Land–Sea Interactions and Human Impacts in the Coastal Zone

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ABSTRACT. The Smithsonian Environmental Research Center (SERC) conducts research on land–sea interactions to understand natural processes and human impacts in linked ecosystems of the coastal zone. Coastal ecosystems support great biological productivity and are of immense ecological and economic importance. In addition, more than two-thirds of the human population resides in the coastal zone, where human activities cause chronic and acute disturbance of every habitat and marked degradation of ecological balance and productivity. The Chesapeake Bay and its Rhode River subestuary are used by SERC as model study systems to conduct long-term, intensive monitoring and experiments. Research at SERC focuses on five grand environmental challenges: (I) impacts of atmospheric change on climate, sea level, ultraviolet radiation, pollutant deposition, and carbon balance; (II) impacts of watershed nutrient discharges causing harmful algal blooms, depletion of oxygen, and destruction of submerged vegetation; (III) food web disruption by pollution and overfishing; (IV) invasive species; and (V) landscape disturbance by agriculture and development. Research by SERC on these grand challenges serves to advise policy and management from improved stewardship of coastal resources.

INTRODUCTION

The coastal zone is of immense economic and environmental importance. More than 50% of the Earth's human population (3 billion people) resides in the coastal zone and relies on the goods and services of coastal ecosystems, and this number is expected to double by 2045 (Creel, 2003). Coastal communities are the most densely populated and fastest growing areas in the United States: 14 of the nation's largest 20 cities are in coastal locations; more than 50% of the U.S. population lives in 17% of the country's land, comprising coastal counties; this population concentration is expected increase to 70% within 25 years; and 23 of the 25 most densely populated counties encompass coastal cities and their surrounding sprawl (Crossett et al., 2004). The coastal environment includes the Earth's most biologically productive ecosystems, and this diverse environment includes unmeasured reserves of strategic minerals, oil and gas, and other nonliving resources. The coastal zone encompasses major hubs of global transportation and commerce and unparalleled opportunities for recreation and tourism, as well as the majority of fisheries and aquaculture industries. At the same time,

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these activities cause chronic and acute disturbance of every coastal habitat: overfishing has removed most large species at the top of the food web, and coastal waters receive most of the waste of urban centers and agricultural runoff of the coastal plain.

Research at the Smithsonian Environmental Research Center (SERC) focuses on land–sea interactions. Scientists at SERC study linked coastal ecosystems to understand natural processes and human impacts in the coastal zone. Ocean productivity is concentrated in the coastal fringe where nutrients run off the land and well up from the deep. The coastal environment includes the Earth's most biologically diverse ecosystems: estuaries, wetlands, mangroves, seagrasses, coral and oyster reefs, kelp forests, and pelagic upwelling areas. Bottom communities and water column processes of the photic zone are most tightly coupled in the nearshore shallows. Coastal waters comprise 95% of the oceans' fisheries. Thus, SERC research focuses on improved stewardship of these marine resources.

CHESAPEAKE BAY AND THE RHODE RIVER SUBESTUARY AS A MODEL SYSTEM

The Smithsonian Environmental Research Center utilizes the nation's largest estuary, Chesapeake Bay and its 177,000 km^2 watershed including six states and the District of Columbia (Figure 1), as its primary research landscape and main study site. In addition to SERC, this study area includes the Smithsonian's museum complex, zoological exhibits, and administrative offices. An area with a long American history of exploitation of coastal resources, the Chesapeake watershed is home to 17 million people, who are mostly concentrated in the urban centers and suburban sprawl of Baltimore, Washington, D.C., and Norfolk. Agriculture, particularly row crops, is the major land use of the Chesapeake watershed, and farming has been the major source of disturbance to the eastern deciduous forest for 400 years.

Established in 1965, SERC owns a unique 1,072 ha land holding for long-term descriptive and experimental studies of linked ecosystems in a model subestuary and subwatershed of Chesapeake Bay—the Rhode River, which is located 40 km east of Washington, D.C., and 10 km south of Annapolis, Maryland (Figure 2). The property at SERC includes cropland, forests in various successional stages, wetlands, and 26 km of undeveloped shoreline; this is the largest contiguous block of land dedicated to environmental research, science education, public access, and stewardship on the western shoreline of Chesapeake Bay. The 585 ha Rhode River subestuary is a shallow (maximum depth = 4 m), soft-bottom embayment in the lower mesohaline zone of the Bay. The facilities at SERC provide strategic support for research at the site and ready access to the rest of the Chesapeake watershed and estuary.

GRAND CHALLENGES OF COASTAL ENVIRONMENTAL RESEARCH

The purpose of this paper is to present examples that highlight SERC's coastal research on five grand environmental challenges. With data sets extending back to the 1970s and 1980s, SERC research monitors decadal-length changes to distinguish seasonal and annual fluctuations from long-term trends in the environment. Importantly, SERC research seeks to determine mechanistic understanding of the causes of change at multiple spatial scales ranging from global change to landscape, watershed, ecosystem, and community levels of organization. The land and long-term studies at SERC's Rhode River site afford multidisciplinary experimental analyses of mechanisms controlling ecological interactions. The research there addresses the grand challenges and advises environmental policy and management for improved stewardship of coastal resources.

Grand Challenge I: Impacts of Atmospheric Change

Human alterations of the atmosphere are causing rapid changes in climate, sea level, ultraviolet radiation, pollutant deposition, and ecosystem carbon balance. Research by SERC on the salt marshes of the Rhode River subestuary provides a good example of the ecological complexities of this challenge. B. G. Drake and colleagues have been conducting the world's longest running experimental manipulation of CO_2 on natural plant communities (1985 to present), which has been testing the effects of rising atmospheric CO_2 concentration in these salt marshes. The experiment measures response of the two dominant plant species at the site: *Spartina patens* and *Scirpus olneyi*. The experiment applied nine treatment combinations of three CO_2 levels in open-top chambers (ambient air at 340 ppm; elevated CO_2 at a twofold increase in concentration of 680 ppm; and a control treatment without chambers) crossed with types of patches (nearly monospecific *S. patens*; nearly monospecific *S. olneyi*; and patches with mixes of the two species) (Drake et al., 1989). Chambers were replaced exactly on replicate marked plots of the nine treatment

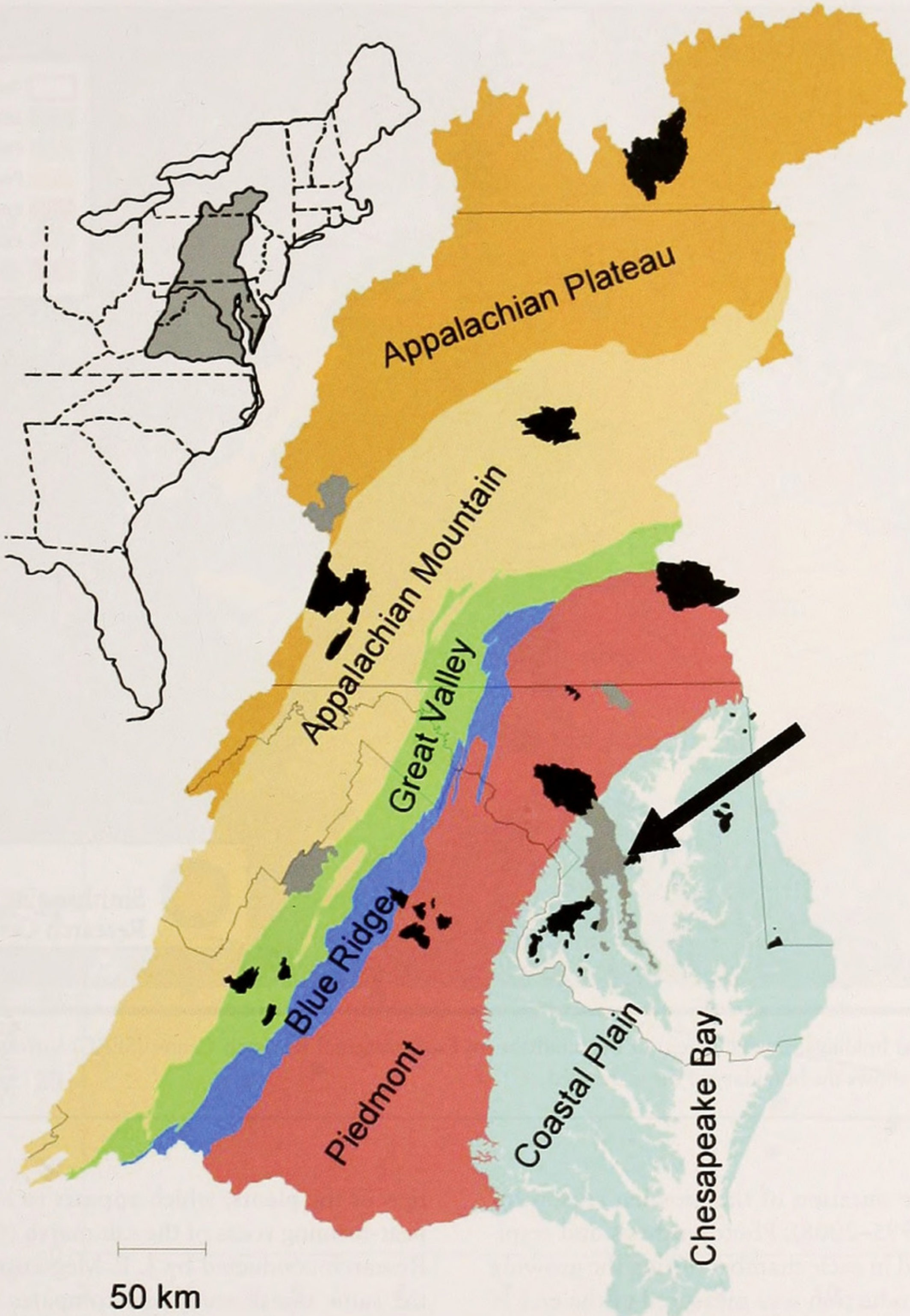

FIGURE 1. Map of Chesapeake Bay and its watershed with six physiographic provinces. Arrow indicates the location of the Smithsonian Environmental Research Center on the Rhode River subestuary and watershed. Darkened areas indicate 17 clusters of 500 subwatersheds that differed in land use and were monitored for stream discharges of nutrients.

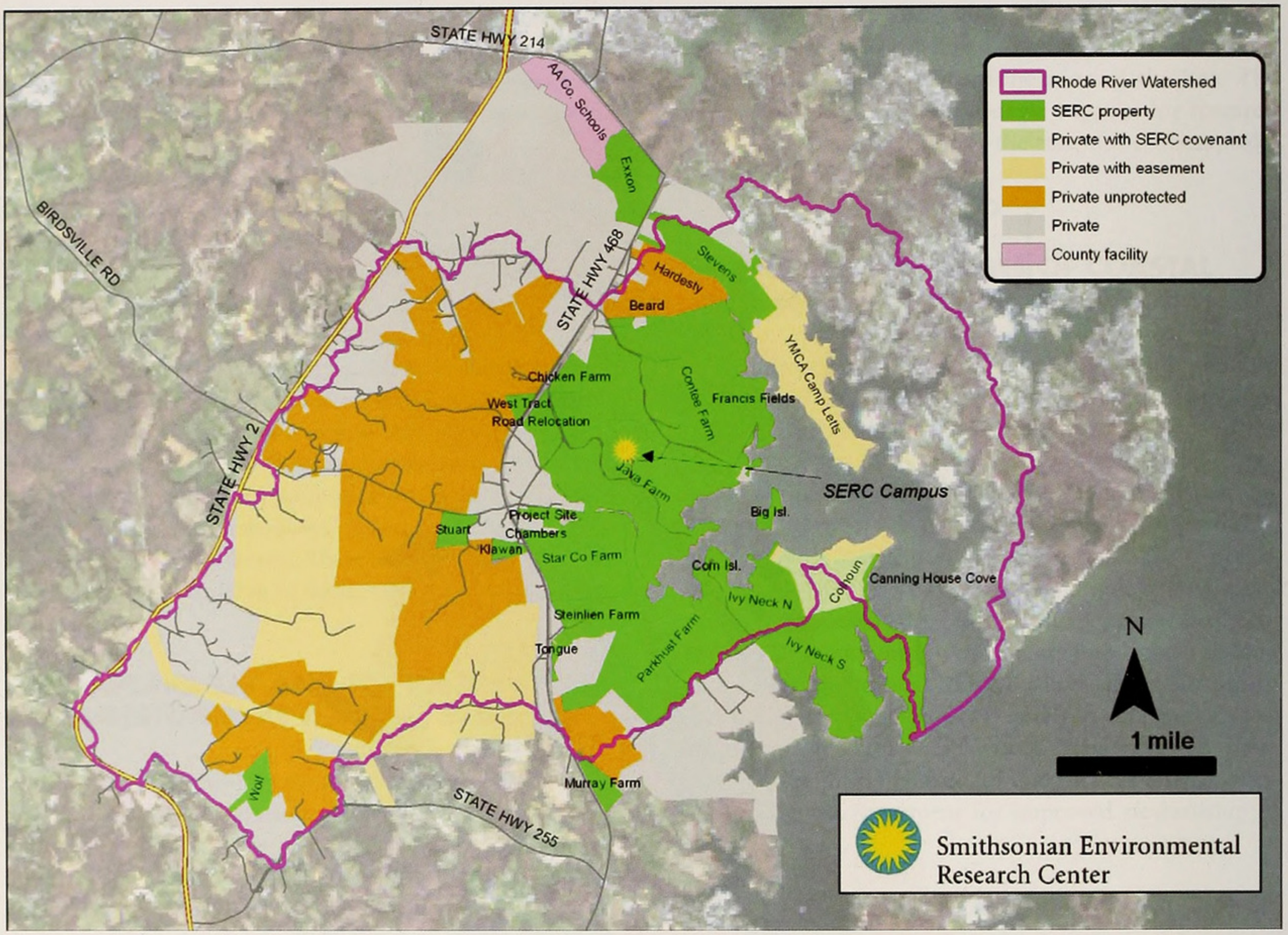

FIGURE 2. Map of land holdings (shaded green) of the Smithsonian Environmental Research Center (SERC) surrounding the Rhode River subestuary. Red outline shows the boundary of the watershed.

combinations for the duration of the growing season for the past 23 years (1995–2008). Photosynthesis and respiration were measured in each chamber during the growing season, and plant production was measured at the end of each season. As predicted, *Spartina patens* is a C_4 plant that responds weakly to rising CO_2, whereas growth and production were greatly stimulated in *Scirpus olneyi* as a C_3 plant (Drake and Rasse, 2003). However, the amount of stimulation of *S. olneyi* is significantly inversely dependent on salinity (i.e., water stress), with lower production in years of high salinities (i.e., low rainfall) (Rasse et al., 2005; and Figure 3).

Salt marsh research at SERC's Rhode River site also explores other ecosystem complexities. New research is tracking the fate of the carbon added by growth stimulation of the plants, which appears to be sequestered in the peat-forming roots of the salt marsh (Carney et al., 2007). Research conducted by J. P. Megonigal and colleagues at the same marsh study site compares effects of increased CO_2 interacting with nutrient additions to the marsh to determine whether peat accumulation is sufficient to keep up with rising sea level. Their initial results indicate that the peat accumulation is equivalent to the current rate of sea-level rise of approximately 3 mm year^{-2}, allowing the marsh to persist instead of becoming submerged. Additionally, a nonnative species, Phragmites australis, is rapidly invading the marsh site, similar to most others in the region (King et al., 2007); and its responses to the interaction of rising CO_2 and nutrients are unknown. The Chesapeake region has high levels of mercury deposition

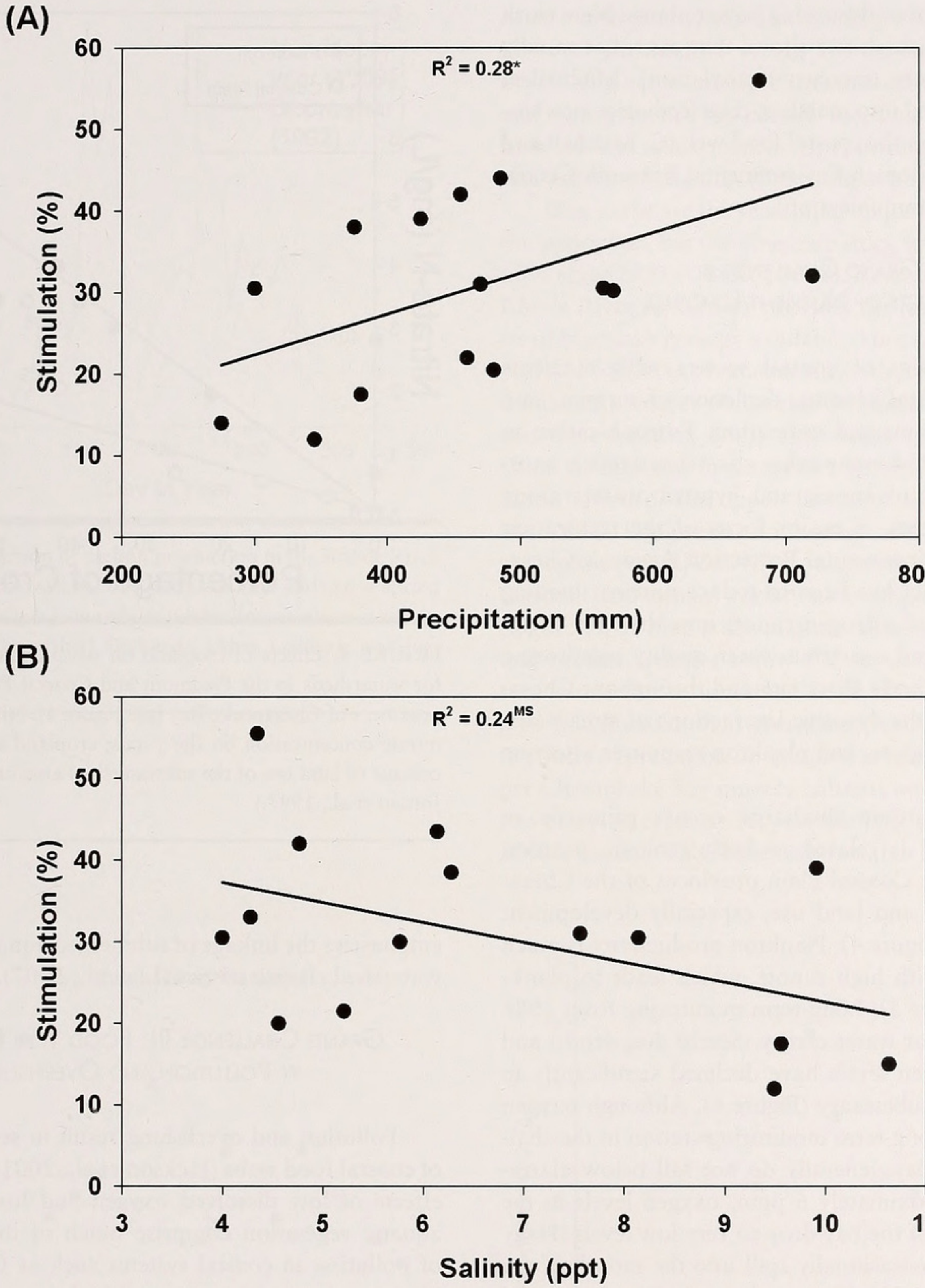

FIGURE 3. Effect of (A) precipitation and (B) salinity (ppt = parts per thousand) on the stimulation of photosynthesis by twofold increase in CO_2 concentration on the sedge *Scirpus olneyi* in open-top chambers placed on a salt marsh of the Rhode River subestuary during a 17-year period (1989–2003). (After Rasse et al., 2005.)

that is derived from coal-burning power plants. New work at the SERC salt marsh site shows that microbes rapidly activate the mercury (mercury-methylation) (Mitchell et al., 2008) deposited into marshes, thus feeding it into biological processes on the coastal food web (C. Mitchell and C. Gilmour, Smithsonian Environmental Research Center, 2008, personal communication).

Grand Challenge II: Impacts of Nutrient Loading

Over-enrichment of coastal waters with nutrients causes harmful algal blooms, depletion of oxygen, and destruction of submerged vegetation. Eutrophication in Chesapeake Bay and many other coastal systems is causing "dead zones" of anoxic and hypoxic waters along deeper bottom areas. A major focus of the restoration efforts of the Environmental Protection Agency's Chesapeake Bay Program has been to reduce nutrient loading by phosphorus and nitrogen runoff into the Bay. Long-term watershed and estuarine water quality monitoring by SERC at the Rhode River site and throughout Chesapeake Bay shows the dynamic interactions of stream discharge, nutrient inputs, and plankton responses affecting oxygen levels.

Watershed nutrient discharge occurs primarily in storm events and is related to both geologic position (e.g., Piedmont or Coastal Plain provinces of the Chesapeake watershed) and land use, especially development and agriculture (Figure 4). Plankton productivity is much higher in years with high runoff, which leads to plankton blooms (Figure 5). Long-term monitoring from 1986 to 2004 shows that water clarity (Secchi disc depth) and near-bottom oxygen levels have declined significantly in the Rhode River subestuary (Figure 6). Although oxygen levels at SERC's long-term monitoring station in the shallow edge of the Bay generally do not fall below alarming levels of approximately 6 ppm, oxygen levels in the deeper mainstem of the Bay drop to very low levels (Hagy et al., 2004) and occasionally spill into the mouth of the Rhode River, killing benthic organisms (A. Hines, personal observations).

With the decline in water clarity, light levels are not sufficient to support growth of seagrasses and other submerged aquatic vegetation, which had largely disappeared from the Rhode River subestuary and much of Chesapeake Bay by the early 1970s. These structured ecosystems are important nursery habitats for fish and crabs in coastal systems such as Chesapeake Bay. Recent SERC research

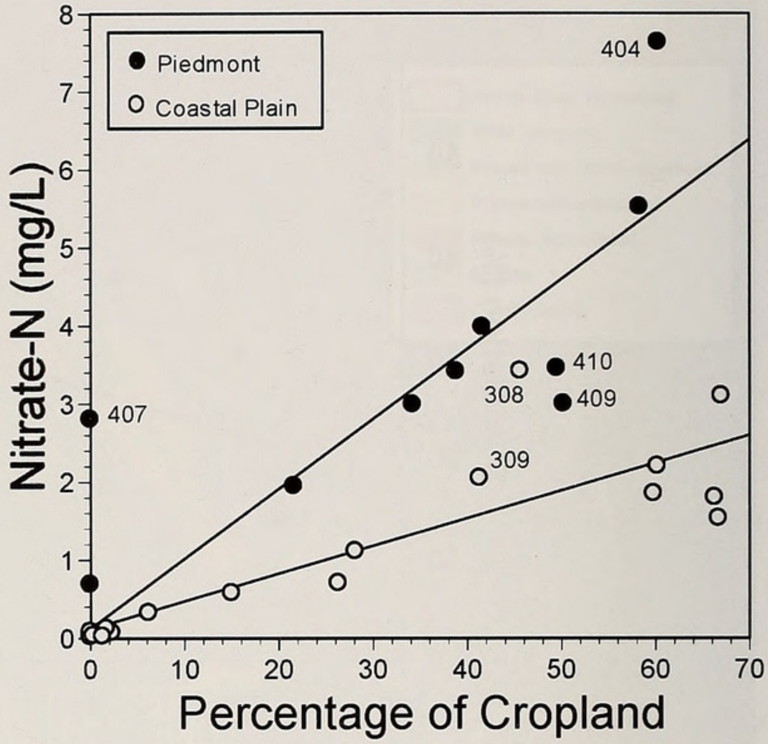

FIGURE 4. Effects of cropland on stream discharge of nitrogen for watersheds in the Piedmont and Coastal Plain physiographic provinces of Chesapeake Bay (see Figure 1). Nitrogen is shown as nitrate concentration on the *y*-axis; cropland is shown as a percentage of land use of the subwatershed area on the *x*-axis. (After Jordan et al., 1997.)

emphasizes the linkage of submerged aquatic vegetation to watershed characteristics (Li et al., 2007).

Grand Challenge III: Food Web Disruption by Pollution and Overfishing

Pollution and overfishing result in severe disruptions of coastal food webs (Jackson et al., 2001). The combined effects of low dissolved oxygen and loss of submerged aquatic vegetation comprise much of the major impact of pollution in coastal systems such as Chesapeake Bay. However, inputs of mercury and other toxic chemicals also markedly affect the food web as they become concentrated at its upper levels, often causing serious effects on seafood that affect human health (Krabbenhoft et al., 2007). Impacts of overfishing and habitat loss have resulted in the loss of sustainable stocks for nearly every fishery species in Chesapeake Bay and in nearly every coastal system worldwide. After a century of intense exploitation, disease, and ecosystem impacts, oysters, as the Bay's most productive

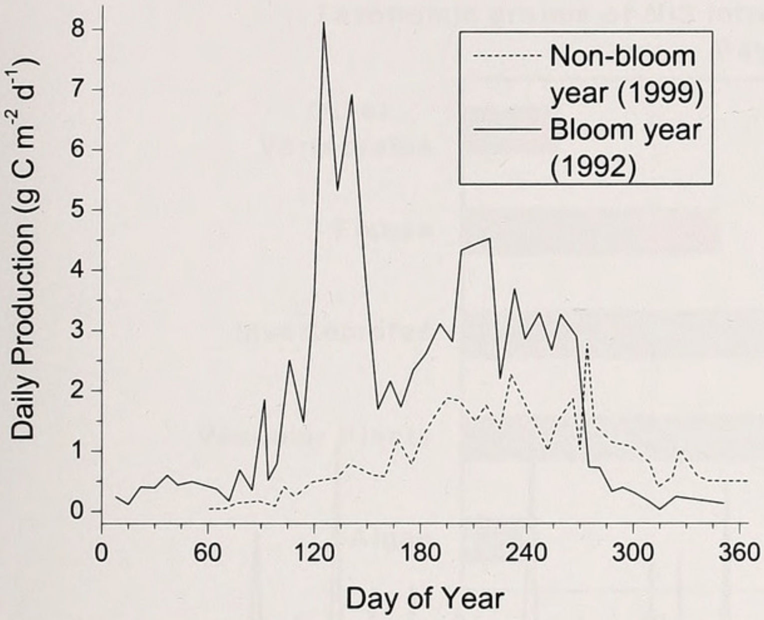

FIGURE 5. Comparison of carbon production in the Rhode River subestuary during two years, one with and one without a spring plankton bloom, which is mainly regulated by variation in spring precipitation and watershed discharge. (After Gallegos and Jordan, 1997.)

fishery historically, are now at only 1% of their biomass in 1900 (Rothschild et al., 1994). Eutrophication and overfishing act as multiple stressors on coastal food webs, and management's too narrow focus on single factors may have adverse consequences for restoring ecosystem health and fishery production (Breitburg et al., 2009).

Blue crabs are the remaining major lucrative fishery in the upper Bay, but the blue crab stock has also declined by 60% since 1991 (CBSAC, 2008). Research by SERC at the Rhode River subestuary provides the most detailed analysis of blue crab ecology available (Hines, 2007). Nearly 30 years of SERC experiments show that blue crabs are the dominant predator on benthic communities in the estuary, and their foraging limits abundance and species composition of infaunal invertebrates as well as causing major bioturbation of the upper 10 cm of sediments (Hines et al., 1990). Long-term monitoring of fish and blue crabs throughout the Rhode River subestuary shows the marked seasonal and annual variations in population abundance (Figure 7), as blue crabs migrate from the nursery habitat and become inactive below 9°C in winter. Annual variation in recruitment into the Rhode River causes more than a 10-fold fluctuation in abundance, with obvious variation in effects of predation on infaunal invertebrates. Many upper Chesapeake Bay nursery habitats now appear to be below carrying capacity for juvenile blue crabs (Hines et al., 2008). Recent SERC blue crab research has focused on de-

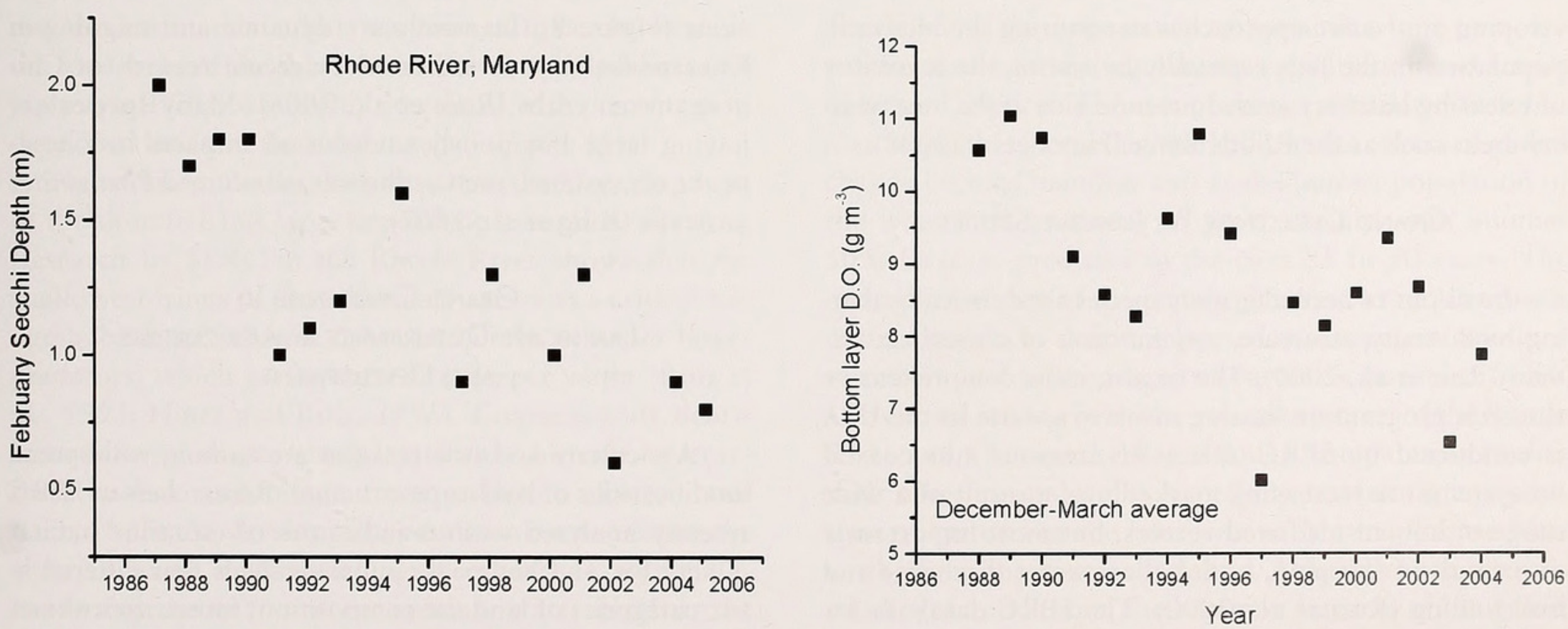

FIGURE 6. Long-term trends in water clarity as determined by Secchi (disk) depth (left) and in oxygen concentration (D.O. = dissolved oxygen; right) in the Rhode River subestuary. (Figure courtesy of C. Gallegos.)

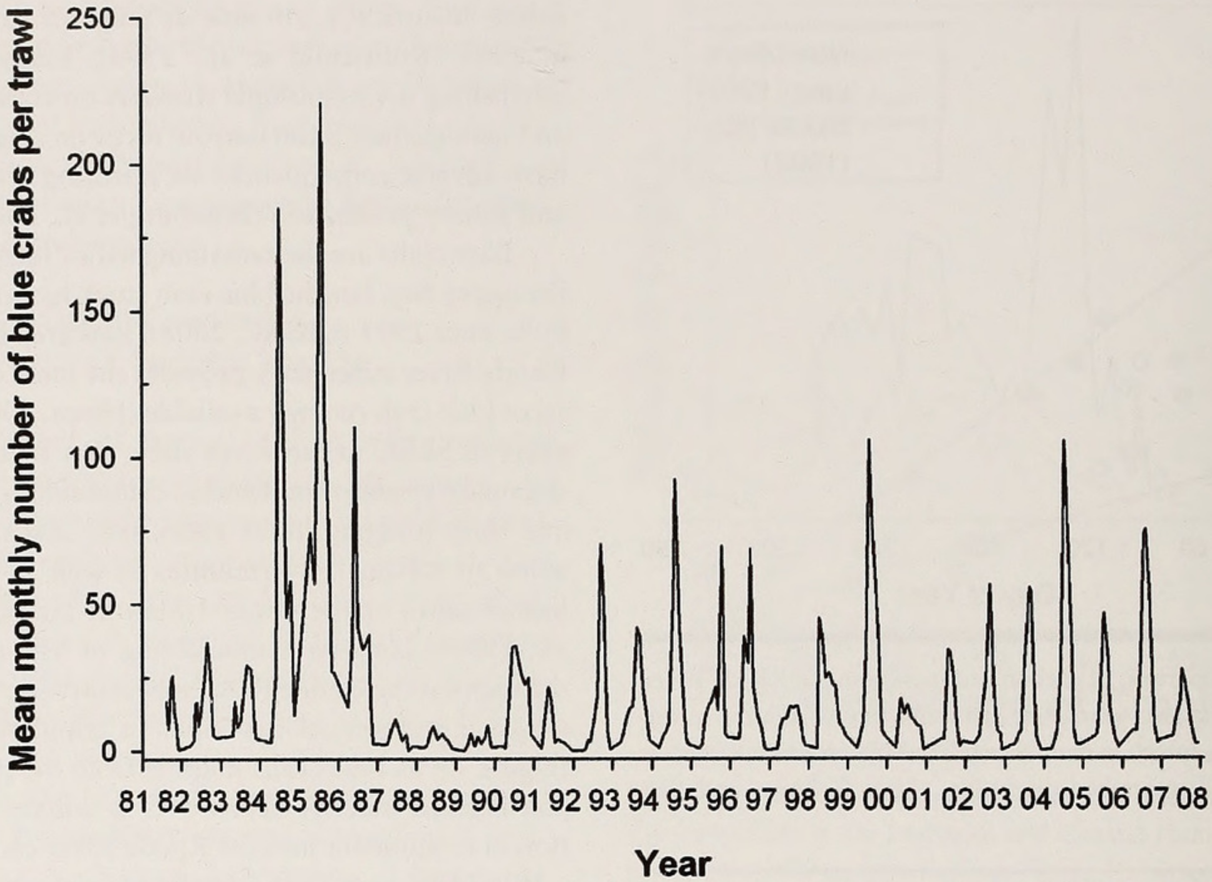

FIGURE 7. Seasonal and annual variation in abundance of blue crabs caught in 3 m otter trawls in the Rhode River subestuary. Abundance is the monthly mean of three trawls at each of three permanent stations within the estuary.

veloping innovative approaches to restoring the blue crab population in the Bay, especially by testing the feasibility of releasing hatchery-reared juvenile blue crabs into nursery areas such as the Rhode River (Hines et al., 2008).

Grand Challenge IV: Invasive Species

Invasions of nonindigenous species are drastically altering biodiversity, structure, and function of coastal ecosystems (Ruiz et al., 2000). The largest, most comprehensive research program on marine invasive species in the USA is conducted by SERC. Rates of invasion into coastal ecosystems are increasing markedly as a result of a wide range of human-mediated vectors, but most importantly as a result of shipping, both ballast water discharge and hull fouling (Ruiz et al., 2000). The SERC database for invasive species (NEMESIS) documents more than 500 invasive species of invertebrates, algae, and fish in North American coastal waters. For Chesapeake Bay approximately 176 species are documented as established invasions (Figure 8). Invasions are dynamic and ongoing in Chesapeake Bay, as indicated by recent records of Chinese mitten crabs (Ruiz et al., 2006). Many species are having large but poorly understood impacts in Chesapeake ecosystems, such as the salt marsh reed *Phragmites australis* (King et al., 2007).

Grand Challenge V: Landscape Disturbance by Agriculture and Development

Agriculture and urbanization are causing widespread modifications of landscape structure. Researchers at SERC recently analyzed various indicators of estuarine habitat quality for 31 Chesapeake subwatersheds that differed in five categories of land use composition: forest, agriculture, developed, mixed agriculture, and mixed developed (Figure 9). These land uses have profound effects on estuarine habitat quality because they increase stormwater runoff and loading of nutrients. Nitrogen discharge into subestuaries of

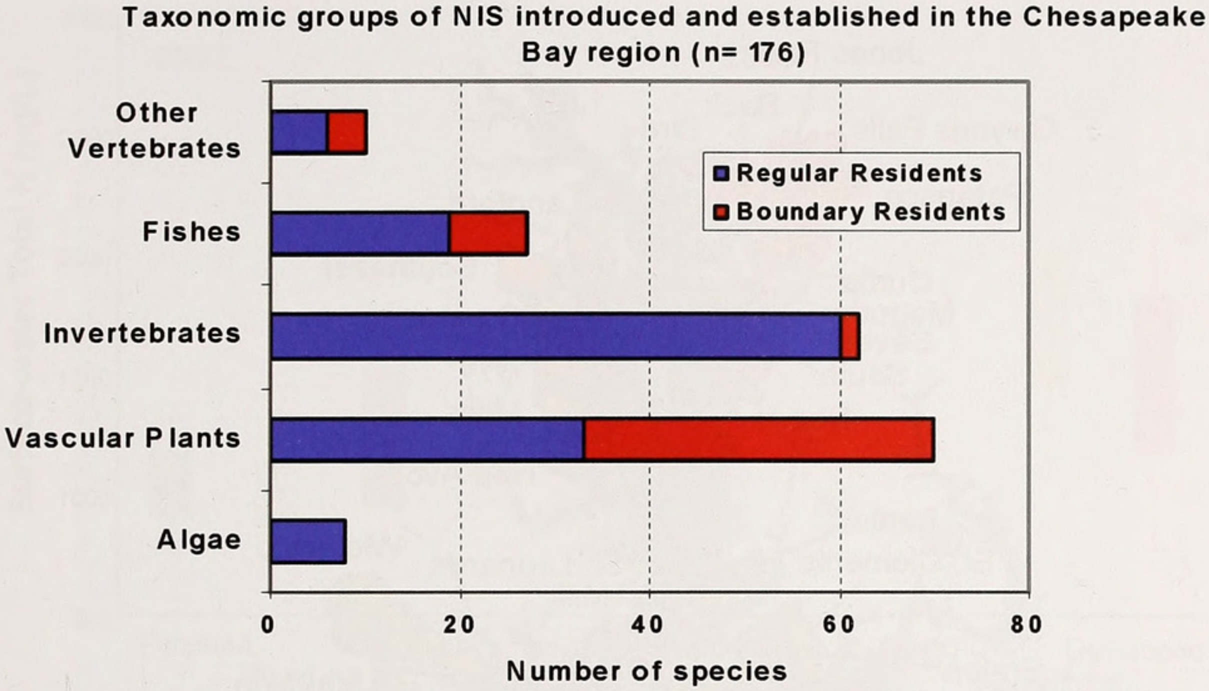

FIGURE 8. Numbers of invasive species documented for algae, vascular plants, invertebrates, fishes, and other vertebrates (total number = 176 species) in Chesapeake Bay. Regular residents are species living in habitats below tidal influence; boundary residents are species primarily living either above the intertidal zone or in non-tidal freshwater and that occasionally move into tidal portions of the Bay. (NIS = noninvasive species.)

agricultural and developed watersheds was high in both wet and dry years, but in dry years it was high only in developed watersheds, which continue to have high human water use regardless of rainfall (Figure 10) (Brooks et al., 2006). Land use also has marked effects on levels of toxic chemicals in the food webs of the subestuaries. Level of polychlorinated biphenyls (PCBs) was highly correlated with percentage of developed lands on the subwatershed (Figure 11).

In addition to effects on the watershed, development of the shoreline has large impacts on coastal ecosystems. Research by SERC in the Rhode River shows that the shallowest fringe of the subestuary serves as a critical refuge habitat for juvenile fishes and crabs to avoid larger predators, which are restricted to deeper water (Ruiz et al., 1993; Hines and Ruiz, 1995). Coarse woody debris from forested shores also plays a valuable role as structural habitat and refuge from predators (Everett and Ruiz, 1993). As development results in cutting down the riparian forest and hardening the shoreline with bulkheads and riprap to prevent erosion, water depth at the shoreline increases and the source of woody debris is lost. With the loss of functional refuge in the nearshore shallows, juvenile fish and crabs become increasingly accessible to predators.

CONCLUSION

The decadal data sets generated by SERC for the linked ecosystems of the Rhode River and Chesapeake Bay clearly show the importance of sustaining long-term, intensive studies to distinguish natural variation and trends of human impacts. The rate of change associated with human impacts is increasing markedly as the effects of global change become manifest and as the human population of the watershed continues to grow rapidly, with another 50% increase predicted in the next 25 to 50 years. The interactive effects of these multiple stressors require much more research to define improved management solutions to restore and sustain these resources. Scientists at SERC also extend studies of the large-scale systems of the Rhode River and Chesapeake Bay through comparative studies with other coastal areas, especially latitudinal comparisons of systems in the Smithsonian Marine Science Network along the western Atlantic. Although each site has its idiosyncratic traits, the common impacts of the grand challenges of atmospheric change, nutrient loading, food web disruption by pollution and overfishing, invasive species, and land development are all manifested pervasively in the linked ecosystems throughout the coastal zone.

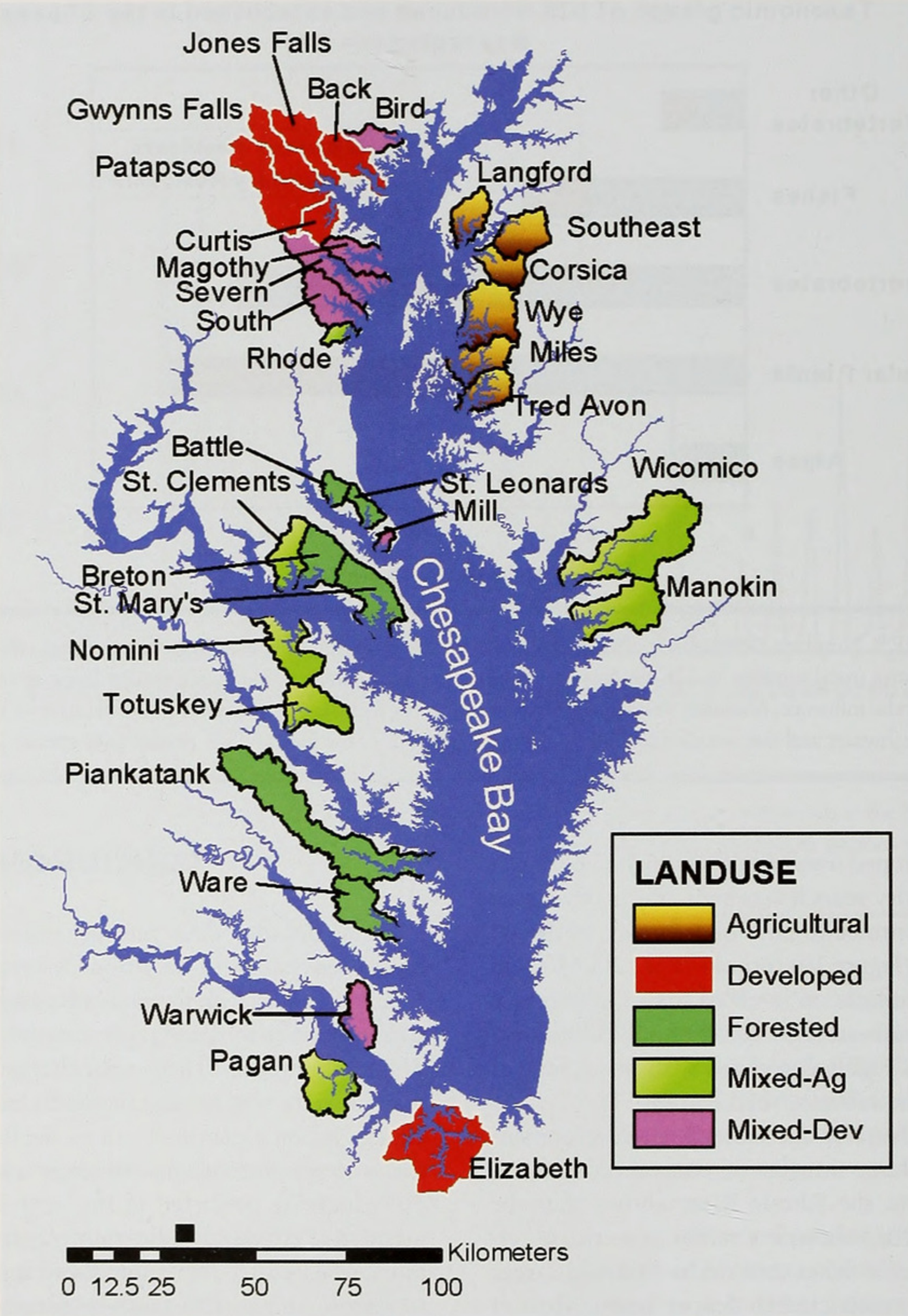

FIGURE 9. Map of 31 subwatersheds of Chesapeake Bay that were sampled for effects of land use on estuarine habitats. Watersheds were categorized in the five predominant categories shown: forest, agriculture, developed, mixed-agriculture, and mixed-developed.

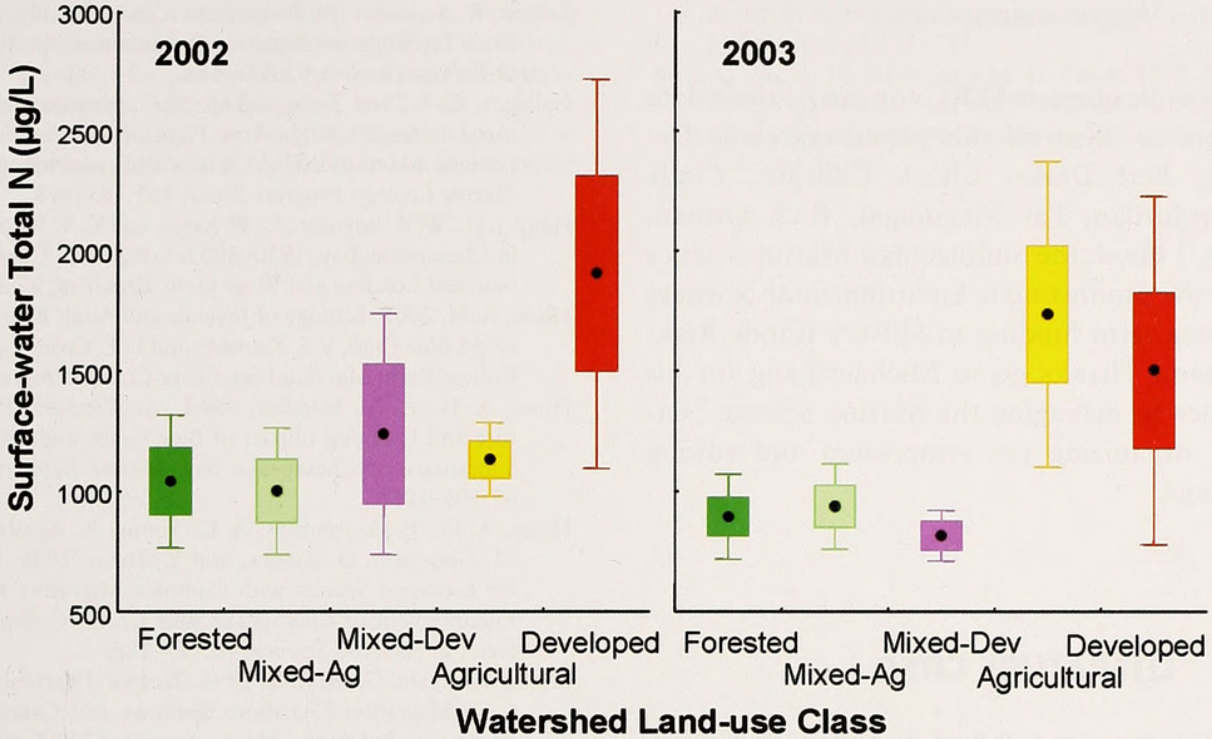

FIGURE 10. Effect of land use on nitrogen discharge from watersheds in the five land use categories shown in Figure 9. Stream surface discharges are compared among land use categories between a dry year with record low rainfall (2002, left) and a wet year (2003, right) with high rainfall. (After Brooks et al., 2006.)

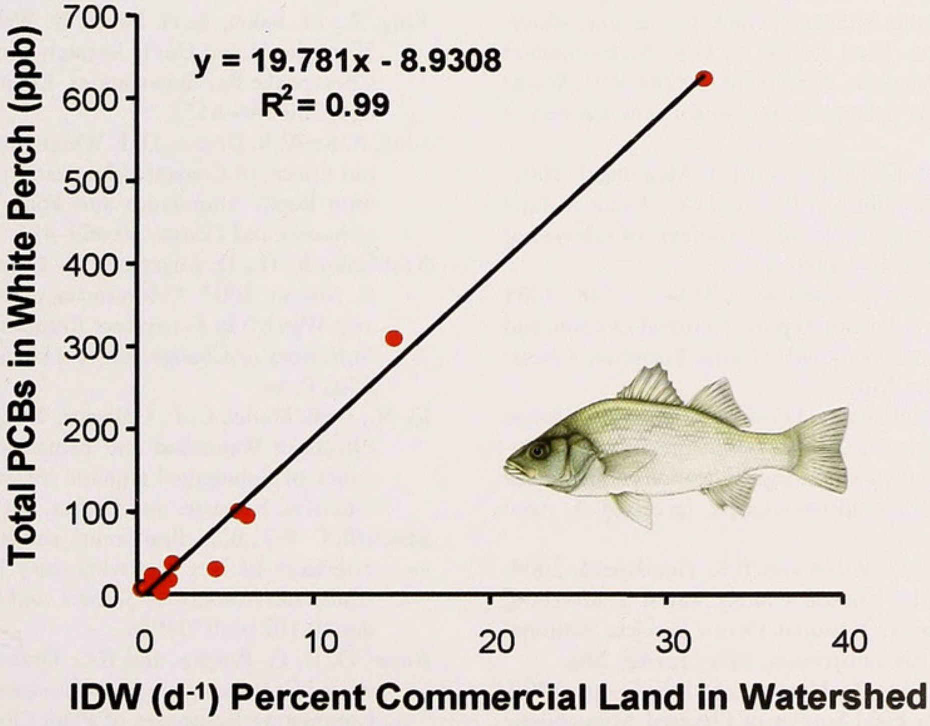

FIGURE 11. Concentration of toxic polychlorinated biphenyls (PCBs) in white perch (*Morone americana*) sampled from Chesapeake subestuaries with watersheds of varying percentages of commercially developed land use (IDW = inverse distance weighted). Watersheds sampled are shown in Figure 9. (After King et al., 2004.)

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LITERATURE CITED

Breitburg, D. L., J. K. Craig, R. S. Fulford, K. A. Rose, W. R. Boynton, D. Brady, B. J. Ciotti, R. J. Diaz, K. D. Friedland, J. D. Hagy III, D.R. Hart, A. H. Hines, E. D. Houde, S. E. Kolesar, S. W. Nixon, J. A. Rice, D. H. Secor, and T. E. Targett. 2009. Nutrient Enrichment and Fisheries Exploitation: Interactive Effects on Estuarine Living Resources and Their Management. *Hydrobiologia*, http://www.springerlink.com/content/02q02l4638972r18 (accessed 1 April 2009).

Brooks, R. P., D. H. Wardrop, K. W. Thornton, D. F. Whigham, C. Hershner, M. M. Brinson, and J. S. Shortle, eds. 2006. Integration of Ecological and Socioeconomic Indicators for Estuaries and Watersheds of the Atlantic Slope. Final Report to U.S. Environmental Protection Agency STAR Program, Agreement R-82868401, Washington, D.C. Prepared by the Atlantic Slope Consortium, University Park, Penn.

Carney, K. A., B. A. Hungate, B. G. Drake, and J. P. Megonigal. 2007. Altered Soil Microbial Community at Elevated CO_2 Leads to Loss of Soil Carbon. *Proceedings of the National Academy of Sciences of the United States of America*, 104:4990–4995.

Chesapeake Bay Stock Assessment Committee (CBSAC). 2008. 2008 Chesapeake Bay Blue Crab Advisory Report. National Oceanic and Atmospheric Administration, National Marine Fisheries, Chesapeake Bay Office, Annapolis, Md.

Creel, L. 2003. Ripple Effects: Population and Coastal Regions. Population Reference Bureau, 1875 Connecticut Ave., NW, Suite 520, Washington, D.C. 20009 USA. http://www.prb.org/Publications/PolicyBriefs/RippleEffectsPopulationandCoastalRegions.aspx (accessed 1 April 2009).

Crossett, K. M., T. J. Culliton, P. C. Wiley, and T. R. Goodspeed. 2004. Population Trends along the Coastal United States: 1980–2008. Coastal Trends Report Series, National Ocean Service, National Oceanic and Atmospheric Administration, Silver Spring, Md.

Drake, B. G., P. W. Leadly, W. J. Arp, D. Nassiry, and P. S. Curtis. 1989. An Open Top Chamber for Field Studies of Elevated Atmospheric CO_2 Concentration on Saltmarsh Vegetation. *Functional Ecology*, 3:363–371.

Drake, B. G., and D. P. Rasse. 2003. The Effects of Elevated CO_2 on Plants: Photosynthesis, Transpiration, Primary Productivity and Biodiversity. *Advances in Applied Biodiversity Science*, 4:53–59.

Everett, R. A., and G. M. Ruiz. 1993. Coarse Woody Debris as a Refuge from Predation in Aquatic Communities. An Experimental Test. *Oecologia (Berlin)*, 93:475–486.

Gallegos, C. L., and T. E. Jordan. 1997. Seasonal Progression of Factors Limiting Phytoplankton Pigment Biomass in the Rhode River Estuary, Maryland (USA). I. Controls on Phytoplankton Growth. *Marine Ecology Progress Series*, 161:185–198.

Hagy, J. D., W. R. Boynton, C. W. Keefe, and K. V. Wood. 2004. Hypoxia in Chesapeake Bay, 1950–2001: Long-Term Change in Relation to Nutrient Loading and River Flow. *Estuaries*, 27:634–658.

Hines, A. H. 2007. Ecology of Juvenile and Adult Blue Crabs. In *Biology of the Blue Crab*, V. S. Kennedy and L. E. Cronin, eds., pp. 565–654. College Park: Maryland Sea Grant College Program.

Hines, A. H., A. M. Haddon, and L. A. Wiechert. 1990. Guild Structure and Foraging Impact of Blue Crabs and Epibenthic Fish in a Subestuary of Chesapeake Bay. *Marine Ecology Progress Series*, 67:105–126.

Hines, A. H., E. G. Johnson, A. C. Young, R. Aguilar, M. A. Kramer, M. Goodison, O. Zmora, and Y. Zohar. 2008. Release Strategies for Estuarine Species with Complex Migratory Life Cycles: Stock Enhancement of Chesapeake Blue Crabs, *Callinectes sapidus*. *Reviews in Fisheries Science*, 16:175–185.

Hines, A. H., and G. M. Ruiz. 1995. Temporal Variation in Juvenile Blue Crab Mortality: Nearshore Shallows and Cannibalism in Chesapeake Bay. *Bulletin of Marine Science*, 57:885–902.

Jackson, J. B. C., M. X. Kirby, W. H. Berger, K. A. Bjorndal, L. W. Botsford, B. J. Bourque, R. H. Bradbury, R. Cooke, J. Erlandson, J. A. Estes, T. P. Hughes, S. Kidwell, C. B. Lange, H. S. Lenihan, J. M. Pandolfi, C. H. Peterson, R. S. Steneck, M. J. Tegner, and R. R. Warner. 2001. Historical Overfishing and the Recent Collapse of Coastal Ecosystems. *Science*, 293:629–638.

Jordan, T. E., D. L. Correll, and D. E. Weller. 1997. Relating Nutrient Discharges from Watersheds to Land Use and Stream Flow Variability. *Watershed Resources Research*, 33:2579–2590.

King, R., M. Baker, A. H. Hines, D. Weller, and D. F. Whigham. 2004. Watershed Land Use Is Strongly Linked to PCBs in White Perch in Chesapeake Bay Subestuaries. *Environmental Science and Technology*, 38:6546–6552.

King, R. S., W. V. Deluca, D. F. Whigham, and P. P. Marra. 2007. Threshold Effects of Coastal Urbanization on *Phragmites australis* (Common Reed) Abundance and Foliar Nitrogen in Chesapeake Bay. *Estuaries and Coasts*, 30:469–481.

Krabbenhoft, D., D. Engstrom, C. Gilmour, R. Harris, J. Hurley, and R. Mason. 2007. "Monitoring and Evaluating Trends in Sediment and Water." In *Ecosystem Responses to Mercury Contamination: Indicators of Change*, ed. R. Harris, pp. 47–86. Boca Raton, Fla.: CRC Press.

Li, X., D. E. Weller, C. L. Gallegos, T. E. Jordan, and H.-C. Kim. 2007. Effects of Watershed and Estuarine Characteristics on the Abundance of Submerged Aquatic Vegetation in Chesapeake Bay Subestuaries. *Estuaries and Coasts*, 30(5):840–854.

Mitchell, C. P. J., B. A. Branfireun, and R. K. Kolka. 2008. Spatial Characteristics of Net Methylmercury Production Hot Spots in Peatlands. *Environmental Science and Technology,* 42(4):1010–1016; doi:10.1021/es0704986.

Rasse, D. P., G. Peresta, and B.G. Drake. 2005. Seventeen Years of Elevated CO_2 Exposure in a Chesapeake Bay Wetland: Sustained but Contrasting Responses of Plant Growth and CO_2 Uptake. *Global Change Biology*, 11:369–377.

Rothschild, B. J., J. S. Ault, P. Goulletquier, and M. Heral. 1994. Decline of the Chesapeake Bay Oyster Population: A Century of Habitat Destruction and Overfishing. *Marine Ecology Progress Series*, 111:29–39.

Ruiz, G., L. Fegley, P. Fofonoff, Y. Cheng, and R. Lemaitre. 2006. First Records of *Eriocheir sinensis* H. Milne Edwards, 1853 (Crustacea: Brachyura: Varunidae) for Chesapeake Bay and the Mid-Atlantic Coast of North America. *Aquatic Invasions*, 1:137–142.

Ruiz, G. M., P. W. Fofonoff, J. T. Carlton, M. Wonham and A. H. Hines. 2000. Invasion of Coastal Marine Communities of North America: Patterns and Processes. *Annual Reviews in Ecology and Systematics*, 31:481–531.

Ruiz, G. M., A. H. Hines, and M. H. Posey. 1993. Shallow Water as a Refuge Habitat for Fish and Crustaceans in Non-vegetated Estuaries: An Example from Chesapeake Bay. *Marine Ecology Progress Series*, 99:1–16.