accept that human demographics, land use practices, and technological capabilities on the Eastern Shore of Virginia have become increasingly complex over time since the arrival of European settlers (e.g., 20th Century society is more complex than 17th Century society).

1. Resistance: Systems with human societies that have more complex demographics, land use practices, and technological capabilities are more *resistant* to perturbation.
2. Resiliency: Systems with human societies that have more complex demographics, land use practices, and technological capabilities are more *resilient* after perturbation.
3. Stability: Human societies are themselves a critical environmental perturbation that drives the future status of the natural-human system.

KEY QUESTIONS

Stability

1. Which, if any, coupled natural-human systems represented by our time period models appear to be stable?

Resistance

2. Which, if any, time period modeled systems exhibit resistance to change, and to what degree? Do systems with human societies that have more complex demographics, land use practices, and technological capabilities exhibit greater resistance to change?
3. What are the critical variables/principal components that contribute to resistance within the modeled systems?

Resilience

4. Which, if any, time period modeled systems exhibit resiliency, and to what degree? Do systems with human societies that have more complex demographics, land use practices, and technological capabilities exhibit greater resiliency?
5. What are the critical variables/principal components that contribute to resiliency within the modeled systems?

In classical dynamics theory and most dynamic systems, one would expect systems that match one of these working hypotheses not to match the other. For example, dynamical systems with the internal inertia to resist external perturbation (i.e., they are resistant) are often unable to rapidly return to their original state once perturbed (i.e., they are not resilient). On the other hand, systems that are able to rapidly return to original operating conditions after perturbation (i.e., they are resilient) often are very responsive to change (i.e., they are less resistant). Thus, the hypotheses are generally thought to be to some degree antithetical to one another. But is this the case in the complex, non-linear, coupled natural-human system that includes human technology and culture?

A distinct advantage of the effort proposed here over most human ecological modeling studies is the broad temporal scope and explicit contrast of distinctive social and technological systems within the same locale. We expect that these efforts will shed light on the complex, non-linear dynamics that characterize the coupled natural-human system at a range of landscape- (and seascape-) scale ecosystems that are nested within the greater human-natural system of the Eastern Shore of Virginia. Identification of salient system characteristics, relative to our hypotheses, may inform current and future policymaking in the Chesapeake Bay catchement and other land-water interfaces inhabited by humans throughout the world. Moreover, lessons learned about the temporal and spatial scales critical to the study of these complex dynamics will strengthen our understanding of complex coupled natural-human system.

Background

The "Eastern Shore" of Virginia sits in the lower tip of the Delmarva Peninsula, enveloped on three sides by the Atlantic Ocean and Chesapeake Bay (see Figure 1). Numerous tidal creeks penetrate the bayside of the peninsula. The seaside is buffered from the ocean by low barrier islands. Between the barriers and the mainland and scattered along the bayside are expansive marshes, the nursery of a myriad of plant and animal life. Human beings have occupied the region for well over 10,000 years, and researchers have a record of human interaction with the environment for longer than perhaps any other site in N. America.

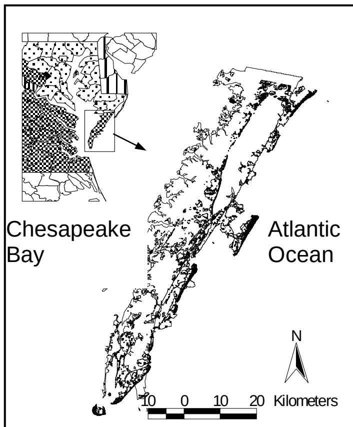


Fig 1. The Eastern Shore of Virginia along the Chesapeake.

Human History – Beginning in the Late Woodland period (1000-500 BP), human interaction with the estuarine system was strengthened to the point that indigenous communities became sedentary on a seasonal basis. Several excavated sites of this age reveal evidence of regular, subterranean food storage and the accumulation of middens, evidence of the establishment of more settled villages in the region. No reliable evidence suggests that horticulture was a factor in the sedentism at this time. By the Protohistoric (500 BP-European contact) period, Native Americans were engaged in extensive maize agriculture. This component of the economy rewarded a new level of residential stability and, as a consequence, more nucleated and permanent settlements were created, often adjacent to tidal creeks.

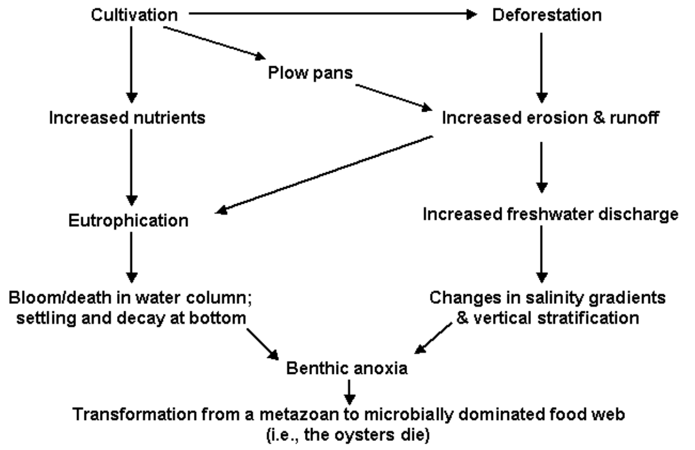
European settlement of the Peninsula began in the first decade of the 17th century. European settlers quickly initiated extensive agricultural development and commerce. A range of agricultural and labor systems developed, beginning with indentured servitude and tobacco production. By 1700, though, Europeans shifted to the use of enslaved persons to work large cash crop plantations. The plantation system that emerged around slavery was not static; instead it shifted constantly to meet market demands, take advantage of new technologies, and move into previously unused lands. Small land holdings were consolidated into large properties with elaborate infrastructures designed for large-scale, profit-oriented, agricultural activity. Towns and connecting road systems were created to foster commerce and it was toward the end of this period that the origins of the modern natural-human ecosystem complex began to form.

By the 1850s a new era was beginning to take shape—one ruled by the development and opportunities of the railroad. The coming of the railroad profoundly changed peninsula’s physical and social landscapes. Traditional industries prospered as farmers and watermen discovered new markets and products. New industries, such as lumbering and tourism, emerged. Changes in agricultural practices, and the application of fertilizers and also contributed to the transformation the landscape. The population boomed, new towns were established along the railroad line, and a network of new roads sprang up to service the towns.

By the 1930s, economic conditions had deteriorated, bringing with it the end of many commercial farming endeavors. Farm abandonment resulted in an increase in forest cover, largely as a result of afforestation. The once substantial market for seafood (oysters, clams, crabs, scallops, and finfish) faced the growing pressure of over-harvesting, pollution (both sewage and nutrient overload in terrestrial runoff), and parasites, which led to the industry’s gradual decline throughout the balance of the 20th Century. In the second half of the century, far-reaching efforts to reclaim or otherwise preserve natural systems (and economic opportunities associated with the management and use of these resources) were initiated by both public and private interests.

Ecosystem Change – In the past 500 years, the Chesapeake watershed has been transformed from totally forested to approximately 40% forested largely as a function of land use practices. After European settlement, the landscape that had previously supported a diversity of forests, ranging from xeric to flooded, changed in rapid succession first into a mosaic of forested patches and small agricultural fields and, later, into large commercially cultivated tracks with only scattered remnants of originally forested stands. The conversion of land to agricultural fields has contributed to decreased evapotranspiration and increased surface runoff. The rate of freshwater discharge into the Chesapeake Bay prior to the introduction of European land use practices is as much as 30% less than under present conditions of 60% deforestation (Bosch and Hewlet 1982). These increases in surface runoff have resulted in increased freshwater discharge into the estuarine system and, eventually, to the gradual increase in freshwater and brackish components in the Bay, with a corresponding change in vertical stratification patterns. Under these conditions, well-oxygenated surface waters are unable to mix with water below the pycnocline. When vertical stratification persists over time, the biological demand for oxygen by organisms living below the pycnocline leads to anoxic conditions. Benthic anoxia is further intensified by estuarine eutrophication, another consequence of post-European land

Figure 2. Effects of European Land Use Practices on the Eastern Shore of Virginia and Chesapeake Bay Ecosystem

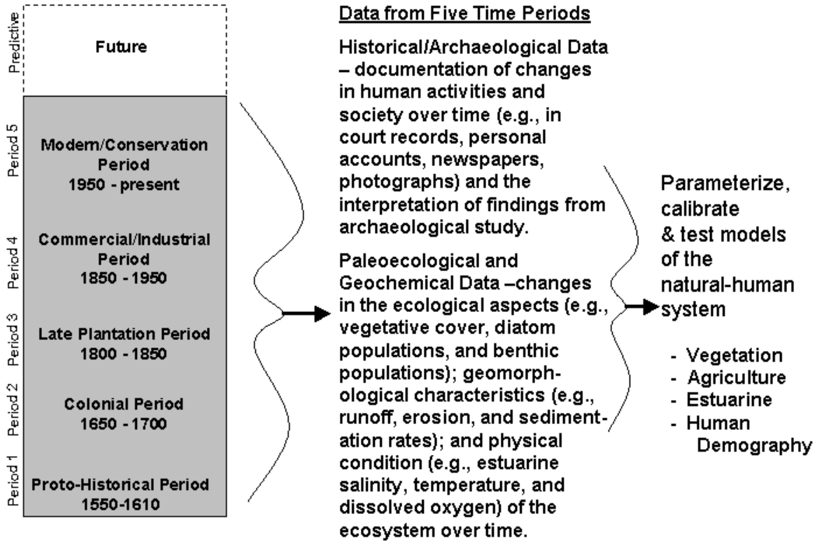


use practices in the Chesapeake catchement due to the increased nutrient load in the runoff associated with N-fertilizer use. Subsequent to a blooming event in the water column, organism death and settling lead to oxygen-consuming decay processes in bottom waters and further contribute to benthic anoxia (Malone *et al*. 1986) (see Figure 2). Land use also affects sedimentation rates within the Bay (Pasternack *et al*. 2001), turbidity (Cooper 1995), light compensation depths, and diatom populations (Cooper and Brush 1993). These dramatic changes in the estuary's physical characteristics also affected its ecology. Perhaps the most obvious example of this impact is the transition of the Bay from a predominantly metazoan-driven food web to the current bacterial-driven food web. This land use-induced induced environmental change also had a tremendous and largely unforeseen impact on a human society that was economically dependent upon the Bay's natural resources (e.g., shellfish harvest/export).

<u>Project Overview</u>

The elements of this project are the elements of the scientific method (observe, hypothesize and test) applied to a complex ecosystem that includes human society as one of its driving components. The project includes the collection of historical, archaeological, ecological, and geochemical data, which will be used to parameterize and validate nested and interactive models of the natural-human system (see Figure 3). Some collection activities will warrant fieldwork whereas other activities will be carried out by the compilation of previously reported records and data. The data will be collected for each of five time periods: Protohistoric (1550-1610); Colonial (1650-1700); Late Plantation (1800-1850); Commercial/Industrial (1850-1950); and Modern/ Conservation (1950-present). Modeling activities will facilitate a study of spatial and temporal scales as they affect the system's complex, non-linear dynamics. Critical characteristics that affect resistance, resilience, and stability will be identified through the use of Monte Carlo simulations and principal component analysis.

Figure 3. Project Synthesis and Overview Presented in Schematic Form



Data Collection Activities

Historical Data **–** Although historic records are not “scientific” data sets in the conventional sense, they contain a wealth of information not otherwise accessible to researchers, and can be used either as inputs to simulations or as “ground truths” against which the results of simulations may be tested. Historical data include court records, personal accounts, newspapers, photographs, and archaeological findings. For more than twenty-five years, the Eastern Shore Public Library (ESPL) has systematically collected material relating to the history of Accomack and Northampton counties, and the general history of the Eastern Shore. Today, the collection consists of more than 1000 printed volumes, 500 rolls of microfilm, and more than 50 linear feet of manuscripts, maps, pamphlets, photographs, photocopies, and public documents. Court records of the Eastern Shore counties of Accomack and Northampton are continuous from 1632 and are among the longest records for the settled regions of British North America. Newspapers and photograph collections contain pictures from the late-19th century showing local agriculture, fisheries, hunting, landscape, transportation, and housing. Other likely historical resources include: *Virginia State Documents*—Statutes-at-large; reports of the commissioners of agriculture, fisheries, forestry; scientific and economic studies compiled by research institutions such as the Virginia Institute of Marine Science, U. Virginia, and the College of William and Mary; *Federal documents*—Reports of house and senate committees and reports of various departments and bureaus such as agriculture, soils, fisheries, forestry, and corps of engineers; and *Personal accounts*—Travelers have visited the Eastern Shore and recorded their impressions in diaries, books, magazines, and newspapers, as have farmers, plantation owners, and others living on the Eastern Shore.

Primary sources published by the U.S. Bureau of the Census provide remarkably detailed quantified data on human population and agricultural activity, especially beginning in the 19th century. These data permit accurate representations of demographic and economic conditions through all but the very earliest historic period. Spatial analyses concerned with population distribution and land use are facilitated by intact property records such as deeds and tax assessments. Census data occur not only in the form of the manuscript census (tracing individual households) but also in other census schedules that track individual agricultural and manufacturing concerns. Access to individual census records is available through 1930. These data will be complemented by individual U.S. Census records (from 1850-1990) at the Integrated Public Use Microdata Series housed at the Minnesota Population Center.

The Virginia Center for Digital History (VCDH) has been mining historic documents, extracting relevant information from them, and storing the information in an easily accessible digital format to be used for historical scholarship since its inception in 1998. VCDH will play a central role in integrating the human textual record with the archaeological, ecological, and geochemical data collected throughout this project. VCDH will simultaneously coordinate synthesis studies to weave these threads of information for specific locations at specific times. In some cases, these synthetic activities will rely upon GIS and information retrieval from diverse historical sources to generate a more complete understanding of human society/environment ecosystems.

Ethnohistorical and Archaeological Data **–** The Protohistorical Period (1550-1610) is best characterized by ethnohistorical and archaeological sources. Ethnohistorical accounts left by English colonists like Captain John Smith (Barbour 1986, Haile 1998) are embedded with diverse, relevant information ranging from Indian population estimates to accounts of Indian subsistence practices to descriptions of the natural environment. These sources have long been productively mined by anthropologists and historians to generate compelling reconstructions of Native American life, including adaptations to the precontact ecosystem (Rountree and Davidson 1997, Kupperman 2000). Based on this work, we will be able to specify seasonal changes in subsistence strategies, including which dietary staples were central according to seasons and how the population dispersed and coalesced accordingly. Archaeological studies include the analyses of burial populations across the region supply good demographic and economic data (Ubelaker 1974, Hutchinson 2002). Sufficient information exists in these sources to construct life tables, as well as gauge (through stable isotope assays) the relative contributions of domesticated plants and marine resources to local diets. Archaeological data are available to support modeling efforts on two primary dimensions: spatial and economic. There is a reasonably representative spatial record of confirmed site locations across the Peninsula. Animal bone, plant remains, shellfish and other evidence can be used to characterize annual rounds (environmental areas targeted in different seasons or years). Archaeological survey data is sufficiently extensive to estimate broad patterns of settlement distribution and function (e.g., Wittkofski 1988, Blanton and Margolin, 1994, Blanton 1996,1999, Lowery 2001). Effective incorporation of archaeological information can be achieved through: (1) *Plot Site Distributions By Time Periods*, in which we will create a comprehensive data file of all known archaeological sites in Accomack and Northampton counties suitable for GIS analyses, including a standardized set of locational, environmental, and cultural variables will be represented in the file; and (2) *Assemble Subsistence Information* that includes ranges of subsistence data. Sources also include paleoenvironmental information such as palynological and sedimentological records generated by archaeological research. When ordered chronologically, these data can be applied to measure changes in human interaction with the local environment.

Consequently it is feasible to compile sound estimates for a host of key variables from documentary sources (see Table 1). Admittedly, the character and precision of even officially published sources can vary. Wherever possible, multiple sets of data (of varying sources) will be integrated to ensure that our interpretation of data and conditions is as accurate and robust as possible. This variable nature of primary data demands the standardization of our proxy sources that will be more common to the earlier time periods.

Table 1. Representative Data Sources for Protohistorical and Historical Periods of Study

Era	***Demographic Evidence***	***Economic Evidence***	***Land Use Evidence***
Protohistoric	Settlmt. Locations	Archaeological fauna	Soil class
	Settlmt. Density	Bioarchaeological data	Elevation
	Settlmt. Sizes	(nutritional stress/infection rates)	Distance to water
	Life tables	Archaeological material culture	Vegetation cover
Historic	Population size	Agricultural statistics	Population density
	Population distribution	(grain production, farm size)	Settlement types
	Population composition	livestock product, farm value)	Soil class
	Cartographic patterns	Commercial statistics	Elevation
		Fisheries statistics	Distance to water
		Tax assessments	Vegetation cover
		Archaeological material culture	Deeds and plats

Paleoecological and Geochemical Data – Records of change in the Chesapeake Bay watershed are documented in pollen, seeds, and geochemistry preserved in its depositional sediments. Seeds of submerged macrophytes show that the aquatic flora has changed considerably in most every part of the Bay and forests were not uniformly distributed throughout the watershed. Rather, the landscape consisted of a mosaic of forest types that differed according to geologic and soil substrates. Changes that occurred within each mosaic were generally synchronous and related to climate change. Human populations that occupied the landscape since at least 10,000 years ago have responded to an environment in which there was great temporal variability and spatial unevenness in resources.

Terrestrial Change - One significant source of ecological/paleoecological data for our work is the Virginia Coast Reserve Long Term Ecological Research (VCR-LTER) site. The VCR-LTER is a complex assemblage of 14 barrier islands, associated inlets and beaches, extensive back barrier islands, shallow bays and deep channels, mud flats, salt marshes, contiguous mainland fringing marshes, deciduous and evergreen forests, and agricultural fields. Island erosion and accretion has reversed direction at least 4 times in the last 350 years (Harris 1992) and most recently in 1967 (Fenster and Dolan 1994). The terrestrial landscape/ecology has undergone substantial state changes within the 20th century as well. Mockhorn Island, once agricultural and formerly forest, has been abandoned and is now a very young salt marsh. One hundred years ago the salt marshes that now fringe the mainland were fenced, upland pastures. The turn of the century bay bottoms with eel grass meadows are now unvegetated (Hayden *et al*. 1991). At the time of "permanent" settlement of Hog Island's town of Broadwater in the mid 1800s, the south end of Hog Island was forested. The island is now an overwash-flat grassland (Rice *et al*. 1976, Hayden *et al*. 1980) and the location of Broadwater is now offshore. The north end of Hog Island was several hundred meters wide and consisted of a narrow beach affronting a marsh in 1852; it is now a complex chronosequence of ridges and swales nearly 1.5 km wide (Hayden *et al*. 1991).

Estuarine Change - Sediment cores will be collected from embayments and other depositional areas throughout the study area. Cores will be sampled at 1 cm intervals and dated using radioactive isotopes, ^{210}Pb and ^{14}C, as well as pollen horizons. Cores are expected to provide a vast body of information about past ecological systems and processes within the embayments and terrestrial patches that contribute sediments to the embayments (see Table 2). For example, diatoms and dinoflagellates, represented by siliceous shells and cysts respectively, are sensitive indicators of eutrophication in estuarine sediments, and will be used to study the dynamics of nutrient enrichment associated with different land uses. Moreover, ratios of arboreal to non-arboreal to ragweed pollen in sediments are also used to reconstruct the history of land use (Brush and Brush 1994).

Table 2. Fossil Indictors from Chesapeake Bay Sediments and Their Interpretation.

FOSSIL	***INDICATIVE OF***	***INTERPRETATION***
pollen grains/seeds	terrestrial vegetation	regional climate; land use
pollen grains/seeds	aquatic vegetation	water quality, salinity
sediment influxes	soil erosion	runoff, turbidity, light limitation
plant pigments	vegetation/algal types	primary producers, grazing
diatoms	spring primary producer	diversity, eutrophication, grazing
dinoflagellates	primary producer	eutrophication, grazing
chrysophyte cysts	diatom/statospore	trophic level of water
zooplankton (copepods)	secondary consumers	grazing, top predators, zooplankton
gastropods	secondary consumers	grazing, consumers, benthic environment
ostracods	secondary consumers	consumers, benthic environment, anoxia
foraminifera	secondary consumers	salinity, anoxia, benthic environment
shells (e.g., small clam)	benthic suspension feeders	benthic environment
C,N,S content	terrestrial/ marine input	land use, sea level change, productivity
soluble Fe	soluble Fe	diagenesis, anoxia
biogenic silica	diatom production	productivity
N,C,S,O isotopes	inorganic/organic matter	sources, land use, sea-level, productivity
chironomid head capsules	chironomid populations	productivity, salinity, acidification, climate

Stable isotope measurements as proxies for paleohistory and climatic reconstruction have potential for supplementing other proxies (Jedrysek *et al*. 1996; Thompson and Bottrell, 1998; Bates *et al*. 1998). Stable isotope analyses (C, N, S, O) will be conducted on the sediment cores to reconstruct the paleoclimate/paleohistory in depositional areas. Nitrogen and carbon isotopes have been useful in assessing productivity in the marine environment (Macko, 1989; Macko *et al*. 1990), while increases in terrestrial input into aquatic systems should be indicated by changes in the ^{15}N in the sediments (Schleser and Kerpen, 1983). Sulfur isotopes should provide supplemental information about changes in fuel use and oxic conditions of the terrestrial environment. Stable isotope compositions can serve as signatures of both the origin of the organic materials, and the specific factors influencing that origin, such as temperature, nutrient levels and productivity. Organic materials in the aquatic environment may originate in the photic zone, or in nearshore environments as terrigenous debris, or as a mixture of these two sources. In numerous environments, relative contributions of terrigenous and marine inputs have been documented through the use of stable carbon isotopes. For example, in the deltas of the Pedernales (Venezuela) (Eckelmann *et al*. 1962), Niger (Gearing *et al*. 1977), Mississippi (Hedges and Parker 1976), Amazon (Cai *et al*. 1988), Orinoco, Nile, and Changjiang Rivers (Kennicutt *et al*. 1987), woody fragments and more finely disseminated terrestrial plant debris give a clear terrigenous isotopic signature to deltaic sediments. Generally, surficial sediments contain increasing amounts of the heavier isotope of carbon (^{13}C) with increasing proximity toward the sea, which is evidence for decreasing influence of land-derived detritus (Sackett and Thompson, 1963; Gearing *et al*. 1977).

In similar fashion, stable nitrogen isotopes may be useful indicators of the source of organic material entering the marine environment. Phytoplankton utilization of nitrogen, and variability reflecting seasonal changes in freshwater inputs, have been documented in the dissolved and particulate components of the Chesapeake Bay (Horrigan *et al*, 1990a, b; Montoya *et al*. 1990). The process of denitrification has been suggested to influence the isotopic composition of materials of the Chesapeake Bay area (Macko 1983). Denitrification reactions on increased nitrogen levels from agricultural fertilizers would account for the modern enrichments in ^{15}N seen in modern plants and sediments of the study area. Interpretation of nitrogen isotopes may be complicated by factors such as microbial action, diagenesis, and recycling of organics. Generally, it is reasonable to assume that changes in isotopic abundances are small or even negligible during diagenesis (Sackett 1964; Myers 1974; Dean *et al*. 1986; Schidlowski *et al*. 1983). However, most large diagenetic changes in isotopic composition have been associated with recent (in some cases recently alive) protein-rich organic materials. Sediments that are not as rich in proteinaceous material (having already undergone diagenesis in the water-column) may uniformly reflect small isotopic shifts, and therefore should be excellent indicators of variations in sources. Variations in sources would allow us to identify sources of carbon and nitrogen (and potentially sulfur) sections of the watershed for different time periods during protohistoric and historic time.

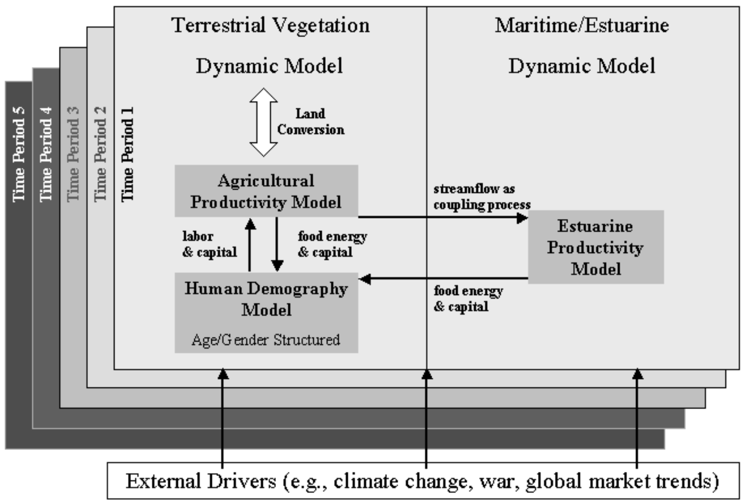
We will also utilize compound specific isotope characterization to identify sediment components and sources. Studies using this technique to date have yielded important information regarding the source and history of the compounds. Isotopic compositions of individual hydrocarbons or fatty acids have the potential for establishing sources for the materials, bacterial or otherwise, and have been useful in correlation techniques both in pollution assessment and origins of sedimentary lipids related to tree waxes (Rieley *et al*, 1991).

Modeling Activities

Environmental change on the Eastern Shore is manifested at a wide range of scales—from abrupt disturbances to progressive changes, often in the same environmental variables. For example, the height of the ocean can vary abruptly over short time scales during hurricanes or winter coastal storms and progressively over long time scales with sea level rise or land subsidence. This dynamism presents past change as a test of our understanding of the ecosystem and an opportunity to test models of the system in real time. We will use dynamic models to represent ecological processes and interactions with human social systems. For several decades, we have been involved in developing an array of models of vegetation and ecosystem dynamics specifically designed to predict the consequences of environmental change (Shugart 1984; 1998). Our modeling approach has been to develop hierarchies of models at different time and space scales that “nest” to feed information from one another and allow for analysis of a given system at a range of spatial and temporal scales. Our work includes individual-based models for a variety of ecosystems in the context of climatic change (Shugart *et al.* 1992, Smith *et al.* 1997) as well as ecological models incorporating physiological and biophysical processes *(*e.g. Gu *et al*. 1999) and dynamic models of mosaic landscapes (*e.g.* Shao *et al.* 1996, Acevedo *et al.* 1996). We are often identified with early and continuing applications of “individual-based models,” a class of models credited with promoting deeper understanding of biocomplexeity (Huston *et al*. 1988).

In all cases, modeling activities will be parameterized with data collected via historical or geochemical research that quantifies the coupled natural-human dynamic of the Eastern Shore, including: human demographics, settlement site selection, land use, economic activity, policymaking, geomorphological change (e.g., shifting barrier islands), terrestrial ecological change (e.g., vegetation patterns), estuarine ecological change (e.g., food web transformations), estuarine physical change (e.g., salinity), and climate change. The VCDH will play a central role in integrating the human textual record with relevant archaeological, ecological, and geochemical data. We believe that this interdisciplinary and, in fact, complementary approach to scholarship will enable us to generate uniquely rich and robust models of the coupled natural-human dynamic. For each of the five time periods identified in Figure 3, we will construct a multiple-commodity dynamic ordinary differential equation model of human populations, natural ecosystems, and agricultural systems. Submodels (see Figure 4) will be the same for all time periods, although internal details will be modified to reflect the technology, land ownership, land use patterns, and environmental conditions of the period. This similar structure will allow direct quantitative comparisons of human/ landscape/seascape at different periods.

Figure 4. Schematic of Submodel Synthesis



***(1) Human Demography Submodel*:** This submodel will be developed as a gender- and age-structured human population model. It may further be partitioned into population strata (Indians, Europeans, African Americans depending on the period) with the resolution being determined by the calibration and test data available. In the oldest time slice, there are ample records of mortality records from archeological investigations to parameterize life table mortalities and indications of population growth (increases in number of village sites and other indications of human presence), which can be used for consistency tests on the resultant demography models. In the historical period, birth and death records supply information for model parameterization and testing.

***(2) Terrestrial Vegetation Submodel*:** We have considerable experience in terrestrial vegetation modeling particularly for forest ecosystems. Our precursor models have been used to reconstruct the past vegetation of the Eastern Shore as far back as 18,000 BP (Bonan and Hayden 1990), to reconstruct the potential effects of Native American burning on the distribution of American Beech on the Eastern Shore (Kirwan and Shugart 2000), and to study vegetative response to changes in disturbance frequency (Fahrig *et al.* 1993) and climate (see Shugart 1998). Moreover, Brush and Zipperer (submitted to Ecology) have shown that changes related to urban hydrology have resulted in a shift from wetland to upland vegetation in the urbanized areas in the Gwynns Falls watershed, Baltimore in NSF Baltimore LTER vegetation studies. Our vegetation model will be developed as a spatially explicit individual-based model distributed at points across the landscape with effects of soils and site incorporated. These are stochastic models driven by environmental conditions and external climate drivers, and include harvests and disturbances. We have tested earlier versions of these models against paleoreconstructions based on palynological data and will do so again with the paleoecological data to be collected in the embayment cores. Individual-based vegetation models are stochastic, requiring that these and other submodels be solved in Monte Carlo simulations.

***(3) Agriculture Submodel*:** We will implement relevant versions of the CERES-series crop models (Goudriaan *et al.* 1999) for the dominant crops planted on the Eastern Shore in the five time periods (Curry *et al*. 1990; Adams *et al*. 1990). Structurally analogous models will be used for non-food crops such as tobacco. Using the pedogenesis component of the CENTURY model (Parton *et al.* 1992) driven by crop or forest productivity models, the expected soil degradation/ rehabilitation can be simulated. Rates of land clearance/abandonment will be extracted from public records. Lauenroth *et al*. 1993 demonstrates our prior experience melding the CENTURY model with the forest simulator FORET (Shugart 1984) under prior NSF funding.

***(4) Estuarine/Maritime Ecosystem Submodel*:** We will use productivity data reported from the Virginia Coast Reserve LTER site to estimate the sustainability and production of estuarine ecosystems and marshes. The model will incorporate external drivers (e.g., sea-level change, salinity change) and change associated with factors from within the coupled human-terrestrial-aquatic system. Variables will include vertical stratification, oxygen levels, nutrient cycling, population types/levels, and food webs within the estuarine system. The submodel will be linked to other modeling components via surface runoff/discharge rates into embayments. Harvested biomass (oysters, clams, crabs, scallops, and finfish) will link to the demographic models.

Model Integration – Each submodel will have different underlying state variables with different dimensions. The human demography model will simulate human numbers in categories of age by gender and group. The terrestrial vegetation/forest submodels will have dynamic variables involving the composition, productivity and density of trees on a landscape. These variables can be transformed into animal habitat, forest yield and other attributes pertinent to the other model sections. The agriculture model will have state variables of productivity and yield per land area, soil condition and climate. Both the vegetation and agriculture model can vary in the land area they represent, which will differ in the different time periods and change dynamically under human action.

Coupling between the submodels will involve multiple commodities. For example, the crop models may demand a given amount of human labor per unit land. Similarly, population growth may demand increased agricultural area and the removal of trees from the forest for construction purposes. While these models are complex, we have prior experience with building simulators of all component parts indicated in Figure 4. We have been involved in early modeling projects stemming from the IBP Human Adaptability Program that simulate indigenous pastoralism, populations, and environment interactions, notably for the Quechua people of the high Andes (Weinstein *et al.* 1979, 1983). We have also assembled similar models for traditional cultures interacting with changing landscapes, including the villages in Jamba Province, Sumatra, Indonesia (the ANDALAS model, see www.icsea.or.id/models/andalas.htm).

Each of these models will be consistent with the data available from the archeological, paleoecological, and historical records of the Eastern Shore landscape in a particular time slice. Moreover, each model will reflect the pervading social, cultural, technological, and economic regime of the period. We have no reason to expect that any particular human/landscape system will be stable (in a systems dynamic sense) and we expect that the systems might change in complex, non-linear ways. While the models are for the same landscapes, there will be different land cover patterns and soil conditions in the initialization of any simulation (due to prior history) and the human cultures will be very different in terms of their technologies and densities. Our interest is in using the models as a concept and data synthesis for the purpose of comparisons to test our central hypotheses.

Hypothesis Testing – To avoid what could become a great collection of "apples-to-oranges" comparisons, we intend to investigate the resiliency, stability, and resistance to change using standard procedures for model inter-comparisons. Because the models are non-linear and stochastic, we will consider stability in a manner analogous to Lyapunov's stability criteria. The system dynamic, as represented by the model when averaged across a Monte Carlo sample of model runs, will have some pattern of change over time. A system will be considered to be stable if it returns to the original dynamic pattern of change when displaced from this path after a perturbation. The amount of perturbation/displacement needed to move the system from its stable state is a measure of relative stability. The system can be further quantified with respect to its resistance to being displaced from its dynamic trajectory (resistance) and by the rapidity of its return to the standard trajectory of change (resilience). The structure and stochasticity of the models precludes formal analysis but these stability measures can be obtained by simulation.

We plan to use the following procedure to obtain these stability measures: (1) Develop a series of computer simulations for each model to establish the expected trajectory of change in the models (in a case in which the system seeks an equilibrium this would be a convergence to a straight line). Since the models are stochastic this would be the average of a large number of independent simulations. (2) Use all variables sampled across the large number of simulations to develop the expected trajectory before running a principal component analysis (PCA) to reduce the dimensionality of the model state-space and scale the variables with respect to their contribution to the overall pattern of variation. The units in a PCA are scaled in standard deviations so that the PCA spaces of different models are normalized with respect to the sources of variation in the simulation. The patterns of the PCA axis can be analyzed to reveal dominant variables in the overall dynamic response of the models. (3) Compute measures of stability, relative stability, resistance and resilience in the PCA space of each model.

Model comparisons can be made among the different PCA spaces because the measures are scaled to the dominant sources of variation in each model. We will compare system properties among the five modeled time periods in order to assess the impacts of increasingly "modern" technological capabilities. Changes can be made to each model, such as the imposition of comparable droughts, by manipulating the environmental drivers to obtain direct comparisons of stability (along with relative stability, resistance and resilience) under equivalent perturbations. We expect that use of time period models as simulators of historical conditions will provide valuable information about the sustainability of historical practices of the natural-human system on a uniquely well-documented landscape.

Additionally, modeled predictions can undergo consistency tests for logical consistency across the data sets. Historical synthesis and modeling outcomes should be consistent with long-term data records. For example, if an increase in human population generates a prediction that land clearing and the number of farms will increase, this should be consistent with changes in composition of the forests observed in other records (such as forest inventory data or pollen cores). Tests against novel information will also be useful: large events such as storms and wildfires exercise change in ecosystem and the dynamic response to these events, both at regional and local scales, tests our predictions. Other sources of novel testing include the use of stable isotopes techniques to assess the degree of coupling between land, estuarine, and human systems. We will analyze heirloom human hair from archived sources to assess the nutritional status of different segments of the human population and use this information to test predicted patterns of terrestrial and estuarine food sources.

Education and Outreach

The use of historical, archaeological, ecological and physical sciences to improve our understanding of the complex dynamic is still a somewhat unique approach to scholarship. We believe it provides for a similarly unique learning opportunity for students who can be exposed to both our methods and findings. Thus, we anticipate an ambitious educational component to our work:

Teleducation – We have developed a cutting-edge, technologically- and pedagogically-robust and proven real time, interactive teleducation program. Real time, interactive courses have been offered between UVa and instructors and students in Mozambique, South Africa, and Virginia (i.e., the College of William and Mary, the Virginia Institute of Marine Science, and Albemarle County, VA High School). Comparable initiatives will promote teaching and learning throughout Virginia (and potentially beyond), including at the Eastern Shore Public Library and Accomack Public Schools (see two Letters of Support).

Elementary and Secondary Education – Educators in the Accomack (VA) Public Schools will help us to develop age-appropriate curricular and extra-curricular materials for K-12 education (see Letter of Support), both on a focused basis on the Eastern Shore and throughout the state of Virginia (web-based study modules that support the Virginia state Standards of Learning (SOLs) for 11th-grade Virginia and U.S. History). The UVa Center for Digital History will publish these free resources to Virginia teachers on the World Wide Web.

Public Outreach – Public outreach will be accomplished via broadly disseminated (Web) and locally focused initiatives, facilitated by an existing agreement between the Eastern Shore Public Library (ESPL) and the VCDH to develop a website devoted to the region's environmental history. ESPL Librarian Dr. Brooks Barnes (see Letter of Support), will coordinate exhibits and presentations to be displayed at the Barrier Island Center (Machipongo, Virginia) and Eastern Shore of Virginia Historical Society (Onancock, Virginia) for community members and other visitors.

Undergraduate Education – Project investigators have prior experience offering upper-level undergraduate courses about modeling human-ecosystem dynamics. This project will spawn another class (to be offered at least three semesters throughout the duration of the project) in which students will use historical and scientific data to model system dynamics. The course will be presented as an interdisciplinary offering between the environmental science, history, and anthropology departments.

Graduate Education – Two doctoral students at UVa will be supported to work at field sites and historical archives, conduct their own project-related research, present at conferences, teach undergraduates, develop interdisciplinary skills, and contribute to K-12 and public outreach efforts.

Postdoctoral Training– Two postdoctoral researchers will conduct major veins of study, mentor of graduate and undergraduate researchers, and organize annual interdisciplinary research retreats.

Broader Impacts

Understanding the mutually interacting influences of human society and the environment upon one another is vital to the stewardship of ecosystems, natural resources, and future generations, both from a scientific and policy perspective. The findings of this study will improve our understanding complex natural-human dynamics on the Eastern Shore of Virginia, in particular, and the countless land-water interfaces inhabited throughout the world in general. Moreover, the identification of variables critical to system resistance, resilience, and stability will inform policymaking in the Chesapeake Bay watershed (and others throughout the world). An ambitious education and outreach program, including K-12 collaboration and pioneering teleducation efforts, ensures that both key findings and methods will be communicated to K-12 students (both on the Eastern Shore and throughout Virginia and beyond), undergraduate and graduate students, and the greater public alike.

Management Plan

- Herman H. Shugart (PI), UVa Center for Regional Environmental Studies and Dept. of Environmental Sciences — Responsible for overall project oversight. Shugart will also lead efforts for modeling of present and past environments.
- Grace S. Brush, (Co-PI), Johns Hopkins University — Palynology and paleoecology analyses.
- Bruce P. Hayden (Co-PI), UVa Dept. of Environmental Sciences and Director, Virginia Coast Reserve Long-term Ecological Research Site — LTER coordination/land-atmosphere dynamics.
- Stephen A. Macko (Co-PI), UVa Center for Regional Environmental Studies and Department of Environmental Sciences — Stable isotope/geochemical analyses.
- William Thomas, (Co-I), UVa Center for Digital History (VCDH)— Historical Synthesis.
- John H. Porter (Senior Personnel), UVa Department of Environmental Sciences and Virginia Coast Reserve Long-term Ecological Research Site — Data management.
- Kimberly A, Tryka, (Senior Personnel), VCDH — GIS and Data synthesis and Archiving.
- Brookes Barnes (Research Fellow), ES Public Library — Outreach and Historical Archives.
- Dennis Blanton (Research Fellow), Anthropology Department, UVa — Archeology.
- Ruth Grillo (Research Fellow), Accomack County Schools — Educational Outreach.

The project involves simultaneous data collection, modeling and historical synthesis across time periods in history and protohistory. The historical synthesis and modeling synthesis will be tested against the incoming data streams from field efforts, which will serve to test the models against new information and also act as a quality filter on the data itself. Educational outreach activities will be initiated in the first year (lesson plans, material for the Virginia "Standards of Learning" tests, and library displays developed in the first and consequent summers by the work of summer fellowships). We will meet annually as a group to coordinate papers and presentations. Meetings among the principals will occur more frequently.

(each X represents two (2) months of work.)

Activity	**Year 1**						**Year 2**						**Year 3**						**Year 4**					
Collection	-	-	x	x	x	x	-	-	x	x	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Analysis	-	-	-	x	x	x	x	x	x	x	x	x	x	x	x	-	-	-	x	x	x	-	-	-
Synthesis	-	-	-	-	-	-	-	-	-	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Reporting	-	-	-	x	-	-	-	-	-	x	-	-	-	-	-	x	-	x	-	-	-	x	-	x
Outreach	-	-	-	-	x	-	-	-	-	-	x	-	-	-	-	-	x	-	-	-	x	-	x	-
Modeling	-	-	-	x	x	x	-	-	x	x	x	-	-	x	x	x	-	-	-	x	x	x	-	-

Year 1	**Year 2**	**Year 3**	**Year 4**
• Archival data collection • Preliminary sample analysis • Field collections • Begin sample analysis • Outreach • Development of Model 1	• Continued sample analysis • Initial synthesis activities • First data finding • Report preparation • Data sharing • Outreach • Development of Model 2	• Complete synthesis across data sets • Report findings • Outreach • Conference presentations • Intensive across data set model testing • Development of Model 3	• Complete synthesis • Report findings • Outreach • Model Tests • Conference presentation; workshop at UVA