Estuaries and Coasts (2012) 35:1–22
DOI 10.1007/s12237-011-9464-9

THE H.T. ODUM SYNTHESIS ESSAY

Synthesis in Estuarine and Coastal Ecological Research: What Is It, Why Is It Important, and How Do We Teach It?

W. Michael Kemp · Walter R. Boynton

Received: 12 September 2011 / Revised: 31 October 2011 / Accepted: 17 November 2011 / Published online: 3 December 2011

Abstract During the last two decades, there has been growing interest in the integration of existing ideas and data to produce new synthetic models and hypotheses leading to discovery and advancement in estuarine and coastal science. This essay offers an integrated definition of what is meant by synthesis research and discusses its importance for exploiting the rapid expansion of information availability and for addressing increasingly complex environmental problems. Approaches and methods that have been used in published synthetic coastal research are explored and a list of essential steps is developed to provide a foundation for conducting synthetic research. Five categories of methods used widely in coastal synthesis studies are identified: (1) comparative cross-system analysis, (2) analysis of time series data, (3) balance of cross-boundary fluxes, (4) system-specific simulation modeling, and (5) general systems simulation modeling. In addition, diverse examples are used to illustrate how these methods have been applied in previous studies. We discuss the urgent need for developing curricula for classroom and experiential teaching of synthesis in coastal science to undergraduate and graduate students, and we consider the societal importance of synthetic research to support coastal resource management and policy development. Finally, we briefly discuss the crucial challenges for future growth and development of synthetic approaches to estuarine and coastal research.

Keywords Synthesis · Integration · Odum · Teaching synthesis · Environmental management · Coastal and estuarine science

W. M. Kemp (✉)
Horn Point Laboratory, University of Maryland,
Center for Environmental Science,
P.O. Box 775, Cambridge, MD 21613, USA
e-mail: kemp@umces.edu

W. R. Boynton
Chesapeake Biological Laboratory, University of Maryland,
Center for Environmental Science,
P.O. Box 38, Solomons, MD 20688, USA

Introduction

When invited to prepare an article for the 2012 “H.T. Odum Synthesis Essay” for publication in *Estuaries and Coasts*, we were initially overcome by the prospects of this opportunity. In the naïve euphoria of our enthusiasm, however, we accepted the offer with no clear idea for an essay topic which would, as noted in the journal’s instructions, “provide synthesis and review for an emerging topic of importance to estuarine and coastal science.” Having been trained by H.T. Odum himself in the Renaissance tradition, aspiring to become what he called *environmental science generalists*, integrative thinking about coastal ecosystems has been part of our culture since graduate school. As we considered alternative potential essay topics, however, we began to wonder what was really meant by the term *synthesis*. After encountering vague and inconsistent uses of this word, we set our sights on defining and describing in clear and unambiguous terms the essential elements of *synthetic research* in estuarine and coastal ecosystems. Our goal became to write a synthesis essay on the topic of *synthesis*, and in doing so, to explain what it is, why it is important, and how it can be taught—thus, the title and focus of this paper.

In recent years, a growing number of estuarine and coastal science meetings and publications refer to integration and synthesis, to comparative analysis and modeling, and to multi- or trans-disciplinary research. Although 20 years ago there was little funding for integrative and synthetic research in ecology and coastal science, this has changed dramatically. This transformation is evident for the USA in the National Science Foundation's programs including National Center for Ecological Analysis and *Synthesis* (NCEAS), Socio-Environmental *Synthesis* Center (SESYNC), Opportunities for Promoting Understanding through *Synthesis*, *Integrative* Graduate Education and Research Traineeship (IGERT), and integrative research observatories such as National Ecological Observatory Network and Integrated Ocean Observing System. It is also evident in the descriptions of other federal research programs such as the US National Oceanic and Atmospheric Administration's Comparative Analysis of Marine Ecosystem Organization and Center for Sponsored Coastal Ocean Research Programs, and the US Environmental Protection Agency's Science to Achieve Results Program.

This expanding focus on integration and synthesis has been motivated by several parallel trends and forces. These include: (1) the explosion of scientific data and information and its associated intellectual opportunities and burdens, (2) the search for coherence to promote maturation of coastal science, (3) the interest in applying scientific knowledge for effective management of coastal resources, (4) the daunting complexity of recent environmental challenges, and (5) the need to train young environmental scientists to tackle these problems.

The purpose of this essay is to discuss integrative and synthetic research as applied to estuarine and coastal ecosystems. We analyze the range of contexts and meanings that have been attributed to these terms and discuss reasons for the recent focus on synthetic thinking in estuarine and coastal research. Five categories of synthetic research methods and approaches are described, and each is reviewed using selected examples and emphasizing their intellectual framework and methodological approaches. This discussion provides a foundation for addressing our primary goals here—namely, to propose broad frameworks and key protocols for teaching integrative and synthetic thinking to students and for breaching social and institutional barriers that hinder this process. We also consider the societal importance of synthetic research in support of coastal resource management and policy development. Finally, we discuss future challenges for growth and development of synthetic approaches to estuarine and coastal research.

What Is Synthesis?

Webster's New World Dictionary (2006) defines the noun *synthesis* as "the process of putting together"; it also uses the following phrases, "bringing into one, building a whole, forming into unity, and making one of many." This dictionary also provides useful synonyms including "combination, organization, integration, unification, and construction." In recent ecological publications, the term *synthesis* has been given a range of related meanings that reflect important nuanced differences in focus. For example, Pickett (1999) suggests that "synthesis occurs when *disparate* data, concepts, or theories are *integrated* in ways that yield *new knowledge*, insights or explanations." These data or concepts may be *disparate* because they: (1) come from different systems or processes, (2) are generated in different disciplines or (3) are at different time/space scales or levels of organization. The term "analysis" is sometimes defined as a process opposite to synthesis (Ford and Ishii 2001), where a whole is separated into its parts "to find out their nature, proportion, function, interrelationship" (e.g., Webster 2006). However, analysis also provides an important method in synthesis, where diverse pieces of information are examined to improve understanding of how they fit together to explain integrated behavior of the whole.

In the ecological literature, definitions of synthesis generally specify what "pieces" of knowledge are being "put together," in what way these pieces are separated from one another and what "whole" is created in integrating these pieces. A key to understanding the synthesis process starts with knowledge of the tools, methods, and approaches used for the integration step. Another important aspect of this general definition is to specify what is *new* about the *knowledge* generated from synthesis. In many cases, the new knowledge is generated to resolve a complex problem where relatively recent observations appear inconsistent with current theories for causal explanation of patterns (Ford and Ishii 2001). Several authors emphasize that synthesis often involves "the bringing together of existing information in order to discover patterns, mechanisms and interactions that lead to new concepts and models" (Hobbie 2000). Similarly, "synthesis takes stock of what we know and generates new knowledge from novel combinations of existing data" (Carpenter et al. 2009a), thus exploiting the trend of rapidly expanding data fields and easy access to them. Others emphasize ecological synthesis to develop linkages across disciplines, joining two or more fields into a single conceptual and empirical structure (Pickett 1999; Sill 2001; Rhoten et al. 2009). Some authors (e.g., Likens 1998) have emphasized the role of synthesis as a process which integrates knowledge across physical scales and levels of biological organization. Odum (1971) discussed the need for an intellectual "macroscope" to facilitate understanding of the ecosystem structure and function that emerges from dynamic interactions within communities and populations and which appears over and over from one ecosystem to another.

Synthesis is a form of inferential reasoning that includes the logic loop between inductive thought, which draws a general explanatory model from multiple specific observations, and deductive thought, which tests the general model for its consistency with specific cases. The commonly linearized version of this cyclical "scientific method" (observe nature→form hypothesis to explain observations→experimentally test hypothesis→analyze results→refine hypothesis if needed) typically emphasizes the deductive processes involving controlled experimentation designed to "falsify" the hypothesis (e.g., Popper 1968; Gauch 2003). Synthesis in ecological science, however, focuses on the inductive thought process whereby *a new integrative explanatory model is developed to provide an effective explanation for how diverse observations work together.* Some investigators have suggested that the over-emphasis on deductive experimental science and the protocol for falsification tests of objective hypotheses (e.g., Popper 1968) retarded synthesis in environmental research severely during the past three to four decades (e.g., Graham and Dayton 2002). Although this "falsificationist" philosophy has been tempered in current ecological science, Pickett (1999) suggests that its "echo" still reverberates occasionally in lectures and discussions and that its emphasis on experimental precision (above generality) slowed intellectual progress (Levins 1966).

Synthesis also has an alternative philosophic meaning as dialectic reasoning (e.g., Kuhn 1970), where an integrative model or paradigm (the "thesis") in a particular field of study is challenged with an alternative, often opposing, model of how nature works (the "antithesis"). This approach generates a period of heated debate between the two "camps of thought" (Naeem 2002) with testing of the opposing models against data, and the eventual development of a new model (the "synthesis") which draws from the strengths of the thesis and antithesis (Graham and Dayton 2002). In the method of "strong inference," research questions are addressed by formulating multiple hypotheses and designing parallel experimental tests, as well as an objective "logical tree" for drawing inference among the alternative models or hypotheses (Burnham and Anderson 2001). This approach, which is inherently more objective and less contentious than the dialectic method, has also been associated with rapidly advancing fields of science (Platt 1964). In environmental science, however, research questions related to causality are not always answered by a single explanation, because observed effects actually arise from interactions among many causal factors (e.g., Lawton 1999). Hence, "strong inference" in environmental science should perhaps focus on "compound" rather than "alternative" hypotheses to unravel complex problems.

The grandest of synthetic analysis in science seeks to establish theories which generate universal laws applying across a range of scales and disciplines. Many famous examples of these "grand syntheses" are familiar to most readers, including Charles Darwin's theory of Evolution and Albert Einstein's theories of Relativity. In many (perhaps, most) instances, the development of these theories has required decades or entire careers of focus to reach fruition. Environmental science has few examples of Grand Syntheses; however, one notable case is H.T. Odum's Energy Theory, which integrates across diverse natural and human systems and includes many component theories such as "maximum power" and the "pulsing paradigm" (e.g., Odum 1971, 1988, 1994). A few other investigators have devoted much of their careers to developing broad synthetic ideas that have helped to integrate and advance coastal science (e.g., Ulanowicz 1997, 2009). Although there is much to be learned about the process of synthetic reasoning from examining these examples of "grand synthesis," this essay will focus on "normal" ecological synthesis, which is a thought process broadly accessible to most researchers in our field on time scales that match funding cycles.

For this essay, we define synthesis in estuarine and coastal science as *the inferential process whereby new models are developed from analysis of multiple data sets to explain observed patterns across a range of time and space scales*. In many instances, this synthesis is motivated by inconsistencies between important new observations and previous models (e.g., Ford and Ishii 2001). Synthesis involves examination and interpretation of data and ideas, which are often associated with different systems, scales and disciplines. Alternative models may be devised to explain the new and old observations, and where possible, the logic of each should be analyzed thoroughly and tested with analytical or numerical tools. In all cases, the model must be articulated to allow its validity to be tested (falsified) through robust empirical experiments using conventional "scientific methods." Synthesis is an intellectually demanding exercise, which may be the most "creative" element in the scientific process (e.g., Leopold 1978; Sill 2001). Although this essay emphasizes the importance of synthesis research, the need and ability to create synthetic models, of course, depend on the availability of high quality descriptive and experimental data generated through the empirical elements of science.

Why Is Synthesis Important?

There are several major reasons for the current focus on synthesis in coastal and estuarine scientific research. We are now recognizing the enormous challenges in this field of study that derive from diverse and complex environmental problems that represent potentially huge ecological and societal costs. These problems include over-harvest in fisheries, invasions of nonnative species, destruction of essential animal habitats, introduction of toxic and disruptive contaminants, and eutrophication of coastal waters. Contending with any one of these would be difficult enough; however, many coastal systems worldwide are now contending with all of these problems at once. Overlying this ensemble of individual environmental problems, is the increasing impact of climate-driven changes and fluctuations in conditions, including sea level rise, increasing temperature, acidification and changing wind and hydrologic patterns. The scientific literature is expanding with numerous examples of individual studies of how coastal systems respond to these changes in environmental conditions. There is, however, growing need for an integrated and quantitative perspective on the response of different types of coastal systems to different combinations of environmental changes (e.g., Hobbie 2000).

Fortunately, extensive observing systems and monitoring programs have been amassing long time series for key properties of water quality, living-resource health, and external drivers in many coastal regions of the world. Although these data sets represent rich sources of information about present conditions and trajectories of change in coastal systems, few have been used in the context of integrated analysis of each system, much less larger synthesis efforts to compare structure and function across systems. Clear and penetrating science questions need to be articulated, and data need to be analyzed to identify and quantify consistencies and discrepancies among systems. We need to formulate creative hypotheses and models that can explain both consistent and divergent time/space patterns among coastal ecosystem (e.g., Pickett 1999). The potential for deep and expansive understanding of these systems, which lies buried in existing data sets, will be unleashed only through focused efforts toward integrated exploration of these data to produce novel synthesis that will advance discovery (Carpenter et al. 2009a). Many fundamental questions remain about how coastal ecosystems work and about the linkages among physical, biogeochemical and ecological processes. This kind of integrated understanding must be applied to improve effectiveness of coastal resource management (Likens 1998). New software ideas for data management, visualization and interpretation are needed to facilitate this process; however, the real challenge is to raise the will of the coastal science community to tackle this huge synthesis effort. Meanwhile, new data and information continue to accumulate at alarming rates in servers and libraries worldwide. Ironically, this proliferation of knowledge creates a "burden" that could impair the efficiency of scientific progress (e.g., Jones 2009). The solution to this dilemma must involve emergence of a new formalized "science of synthesis."

This challenge needs to be focused over local-to-global scales. Most of our current science emphasizes study of fundamental but small-scale processes and system dynamics for individual estuaries, bays, and bights. Throughout the world, however, many of these processes and systems are experiencing similar changes associated with climate, eutrophication, fishing pressure, and other powerful forces. Nevertheless, scientific studies for most of these systems provide relatively ad hoc explanations for these changes. A synthetic approach to address these questions for many systems would provide explanation and models for interpreting and forecasting broad response trajectories for any system experiencing its own mix of changing external forces (Boesch et al. 2000). These synthetic models require a multidisciplinary approach that considers all relevant processes, integrates across diverse fields of study and applies to different types of coastal systems located in different regions of the world (e.g., Graybill et al. 2006). We have every reason to believe that future challenges associated with solving these environmental problems will be even more complex and will require versatile, innovative and integrated approaches. Future environmental problem solvers will need to be nimble and skilled in the *science of synthesis* to address these complexities, and our greatest challenge is to prepare the next generations of students with a formalized version of this new synthetic science (e.g., Moslemi et al. 2009). The time is right to define and create this *science of synthesis* (Sill 2001).

Approaches and Methods of Synthetic Research

If asked to list our favorite examples of *synthesis science* in estuarine and coastal research, many of us could intuitively identify a number of cases that generate a large integrative explanation to address an interesting research question. A compilation of these lists might reveal a diversity of research methods and approaches that have been applied to a range of research problems in many different systems. The question of what unique characteristics distinguish these examples of *synthesis science* from other studies would likely give us pause for thought. This reaction is not surprising given that there is no published work providing a well-tested list of approaches, steps and/or methods for conducting synthetic research. The introductory chapter of a recent book (Hobbie 2000), however, identifies different synthesis methods applied in the book and distinguishes them on the basis of: (a) the modeling and statistical tools used, (b) the scientific disciplines involved, and (c) the number and scale of ecosystems studied. Although we do not pretend to have devised a fundamentally correct and exhaustive list of the methods of *synthesis science*, we offer here a starting point toward defining and explaining the approaches and methods for synthesis research in coastal science. We provide a schematic flow diagram (Fig. 1) to illustrate how five basic steps of synthesis research identified below are initiated and implemented with data, analytical tools and research methods to produce an innovative

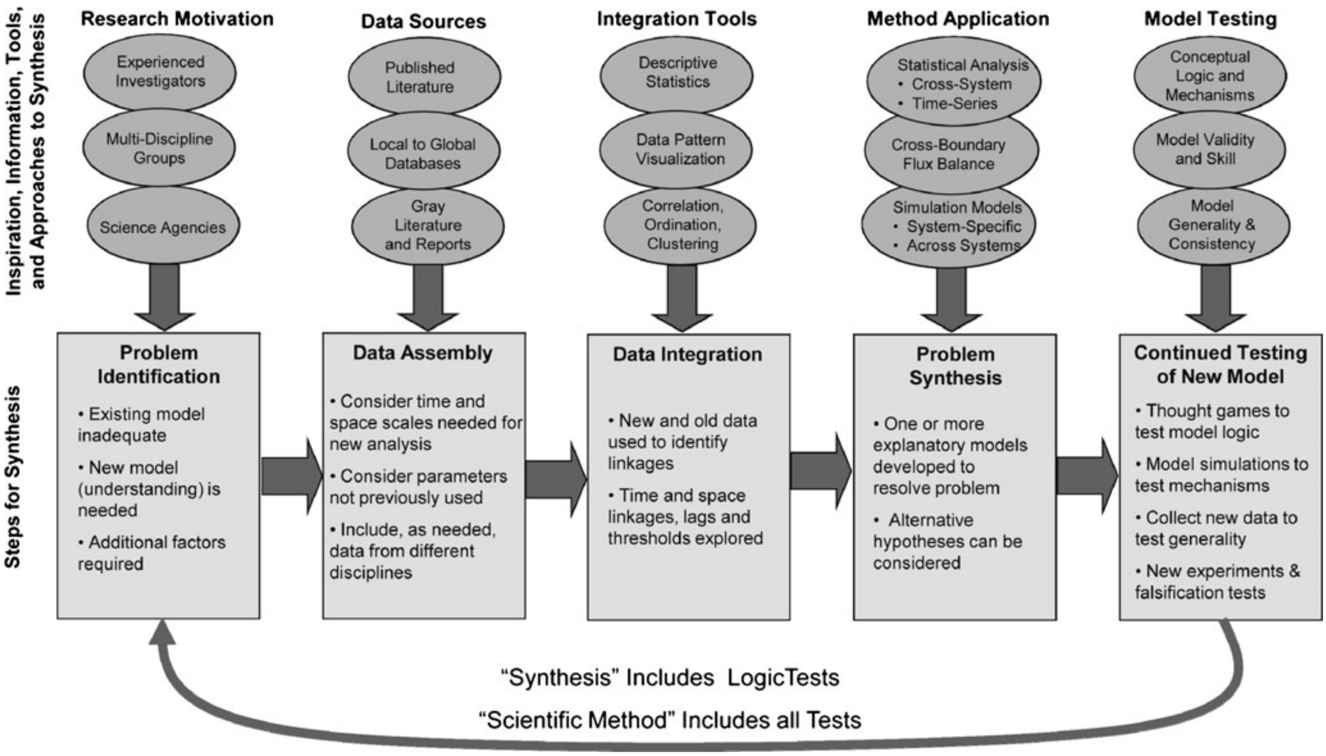

Fig. 1 Schematic flow diagram describing how five basic steps of synthesis research identified here are initiated and implemented with external information, analytical tools, and methods to produce an innovative explanatory model that can be tested for logical consistency, mechanistic explanation, generality of application as part of *integration and synthesis in coastal and estuarine science*, and the inferential part of the fundamental scientific method

explanatory model. This synthesis model can then be tested for logical consistency, mechanistic explanation, and generality of application, all of which are fundamental parts of the scientific method.

Steps in Synthesis Research

Obviously, each of the synthesis methods discussed here must share the key elements described in our definition of synthesis. Thus, all synthesis research will generate a new empirically testable explanatory model that is based on analysis of multiple data sets for relevant variables and derived through a creative inferential process to provide a consistent explanation for all observations. These elements can be organized into five essential steps for synthesis.

1. *Problem Identification.* The first step is to identify a key (sometimes vexing) intellectual problem or question that arises when attempting to explain observed ecological properties or processes. This research question may be defined by seeking new relationships in existing data, or by recognizing that new data are inconsistent with (or contradictory to) existing explanatory models and seeking a revised model that may include new interactions and/or controls.
2. *Data Assembly.* To move toward synthesis and development of a new explanatory model, additional information and data relevant to the problem are assembled, typically from previous studies and existing sources. This information may include observations on different parameters from different disciplines, and they may need to be organized into efficient data bases with consistent time and space scales.
3. *Data Integration.* The additional data are integrated together with previous observations to help identify apparent linkages and interactions among data units and system variables. This integration step often involves analysis with visualization and statistical tools to identify and quantify relationships among variables over time and space.
4. *Explanatory Model Development.* Hypotheses and models are derived from these integrative data analyses, applying a broad perspective across systems and disciplines to explain newly recognized relationships, patterns, and/or trends. If more than one compelling model can be devised to explain and resolve these new relationships, they should be considered as alternative or interactive hypothetical models, which can be tested systematically. Conceptual models may help explain new causal links and feedback interactions, the strength

of which may be statistically quantified. In addition, analytical or numerical models can be developed and/or applied to simulate qualitative and quantitative interactions directly.

5. *Testing Model Validity.* The hypothesized causal relationships, by which this new model explains observed patterns, must be testable in terms of their logic, consistency, validity, and predictive capability. In our proposed definition and context for synthesis, we distinguish between "tests for model logic," which we consider part of the synthesis process, and experimental "tests for model quantitative predictive skill," which we consider an essential deductive element of the *scientific method* involving falsification tests.

Methods Used in Synthesis Research

We identify five different (but often linked) methods commonly used in estuarine and coastal synthesis research. Here we describe key elements of these methods and provide examples from the literature to illustrate their application in synthesis research.

Comparative Cross-system Analysis Cross-system comparative analysis involves using similar data from many different systems to develop a model, which quantifies how one or more key property or process varies in relation to differences in external drivers or other internal properties. This synthetic analysis involves assembling data from a diversity of ecosystems or studies and applying these data to develop a quantitative statistical model. The method has been used effectively to address a range of questions including how nutrient loading to coastal systems may control phytoplankton growth (e.g., Boynton et al. 1982; Monbet 1992), benthic invertebrate biomass (Josefson and Rasmussen 2000), and fisheries harvest (Nixon and Buckley 2002). In general, this comparative approach to synthesis uses a finite data set to produce the initial model, which is often structured as a statistical regression, quantifying how a dependent variable of interest (Y) is related to one or more independent variables (X_i). The initial model can be tested repeatedly using an ever expanding set of data from different systems, leading, in principle, to a more robust model (e.g., Boynton and Kemp 2000). It is sometimes assumed that a model produced using comparative synthesis of time-averaged data from different ecosystems can be applied to predict (or explain) the trajectory of a specific system's response to temporal changes in the external driver, representing a kind of space-for-time substitution (e.g., Pickett 1988). Analyses of long-term time series, however, reveal that response trajectories often follow nonlinear trends with time delays, thresholds and hysteretic patterns (Folke et al. 2004; Kemp and Goldman 2008). In other cases, trends are blurred by "shifting baselines" associated with changes in other conditions not included in the model (e.g., Duarte et al. 2009).

As with most models, those generated from comparative analysis may include outliers, revealing that other independent variables are needed to generalize the model. For example, a statistical model relating phytoplankton abundance to nutrient loading for estuaries or lakes might include observations departing from the regression line associated with systems having different physical conditions. These systems may, for instance, vary substantially in mean depth from deep to shallow or they may vary in physical circulation from stagnant to well-flushed, suggesting that the model might benefit from including effects of depth and water residence time, respectively (e.g., Vollenweider 1976; Boynton and Kemp 2000). Ironically, if all the systems used in the analysis had similar depths and flushing rates, a simple linear regression model may have worked well; however, the synthesis process would have generated less information (e.g., Boynton and Kemp 2000). The primary statistical method used in comparative analysis is application of regression models which may be linear or nonlinear and may involve bivariate or multivariate relationships. Meta-analysis, which is a term for comparative analysis of data from many controlled studies, applies a unique statistical approach (e.g., Hedges and Olkin 1985) that can generate insightful synthesis and integrated understanding of complex interactions, for example, nutrient effects on fish (Micheli 1999) or controls on trophic cascades (Borer et al. 2005). In other instances, comparative analysis uses conventional statistics to interpret results from parallel field experiments conducted in multiple systems to address general scientific questions, such as factors controlling observed salt marsh die-offs across broad geographic regions (e.g., Silliman et al. 2005).

Many synthetic coastal studies have applied methods of cross-system comparisons to generate new models that quantify key ecological relationships across scales from ecosystems to cells. At ecosystem levels, comparative analysis produced models relating fisheries harvest to primary production (Nixon 1988; Breitburg et al. 2009) and explained shifts in the ratio of pelagic-to-demersal species in fishery harvests (e.g., de Leiva Moreno et al. 2000; Kemp et al. 2005). The approach has also been applied to relate denitrification to nitrogen (N) loading (Seitzinger et al. 1984; Seitzinger 1988), and burial plus denitrification to water residence time in estuaries and lakes (Fig. 2; Nixon et al. 1996). Population-level comparative analysis of water clarity and the maximum water depth at which seagrass survive (Petersen 1918) provides an elegant model for estimating the minimum light required for survival of seagrass species (Duarte 1991; Duarte et al. 2007). At physiological scales, comparative analysis has generated many significant

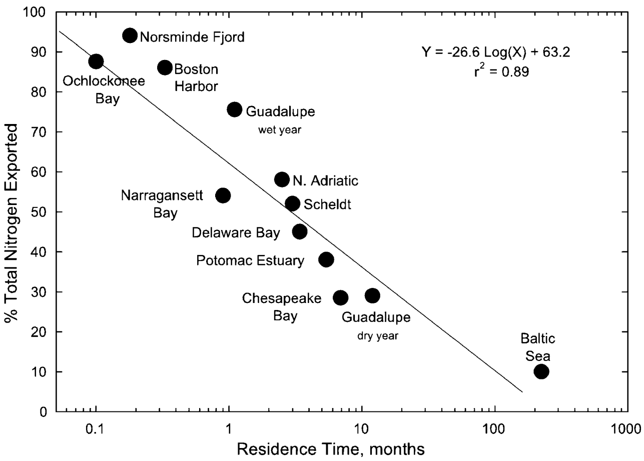

Fig. 2 Percent of the total nitrogen input from land and atmosphere that is exported from estuaries (*solid circles*) as a logarithmic function of mean water residence time in the system (Nixon et al. 1996)

allometric models describing how metabolism and growth rate vary with organism size for individual organisms and populations (Peters 1984; Brown et al. 2004; Harris et al. 2006). Mathematical derivation from physical principles has shown the theoretical basis for these empirical models (West et al. 1997). At cellular scales, a model relating algal chlorophyll-to-carbon ratios to temperature, light and nutrients derived from comparative analysis of data from hundreds of cultures, was subsequently tested with field measurements in natural estuarine communities (Cloern et al. 1995).

Analysis of Time Series Data Current coastal and estuarine research is often motivated by questions related to factors that drive temporal changes in key ecological variables. In modern ecology, enhancing predictive skills is a fundamental goal (e.g., Peters 1991) that requires clear understanding of previously observed temporal changes in important variables (Clark et al. 2001). Thus, synthesis by analysis of time series data provides a powerful method for acquiring this understanding from retrospective study of past trends. There are obvious parallels between this method and synthesis by cross-system comparative analysis. Whereas *comparative analysis* uses time-averaged data from many systems to develop empirical relationships between a dependent variable (Y) and independent variables (X_i) that may influence it, *time series analysis* infers information on how X_i influences Y by statistically interpreting parallel trends. This analysis often focuses on identifying and quantifying periodicity, time lags and shifts in data series for Y and candidate X_i variables. Diverse statistical tools are applied for integrated analysis of time series data sets including Fourier spectral methods, generalized linear regression models, principal components, classification and regression trees, change points, autocorrelations and auto-regressions (e.g., Box and Jenkins 1976; Hanninen et al. 2000; Weijerman et al. 2005; Andersen et al. 2008). In some cases, time series data trends are so striking (and free of autocorrelation) that synthetic hypotheses can be formulated with simple statistics (e.g., Pauly et al. 1998; Estes et al. 1998; Myers and Worm 2003). Although multi-decadal time series data for routinely measured water quality and ecological variables had been limited two to three decades ago, such data series are becoming increasingly available for estuaries throughout the industrial world (e.g., Hagy et al. 2004; Carstensen et al. 2006). Many long term data sets for fisheries, climatic and socio-economic variables are widely available for the last century. Together, these data have supported a recent explosion of synthetic coastal studies applying time series analysis (e.g., Miller and Harding 2007; Kimmel et al. 2009). Very long time series (decades to millennia) of key data can be derived using paleoecology methods, where biological and chemical analyses of dated sediment-core strata serve as proxies for key ecological, anthropogenic, and climatic variables (e.g., Cooper and Brush 1991; Cronin and Vann 2003; Savage et al. 2010).

A spectrum of scientific questions and management concerns has stimulated synthesis by time series analysis. For example, the need to understand fluctuations and declining trends of fisheries harvest has led to numerous studies of how climate and fishing mortality control fish stocks in open ocean waters (Ottersen et al. 2006; Andersen et al. 2008). Many synthetic investigations have applied time series methods to link fisheries patterns and trends to variations, gradual changes, and abrupt shifts (de Young et al. 2008) in regional multi-decade climate cycles, including the Pacific Decadal Oscillation (e.g., Mantua et al. 1997) and the North Atlantic Oscillation (NAO; Stige et al. 2006). In recent years, similar retrospective time series analysis has attributed fluctuations and changes in estuarine and coastal ecosystems to shifts and long term changes in climatic conditions (e.g., Philippart et al. 2007; Nixon et al. 2009). For example, analysis of 30 years of data on phytoplankton, fish and invertebrate landings, and climate concluded that major synchronous temporal jumps in biological variables were driven by shifts in climatic cycles (Fig. 3; Cloern et al. 2010). This approach has also been used to explain how small salinity changes in a Danish coastal lagoon triggered a chain of ecological responses transitioning from turbid to clear water conditions (e.g., Petersen et al. 2008). Similar analyses were applied to distinguish how inter-annual variations in Chesapeake Bay hypoxia were related to interactions between reduced nutrient loading and changes in climatic drivers (Murphy et al. 2011). On the other hand, parallel time series for key variables in multiple Danish estuaries revealed similar phytoplankton trends all linked to changes in temperature and nutrient loading (Henriksen 2009). Ensemble analysis of contemporaneous long-term

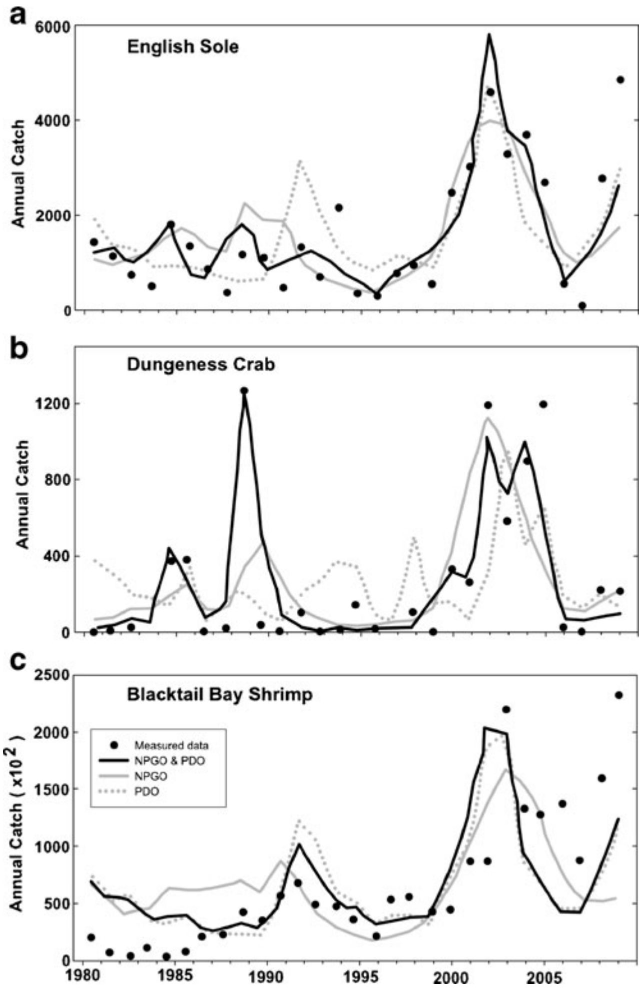

Fig. 3 Time series analysis for harvest of three key fisheries species measured (*blue dots*) and predicted from variations in climate cycles NPOO and PDO. Note that model using both NPOO and PDO fits best, especially for Dungeness crab (Cloern et al. 2010)

data sets for water quality, plankton, benthos, fisheries, climatic, and oceanographic variables showed abrupt synchronous changes in coastal ecosystems throughout NW Europe associated with decadal shifts in NAO (Weijerman et al. 2005).

Balance of Cross-boundary Fluxes Many fundamental questions about how hydrodynamic, ecological and biogeochemical processes control the fate of matter and energy can be addressed by quantifying the balance of fluxes for specific chemicals, energy types or other materials across the boundaries of particular systems (e.g., Boynton and Nixon 2012). At the level of an estuarine system, flux-balance analysis can help explain whether an integrated ecosystem is a net consumer or producer of organic matter (e.g., Kemp et al. 1997), the relative contributions of fish migration and harvest to total sources and sinks for an estuarine nutrient budget (Deegan 1993; Hjerne and Hansson 2002), or the degree to which outbreaks of gelatinous zooplankton may affect food availability for striped bass (Baird and Ulanowicz 1989). Ecosystem scale estuarine N budgets have been used to quantify the importance of brackish tidal marshes as sinks for N inputs (Fig. 4, Boynton et al. 2008) or the relative significance of oceanic or riverine N sources (Nixon et al. 1995). The focal systems of interest can range widely in levels of organization from individual organisms and populations (e.g., Jordan and Valiela 1982), to communities or habitats (e.g., Risgaard-Petersen et al. 1998), to whole estuarine ecosystems (van Beusekom and de Jonge 1998). In all cases, however, their respective spatial boundaries and temporal scales must be clearly defined. Although quantities of data assembled to generate a balanced budget of cross-boundary mass or energy fluxes may be vast and derived from numerous sources, the fluxes must be measured with common units and integrated or averaged over common time frames. In many instances, the budget analysis assumes static steady-state conditions, where the sum of all sources is equal to the sum of all sinks for the substance of interest. Alternatively, however, the analysis can also account for dynamic changes in pool size within the system boundaries integrated over the time period of interest (e.g., Testa and Kemp 2008).

Ecosystem scale budgets have been developed to quantify sources and sinks of organic carbon (e.g., Twilley et al. 1992), dissolved oxygen (e.g., Hoppema 1991), inorganic nutrients (e.g., Morris 1991; Smith and Atkinson 1994), salt and heat (e.g., Smith 1994), and suspended sediments (Schubel and Carter 1977), as well as radio-nuclides (Turekian et al. 1980) and toxic contaminants (e.g., Marcus et al. 1993). Calculation of sources generally requires data on anthropogenic point discharges, while data on

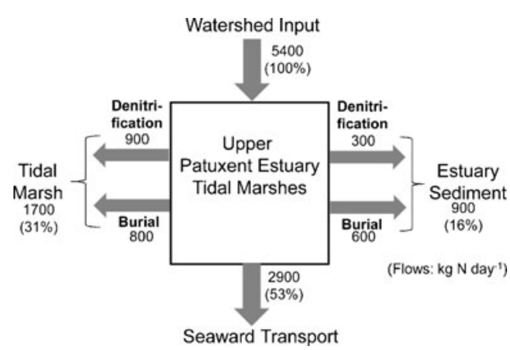

Fig. 4 This N budget for upper of Patuxent River estuary indicates that two thirds of the N-removal in the region occurred in adjacent tidal marshes. Based on reports that simulation experiments with a coupled hydrodynamic–water quality model (which did not include marsh effects) consistently over-estimated estuarine N levels, it was hypothesized that these tidal wetlands provided a major N sink. Note that denitrification and burial in these marshes removed 31% of total N input from Patuxent watershed, despite the fact that these tidal wetlands represent only 2% of the watershed area (adapted from Boynton et al. 2008)

atmospheric sources are obtained from public monitoring programs. Diffuse watershed loadings are often compiled from river monitoring or hydrochemical modeling. Sinks are usually derived from field-based estimates (e.g., sedimentation and denitrification), as well as from public data on fisheries harvests (e.g., Kemp and Testa 2012). Rates of tidal exchange for a material at the estuary-ocean boundary are generally derived from analytical or numerical models (e.g., Boynton et al. 1995; Testa and Kemp 2008). Although many science questions can drive applications of cross-boundary flux analysis for synthesis, nutrient budgets tend to focus on quantifying the relative significance of natural versus anthropogenic sources and sinks to support eutrophication management (Savchuk 2005; Artioli et al. 2008). Carbon and oxygen budgets are often developed to investigate integrated ecosystem production and respiration (e.g., Smith et al. 2005). A fundamental problem with ecosystem budget analysis is the potentially large error that is propagated through numerous calculations for each cross-boundary flux. Recent studies have, however, applied relatively straight-forward protocols for calculating the associated uncertainty and found that errors can be constrained to allow statistical comparisons among fluxes in a calculated budget (e.g., Habib et al. 2008; Lehrter and Cebrian 2010).

Trophic network models are a special case of synthesis by the *cross-boundary flux balance* method, where a steady state mass-balance is created for physiological and ecological inputs to and outputs from each population or trophic guild (Baird and Ulanowicz 1989; Christensen and Walters 2004). Here, input fluxes for feeding and recruitment and output fluxes due to mortality, respiration and excretion are computed (typically, in units of carbon, nutrients, or energy) for each trophic group, and these fluxes are linked by feeding and mortality rates that together form a mass balance for the entire ecosystem. Formal analysis of the trophic network provides information on total ecosystem production and respiration, feeding cycles, trophic efficiencies, trophic dependencies of one group on another, average trophic level for each feeding guild and total number of trophic levels for the ecosystem. Integrative information generated from flow balances in these network models can be used in other synthesis research including comparative analysis (Pauly et al. 1998) and simulation modeling (Christensen and Walters 2004).

System-Specific Simulation Modeling Mechanistic models are widely used tools for simulating observed or expected temporal and spatial patterns in coastal systems and for integrated analysis of physical, biogeochemical, and biological controls on ecosystem processes. A substantial number of hydrodynamic models have been developed to simulate water circulation in estuaries, bays, lagoons, and inner-continental shelves and to compute physical responses to atmospheric and hydrologic forces. These models are often linked (directly or indirectly) to other models that simulate biogeochemical and biological processes to address broader questions of ecological responses to external drivers. Alternatively, in situations where physics are thought to be of secondary importance, ecological models are sometimes simulated in stand-alone (zero dimensional) modes to address science questions. Although much of the synthesis research discussed here could involve application of these kinds of numerical tools to test the logic and validity of hypothesized explanatory models, most simulation modeling has been focused on detailed science questions and used for scenario forecasting. The great advantage of incorporating these numerical tools into the synthesis process lies in the ability to explain observed patterns in nature in terms of mechanistic controls, which are explicitly embedded in model structures. Several example applications are described below for specific ecosystems.

The depletion of dissolved oxygen from bottom waters of stratified coastal systems (hypoxia and anoxia) is a growing problem that is often linked to anthropogenic increases in nutrient loading and to changing climatic factors (e.g., Diaz and Rosenburg 2008). For example, an analysis of time series data for Chesapeake Bay revealed an abrupt shift-up in annual hypoxia extent per unit nutrient loading in the mid 1980s, leading to speculation that this shift was attributable to loss of crucial ecosystem functions (Hagy et al. 2004). Although further retrospective data analyses concluded that changes in physical circulation were likely more important than shifts in ecosystem structure, mechanistic explanations were limited (e.g., Kemp et al. 2009; Murphy et al. 2011). Drawing from observations and analysis for other coastal systems (e.g., O'Donnell et al. 2008), a recent study hypothesized that Chesapeake Bay's jump in hypoxia per nutrient loading was attributable to reduced ventilation of bottom waters caused by a shift in the direction of prevailing summer winds that are controlled by the NAO climate cycle (Scully 2010a). To test the reasoning behind this hypothesis, Scully (2010b) modified an existing physical circulation model (Regional Ocean Modeling System) by adding simple algorithms for oxygen air-sea exchange and respiratory consumption. Numerical experiments (Fig. 5) showed that the observed NAO-driven shift in wind direction was sufficient to increase hypoxia by retarding rotational ventilation of oxygen-depleted bottom waters in Chesapeake Bay (Scully 2010b).

Other diverse examples have been reported for synthetic research applying physical circulation and/or ecological process models to address important science and management questions about a particular coastal ecosystem. For example, a physical circulation model with parameterized biological oxygen consumption similar to that used in the above Chesapeake Bay case, was applied to test hypotheses

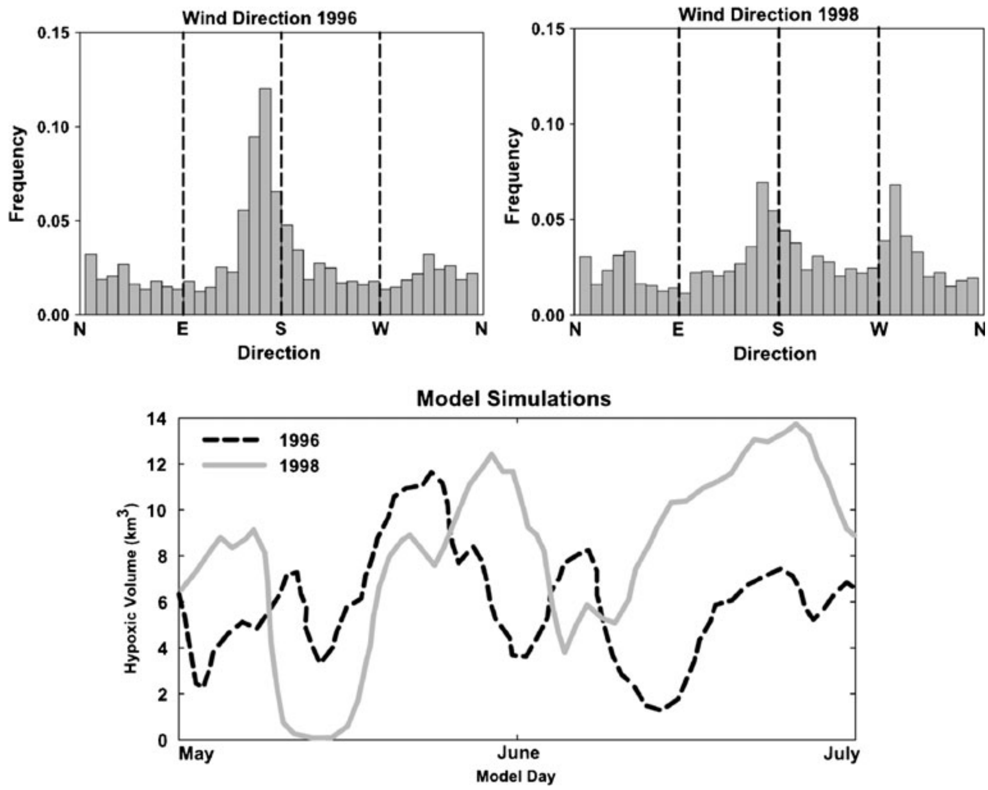

Fig. 5 Comparison of Chesapeake Bay wind and hypoxia in 1996 and 1998, 2 years where summer river flow and wind speed were similar but wind direction was very different. **a**, **b** Frequency histograms for observed wind direction for the 2 years, **c** temporal simulation of Bay hypoxia volume for May–June in 1996 and 1998 (Scully 2010a, b)

about relative roles of biological and physical processes in dynamics of bottom water hypoxic zones and how they vary in the northern Gulf of Mexico (Hetland and DiMarco 2008). Similarly, models with detailed physical circulation and simplified biological processes have also been used to address large synthetic hypotheses about how water transport and benthic grazing by filter-feeding bivalves interact to regulate phytoplankton distribution and productivity in various coastal systems (e.g., Banas et al. 2007; Lucas et al. 2009). Alternatively, models with detailed mechanistic structure for both physical and biological processes have also been applied to examine ecological effects of benthic bivalve grazing, including simulations of the current and historical levels of benthic grazing control on phytoplankton biomass in different regions of Chesapeake Bay (e.g., Cerco and Noel 2007, 2010). In contrast, models with detailed biological structure and simple parameterized physics help test hypotheses about factors controlling ecological responses to different drivers including nutrient loading in eutrophic systems such as Chesapeake Bay (Madden and Kemp 1996), Baltic Sea lagoons (Humborg et al. 2000), and northern Gulf of Mexico (Justic et al. 2003).

General System Simulation Modeling Mechanistic simulation modeling has also been a key method in synthesis research that addresses general hypotheses concerning ecological and physical processes occurring in bays and estuaries worldwide. An excellent example of such synthesis research addresses the broad question of how water-column light attenuation and depth of the upper mixed layer interact to regulate phytoplankton standing crop in nutrient rich coastal waters (Wofsy 1983). Starting with a classical (Riley 1946) differential equation describing phytoplankton growth, Wofsy (1983) assumed steady-state and light-limited algal growth to derive an expression that indicates a direct relationship between light attenuation and depth of the mixed layer. A cross-system comparison of data compiled for eutrophic aquatic systems empirically validated this hypothesized explanatory model, and further tested the model logic revealing a similar but off-set relationship for other systems rich in suspended sediments. This work, thus, described a homeostatic feature of light-limited coastal systems whereby vertically integrated (areal concentration) phytoplankton biomass (as chlorophyll) in the euphotic zone tends to be constant, while mean volumetric concentration is related inversely to mixed-layer depth. It also implies that depths of the mixed layer and euphotic zone will tend to coincide in these nutrient-rich systems (Wofsy 1983). A subsequent synthesis study that applied a simple analytical model to provide formal context for extensive cross-system comparative analysis (>400 studies) addressed similar questions of how chlorophyll and light attenuation affect photosynthesis for phytoplankton as well as for macrophytic algae and microalgal mats (Krause-Jensen and Sand-Jensen 1998). Volumetric photosynthetic rates and chlorophyll concentrations were also shown to decrease with photic depth while areal (vertically integrated) rates and concentrations were independent of depth, with patterns generally holding for all aquatic plants across depth scales from 1 mm to 100 m.

An example of a numerical simulation modeling system developed to represent processes and address general questions for a broad category of coastal systems is the linked watershed-river-estuary model devised to simulate the idealized dynamics of the hypothetical "Phison River" and "Eden Bight" system of Western Europe (Billen and Garnier 1997). This model tested hypotheses about how the coastal waters of Western Europe have changed over the past century in response to industrial development and how future management actions might mitigate these changes. Modeling studies revealed that while elimination of nitrogen from wastewaters would have little impact on coastal plankton, phosphorus removal would dramatically reduce algal blooms. Later studies by these authors applied similar models calibrated to a specific river-estuary (the Seine) to address questions of aquatic ecosystem responses to nutrient management (Billen et al. 2001; Garnier et al. 2001). In fact, many synthesis studies have applied models, which were initially developed and calibrated to address system-specific synthesis questions, to test broader hypotheses about coastal systems in general such as spatial variations in ecosystem metabolism (Hopkinson and Vallino 1995; Vallino et al. 2005) and hysteretic nonlinear responses to changes in nutrient loading for phytoplankton and seagrass (Fig. 6; Webster and Harris 2004).

A number of synthesis studies have also developed and applied simple spatially aggregated simulation models to test generic hypotheses about controls on broad ecological processes. For example, a series of numerical ecosystem

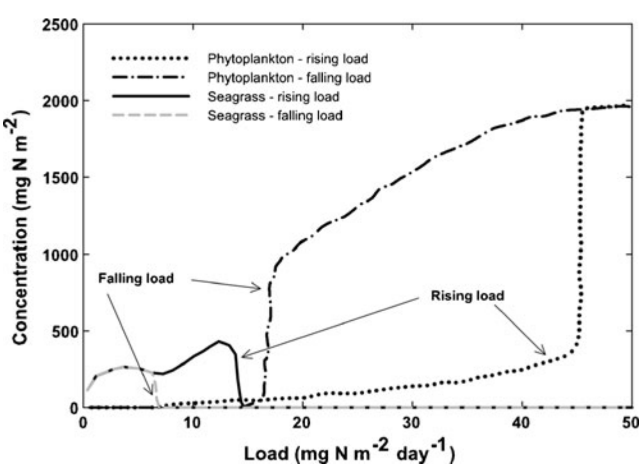

Fig. 6 Scenario forecasts from general system mechanistic model of hypothetical shallow lagoon simulating phytoplankton and seagrass responses to increasing and decreasing loading rates of total nitrogen. Note the highly nonlinear response trajectories showing hysteretic patterns for both phytoplankton and seagrass communities (Webster and Harris 2004)

models with two to five state variables was developed to test broad hypotheses that fish production will decline and trophic transfer efficiency will be unchanged in response to reduced nutrient loading to bays and estuaries (Kemp et al. 2001). This and subsequent simple model structures (Kemp and Brooks 2009) suggested that fish production will tend to remain unchanged across a broad range of nutrient loading, declining only under very low loading rates. A similar model structure was used to explore estuarine response and susceptibility to nitrogen loading and to test a range of hypothetical responses to changes in tidal flushing (Swaney et al. 2008). A comparably simple model of nutrients, phytoplankton and zooplankton in two adjacent habitats of differing mean depth tested a hypothesis about how physical transport between shallow autotrophic and deeper heterotrophic habitats affects secondary production and trophic efficiency of the overall estuarine ecosystem (Cloern 2007). Although these kinds of models do not provide definitive simulations of estuarine processes, they offer a powerful tool to examine and test the logic of synthetic hypotheses involving linkage and integration of multiple mechanisms.

Other Methodological Factors

Many factors influence method selection, application and effectiveness in synthetic research that addresses hypotheses about controls on ecological processes, and every synthesis study has a unique context and motivation that may constrain data availability, depth of analysis, and methods applied. For example, large collaborative synthetic studies may have more skills and resources available to apply multiple methods and access diverse data bases. On the other hand, many elegant synthesis studies have involved one or two investigators working with standard statistical methods and limited published data. Reviews of the literature often lead to insightful synthesis that addresses questions and generates hypotheses that have driven discovery and progress in a particular field of study. There are, however, different levels of literature reviews with some involving analysis, integration and synthesis of data and information that are extracted from published reports (e.g., Cloern et al. 1995; Krause-Jensen and Sand-Jensen 1998) while other reviews have more modest goals directed toward assessing the status of the discipline with limited attention to synthesis (e.g., Cornwell et al. 1999; Berman and Bronk 2003; Rabalais et al. 2010).

Much of the synthesis research in coastal science has applied multiple methods to produce robust results. For instance, nitrogen export from estuaries to the North Atlantic Ocean were derived from cross-system comparative analysis of N fluxes derived from estuary-specific N budgets (Nixon et al. 1996; Fig. 2) and from comparative analysis of watershed N budgets used to develop models that predict N loading to estuaries (Howarth et al. 1996, 2006). In another example, a hypothesis about climate control on seasonal hypoxia in Chesapeake Bay was inferred from time series analysis of data on prevailing winds (Fig. 5), and this hypothesis was then tested using numerical model simulations (Scully 2010a; 2010b). On the other hand, a general synthetic explanatory model that computes potential N removal by tidal wetlands has evolved from multiple parallel analyses using different methods, including a system-specific simulation model (Williams et al. 2006), a mass-balance calculation (Boynton et al. 2008), and a cross-system comparative analysis (Jordan et al. 2011). Although simulation models could be readily applied to test hypothesized controls and interactions inferred from many cross-system comparisons and time series analyses, there are surprisingly few examples of such synthetic research that combines numerical models and data analyses (e.g., Di Toro et al. 1987; Morrison et al. 1997; Wang et al. 1999).

Teaching Synthesis and Integrative Thinking

Understanding Synthesis to Teach It

The inspiration for this essay derives in part from our keen interest in developing a foundation for the successful teaching of synthetic approaches to research in courses taught to undergraduate and graduate students interested in coastal and estuarine science (Ford and Ishii 2001; Carpenter et al. 2009b). An important way to develop skills for conducting synthetic research involves a process of "learning by doing." Results from assessment studies in IGERT and related experiential graduate student programs, however, suggest a clear need to develop and implement routine graduate classes that provide background and foundations for successful collaboration in synthesis research projects (e.g., Rhoten et al. 2009). Although a few ongoing efforts are developing such graduate courses for synthesis in environmental science (e.g., Hackett and Rhoten 2009), this process is not well developed (Sill 2001) and will require long-term concerted efforts to get it right (e.g., Andelman et al. 2004). Indeed, a growing outcry calls for increased focus on teaching synthetic approaches in many fields (Pennisi 2000; Liu 2005) including ecology and environmental sciences (Carpenter et al. 2009a).

We argue above that progress in coastal and estuarine science will require enhanced ability to conduct synthetic research, which, in turn, will require a new generation of scientists well trained for these investigations. We also argue that we cannot teach synthesis (or anything else) unless we fully understand what it is. Toward that goal, we develop here a definition of synthesis, essential steps for conducting synthesis research, and a description of synthesis research methods illustrated by case studies (Table 2). We also attempt to explain how synthesis research is a central (but often neglected) element in the traditional scientific method. Assuming that our initial ideas and their future refinements can provide a foundation for such courses in synthetic research, we offer here a few strategies and perspectives for teaching synthesis.

Finding and Analyzing the Problem

The most challenging and rewarding part of synthesis research comes in finding new relationships in existing data or in recognizing that new observations are difficult to explain with old models and in the subsequent formulation of an initial explanatory hypothesis. This is where synthesis research begins. Several authors have emphasized that this "framing, discovery, or envisioning of the creative [synthesis] question" may be more satisfying than generating the final research products (e.g., Getzels and Csikszentmihalyi 1964). In any case, innovative synthesis generally grows from interesting and well-structured scientific questions. These essential scientific questions often arise from cross-disciplinary (or "bisociative") thought, which involves combining separate domains of study to generate new synthetic ideas (Pickett 1999; Moslemi et al. 2009; Rhoten et al. 2009). Thus, formulation of synthetic scientific hypotheses commonly emerges from engaging diverse scientists into lively discussions (Ford and Ishii 2001). Ultimately, inspiration for synthesis research comes from a combination of personal experiences, the traditions of collaborative studies, and the larger multi-disciplinary culture of science (e.g., Peters 1991). We caution, however, that not all scientific questions and problems are equally amenable to synthesis research. Some are too large and vague or generally lacking in data to be evaluated and tested with current capabilities. Challenging problems are good, but "impossible" problems are not. Although formal programs like IGERT and NCEAS provide graduate students exposure to the synthesis process, this experience often excludes the first step, which is identifying the synthesis question. Typically, this problem arises because that first step normally occurs in the process of developing a successful NSF proposal, well before students convene with the synthesis team.

Training the Mind to See Patterns and Anomalies

So, how do we find and recognize an appropriate question to initiate synthesis research? Broadly speaking, one reads the literature and considers data from diverse sources. In examining data presentations and visualizations, one must recognize patterns, shapes, trends, periodicities, and gradients in data series and in graphs of *Y* versus *X* relationships. Typically, this effort requires intense searching through endless data presentations, asking what drives a given pattern and how to explain parallel patterns among multiple variables. The search for patterns in data is fundamental; however, recognizing anomalies, outliers and other divergences from these patterns is equally important. These nonconforming data should, in fact, grab our attention because they represent new information that begs explanation. These precious anomalies are sometimes referred to as hot spots, focal points, holes, spikes, events, and shifts in background patterns.

We also need to ask questions about how ideas and relationships that are well described in one field of study might apply to other ostensibly unrelated fields. Analogous, parallel or "isomorphic" relationships described in a particular discipline or system may also apply to a diverse spectrum of disciplines or systems (e.g., Von Bertalanffy 1972; Sill 2001). Although outside the normal realm of science, analogies and metaphors are often useful for generating ideas through "thought-games" (e.g., Sill 2001). How well do relationships between variables derived from one coastal system (or one kind of system) apply to comparable variables in another system or kind of system? How might relationships between variables derived from cross-system comparisons apply for any one of these systems over time? Sometimes we need to question how traditional mechanistic explanations (for how one process controls another one) might be different under alternative conditions.

Variations in background patterns are often large and obvious, but other times they are more subtle and difficult to discern. Large "regime shifts" are often evident in coastal ecosystems where, for example, a multi-decadal relationship between nutrient loading and hypoxia abruptly doubles over 2–5 years (e.g., Hagy et al. 2004; Conley et al. 2009; Steckbauer et al. 2011) or where a 30% increase in salinity in 1 year causes a 300% increase in water clarity that persists for decades or more (Petersen et al. 2008). In synthetic cross-system comparisons, obvious but initially unexplained outliers can, upon further examination, reveal effects of factors not included in the original model (e.g., Boynton and Kemp 2000). In time series analysis, effects of extreme weather events (e.g., Boynton et al. 1982) or shifting climate cycles (e.g., Cloern et al. 2010) are readily visible and quantitatively detectable using statistical methods. It is typically easy to see these large divergences from expected patterns. Recognizing other more subtle changes in data series or mismatches between new data and old models may require greater scientific acuity, a trait which grows from experience but which we must learn to teach in a new curriculum of *synthesis science*. Although the formulation of hypotheses and models ultimately involves a creative leap of inductive reasoning, which is fundamentally difficult to teach, advances in artificial intelligence programming may eventually facilitate this learning experience (e.g., Flener and Schmid 2008).

Recognizing patterns and anomalies becomes easier if we broaden our knowledge base to become aware of major concepts, paradigms and methods in several fields of study beyond our own area of expertise. In a sense, we can strive to become a "Renaissance Person" with broad knowledge from diverse disciplines. Obviously, this effort requires a time commitment to read literature and hear lectures in other fields, but for some scientists this multidisciplinary self-training might be thought of as an avocation (Rhoten and Parker 2004), which enriches one's specific disciplinary vocation. Some colleagues have found this Renaissance expansion of one's multidisciplinary knowledge tends to evolve through participation in synthesis research activities (Carpenter et al. 2009a; Hackett et al. 2006). For graduate students, however, beginning students are often more successful in synthesis activities than are advanced students (Rhoten et al. 2009), who are concerned about career risks associated with less focused, more creative synthesis activities (McConnell et al. 2011). While diverse knowledge and skills are valuable for synthesis, collaborators generally need a depth of knowledge in their specialized discipline to enhance their contribution to the group (e.g., Moslemi et al. 2009). Thus, young scientists might be best served to focus on developing a depth of knowledge in their specific discipline while diversifying their breadth of knowledge through collaborations in multidisciplinary synthesis projects (e.g., Wake 2008).

Learning Quantitative and Qualitative Skills

Although many of the steps in synthesis that we have outlined are qualitative in nature, the overall process and ultimate products of synthesis research need to be quantitative and testable. Synthesis research is not magic; it involves demanding and sometimes frustrating work through a cycle of generating, reshaping, discarding, and re-creating ideas and hypotheses (Leopold 1978). Fortunately, many powerful and easily applied tools and resources are available to facilitate the hard work of synthesis research (e.g., Andelman et al. 2004).

The online availability of large and diverse databases represents a huge resource for building and testing synthetic models in coastal and estuarine science. Ability to access and manipulate these data may require a few basic quantitative skills, including familiarity with query-based data systems that make accessing, manipulating, analyzing, and visualizing these data particularly efficient (Andelman et al. 2004). Many existing data management cyber-infrastructure systems have been transformative in facilitating application of data to synthesis research that addresses challenging problems (Ball et al. 2008; Murphy et al. 2011). Recognizing this need, programs such as NCEAS maintain expertise and support in these areas as an essential component of a synthesis center (Hackett et al. 2006). In addition to the explosion of increasing data availability, there has been a parallel expansion in statistical and other analytical techniques now readily available for application to ecological problems. Thus, an ever-expanding toolbox of nonparametric, nonlinear, multivariate methods are available for building models using one of many commercial or open-source software systems (e.g., *SAS, Matlab, R,* and *PEST*) to support synthesis research (e.g., Carpenter et al. 2009a). The once rare and specialized skill of numerical simulation modeling has become widely accessible to nonspecialists with user-friendly software like *Stella*, *Simile*, and *Spatial Modeling Environment*, and with well-supported open-source physical circulation and biogeochemical models like the Regional Ocean Modeling System (e.g., Scully 2010b). Similarly, a range of numerical and analytical tools for trophic network analysis and simulation are also well-supported as downloadable open-source packages (e.g., *Ecopath with Ecosim*, Christensen and Walters 2004). All of these tools offer quantitative power for synthesis efforts.

The selection of appropriate tools and the overall skills needed to construct integrative models of one type or another both come with the experience of actual synthesis activities. Details regarding potential uses and methods of application for these quantitative tools, however, involves mental skills that also need to be learned early in formal classrooms and laboratories of graduate schools (Hackett and Rhoten 2009; Rhoten et al. 2009). Fortunately, all collaborators in synthesis research do not need to be proficient in the use of all quantitative methods because, in large multidisciplinary synthesis groups, some participants will have the technical skills others lack and vice versa (Carpenter et al. 2009b). Thus, experiences gained by involvement in synthesis research can facilitate one's abilities both to apply appropriate tools and to discover rich questions that inspire future synthesis studies.

To be successful, collaborators in multidisciplinary synthesis research also need several key social skills to build an efficient research team. While an environmental science classroom may not teach these social skills, their value for the goals of synthesis can be discussed. Since synthesis research often involves diverse groups of scientists, participants must be able to articulate and communicate complex ideas between and among individuals from different disciplines. Use of formalized conceptual models can help organize and communicate ideas (Rhoten et al. 2009) and catalyze creation of positive group dynamics with all members contributing to discussions on the basic structure of how something works. This process can use one of many languages from simple box-and-arrow diagrams to icon-based systems available on line (e.g., http://ian.umces.edu/) to more formal symbology of the Odum *energy circuit language* (Odum and Odum 2001). Many other social skills are important for productive and creative collaborations in a synthesis research group. We combined the early ideas suggested by Likens (1998) with those presented in more recent publications to distill and assemble a list of social attributes needed for successful synthesis, including inquisitiveness, curiosity for new ideas, tolerance and respect, team orientation, open-mindedness, willingness to share and ability to see the "big picture" (Table 1).

Table 1 A summary of key professional and social skills for conducting synthesis research

Personal characteristics	Qualities and skills needed for synthesis	Research benefits and importance
Professional	Tested native intelligence	Confidence with complex problems
	Expertise in specific research area	Bring specific knowledge to synthesis process
	Critical, logical thinker	Conceptual understanding of complex problems
	Pattern recognition and visualization	Sorting through large data sets to develop models
	Quantitative skills (statistics, models, data management)	Quantitative analysis and model building
	Writing and speaking skills	Key to interdisciplinary communication
Social and psychological	Inquisitive attitude	Needed to go beyond disciplinary boundaries
	Willingness to develop and try new ideas	Tackling innovative high risk/high reward ideas
	Tolerance and respect for unusual ideas	Creativity involves trying novel untested ideas
	Interest in "Big Picture" issues	Need to understand context at larger scales
	Team orientation, interdisciplinary	Finding synthesis at disciplinary intersections
	Good listener and open minded	Synthesis occurs with merging of new and old ideas
	Willingness to share (ideas, data, and publications)	Integration of information leads to new synthesis
	Constructive criticism	Avoids crushing creative ideas in early development

References for this table: Carpenter et al. 2009a, b; Graybill et al. 2006; Hackett and Rhoten 2009; Likens 1998; Pickett 1999; Moslemi et al. 2009; Rhoten et al. 2009; Sill 2001; Wake 2008

Learning Synthesis from Analysis of Case Studies

Previous essays have emphasized that effective teaching of synthesis should involve analysis and discussion of published examples of synthesis research (e.g., Pickett 1999; Moslemi et al. 2009; Musante 2004; Andelman et al. 2004). In the above section of this essay discussing methods of synthesis research, numerous examples of synthesis studies in coastal and estuarine science are discussed, while highlighting a few exemplary cases. This initial group of case studies could be analyzed for teaching synthesis in undergraduate and graduate classes (Leopold 1978). These and other examples of synthesis research in coastal and estuarine science synthesis papers could also be examined to identify our proposed sequence of steps in synthesis (Table 2; Fig. 1). In classroom or laboratory settings, students could be asked to address "find-and-discuss" questions like the following inquiries. What was the central question that motivated and organized this research, and how was it discovered and formulated? How did the authors assemble data and what time and space scales and boundaries were defined? How were data integrated and critical relationships discovered? What statistical, modeling or visualization tools were selected for use in this step of the process? What kind of explanatory models were used to resolve the problem? Which of the five general synthesis methods were used and was a process included or proposed for testing the validity and generality of the new model? In a sense, such classroom exercises could serve as proxies for first-hand student experience in conducting synthesis research. Perhaps, clever teachers could bring life to their classrooms by recreating a vicarious experience for students to imagine or mimic the

Table 2 Summary of ideas for conducting, teaching, and supporting synthesis research in estuarine and coastal science

Conducting, teaching, and supporting synthesis	Explanations and comments	References
Steps in synthesis research		
Identity challenging science problem	This flit step in the synthesis process is exciting and rewarding	Leopold 1978
Assemble relevant data	Process is facilitated by web-based data and data management tools	Andelman et al. 2004
Integrate data by identifying linkages among units	Powerful statistical, numerical and analytical tools available for application	Hackett et al. 2006
Define alternative models that explain or test problem	For some environmental problems there are multiple mechanistic controls	Platt 1964; Sill 2001
Select simpliest model that maximizes explanation	Strive for elegant solutions that cut to the crux of the problem	Ford and Ishii 2001
Mental exercises to build synthesis skills		
Search for unconventional but general explanations	Fresh ideas, data, and tools needed for some complex problems	Pickett 1999
Use isomorphisms, homologies analogies	Identify related patterns in diverse multi-disciplinary data	Von Bertalanffy 1972
Tackle hard problems, but avoid impossible ones	Avoid problems that are untestable vague with limited data	Likens 1998
Develop conceptual models with links and causality	Conceptual models to organize, communicate, and stimulate ideas	McConnell et al. 2011
Use consistent time, space, and complexity scales	Integration and synthesis requires coherent scales for data analysis	Andelman et al. 2004
Broaden knowledge base	Need teams of experts who are knowledgable in other key disciplines	Carpenter et al. 2009a, b
Work in team oriented interdisciplinary groups	Need to respect and appreciate the cultures of "other scientific tribes"	Wake 2008
Look for the Big Picture; find the "Macroscope"	Need to understand the Larger context and hierarchical structure of problem	Pickett 1999
Develop diverse quantitative skills	Synthesis team members need to contribute Quantitative and qualitative skills	Rhoten et al. 2009
Study many synthesis examples	Analyze case studies into essential steps and methods for insight and practice	This paper
Institutional support for synthesis		
Reward multi-disciplinary research	Need to support interactions among disciplines to enhance synthesis	Moslemi et al. 2009
Recognize and reward collaborative research	Administrators need insight to fairly evaluate productivity and significance	Rhoten and Parker 2004
Increase funding for synthesis research	Social importance and complexity of environmental problems requires funds	Graybill et al. 2006
Emphasize team aspect of synthesis research	Transition needed from traditional individual values to group or shared values	Liu 2005; Wake 2008
Facilitate but do not institutionalize synthesis	Beyond synthesis centers, smaller informal synthesis teams need support	Carpenter et al. 2009a, b

kinds of discussions, debates, and arguments that might have taken place during the original study.

Synthesis for Environmental Management

There are growing concerns about the spectrum of complex environmental problems that challenge the health and resilience of coastal and estuarine ecosystems (e.g., Gunderson et al. 2006). Changing climatic and associated environmental conditions, including increased sea level and ocean acidity, as well as altered patterns of droughts, floods, and extreme storms, are causing global-scale modifications in coastal systems. In addition, widespread increases in anthropogenic disturbance of coastal systems at local and regional scales together manifest the globally expanding "human footprint" (e.g., Diaz and Rosenburg 2008). Thus, effects of climate-change, eutrophication, overfishing, and habitat destruction across local-to-global scales create a suite of interwoven environmental problems that can only be understood through multidisciplinary synthetic approaches. Development of effective strategies to manage the maelstrom of degrading coastal ecological processes also requires the integrated holistic understanding of these ecosystems that is accessible only through synthesis research. The scale and complexity of these coastal environmental problems preclude reliance on conventional reductionist science to provide necessary knowledge for managing these valuable ecosystems.

Synthesis research generates scientific understanding that can provide guidelines and tools for direct application to manage water quality and living resources in coastal ecosystems. Several instances have already been mentioned above as case studies in our discussion of synthesis methods. Other synthetic research has demonstrated direct link between tidal marshes and fisheries harvest (e.g., Turner 1977), as well as economic benefits of wetland systems for sequestering wastewater nutrients (e.g., Day et al. 2004) and cost-effective approaches for restoring mangrove wetlands (e.g., Twilley et al. 1998). Other studies have provided guidelines and spatial strategies for nitrogen and phosphorus nutrient management in estuaries (e.g., Paerl et al. 2004; Paerl 2009). In addition, synthesis research, particularly comparative analysis and general system models, can aid "scaling-up" from local studies to more regional and global management applications (Boesch et al. 2000). Synthetic models can support ecosystem-based fisheries management (EBFM), relating multi-population fisheries management to physical circulation, food production and fishing-related mortality (e.g., Christensen et al. 1996; Houde 2011). Cross-system comparative analysis has also enhanced EBFM in coastal waters across the globe (Megrey et al. 2009; Pitcher et al. 2009; Murawski et al. 2010). "Adaptive management" is an inherently synthetic approach, which assesses management effectiveness using simulation modeling and monitoring of ecosystem responses to interventions (e.g., Walters 1986; Gunderson et al. 2006). In principle, adaptive management projects represent large-scale experimental tests for models derived from synthesis research. Although adaptive management would improve both management effectiveness and scientific understanding (e.g., Gunderson and Light 2006), resource limitations and social barriers have too often limited its application (Walters 1997).

Many industrialized nations across the world instituted (two to five decades ago) extensive long-term programs for monitoring diverse variables that measure key properties of coastal ecosystems and the external (atmosphere, watershed, and ocean) processes that drive them. Although, these monitoring efforts were designed to detect trends of environmental degradation or improvement, they also represent a treasure trove of information ripe for synthesis research that improves scientific understanding of coastal systems, as well as supporting management applications (e.g., NRC 1990). A fundamental problem with many of these monitoring programs is the fact that they lack mechanisms for insuring adequate data analysis to enhance environmental management (e.g., Malone et al. 1993; Levin et al. 2009). Synthesis research using cross-system comparative analysis of monitoring data has produced simple models used for managing of nutrient loads to specific coastal systems. For example, empirical models relating nitrogen and phosphorus loading to phytoplankton chlorophyll were used in Tampa Bay and other Florida (USA) estuaries to compute allocations of nutrients to these systems (Morrison et al. 1997; Steward and Lowe 2010). Similar comparative synthesis produced models for estimating nutrient load limits for maintenance and restoration of environmental conditions in shallow estuaries along the east coast of North America (Caffrey 2004; Latimer and Rego 2010). Much more ambitious research will, however, be needed in the future to provide synthetic scientific support for dealing with more complex problems that require integrated management of water quality, fisheries and habitats under changing climatic conditions (Duarte et al. 2009). Towards this goal, coastal synthesis will need an arsenal of well-tested, well-maintained, and broadly applicable simulation models designed for both management and research application.

Progress and Future Challenges

A range of institutional and science-based issues continues to retard the development of synthesis science (Table 2). Many of these institutional barriers to synthesis are more cultural in nature because they reflect out-dated philosophical views on what constitutes excellence in research. Pickett (1999) offered five common institutional biases, manifest as too much emphasis on: (1) narrow reductionist methods,

(2) production of original data, (3) data analysis rather than integration, (4) critical rather than synthetic arguments, and (5) experimental studies aimed at hypothesis falsification. Other institutional barriers may be more operational, in that the solutions require new approaches rather than a new culture. Examples include a need for institutions to support creation of diverse synthesis groups using vehicles such as seminars, courses, workshops, retreats and small grant programs (Moslemi et al. 2009). National science institutions and mission-oriented agencies need to create special and routine funding opportunities for synthesis research (Graybill et al. 2006) supporting both shorter-term focused studies for a few collaborators and longer-term multi-investigator research on complex and difficult issues (Wake 2008; Liu 2005). In addition, academic institutions must devise innovative ways to evaluate individual contributions to collaborative research projects and the publications they generate (Leopold 1978). Sadly, as we (the authors of this essay) approached our own tenure decisions in the late 1970s, we were warned, "stop working together if you expect to be awarded tenure." In our naïve but flippant fashion, we simply ignored the warning and have survived to the present. Fortunately, many such attitudes have changed since then.

We suggest that academic administrators need to delve more deeply into deciphering roles individuals play in synthesis work rather than simply counting the number of first-authored papers and citation frequencies. Scientists involved in synthesis need to take leadership roles, but leadership, creativity and significant contribution are not always indicated by the order of authorship. Many environmental problems are simply too large and complex to be tackled using traditional single investigator approaches. Institutions like the US NSF should continue to support synthesis centers like NCEAS and SESYNC to preserve and expand the "creativity, innovation and productivity" that has emerged from these centers (Carpenter et al. 2009a). Although some have argued that that these centers "cannot be matched by any other mechanism for synthesis," a limited number of centers are unlikely to meet the growing need for synthesis training and research (Carpenter et al. 2009b). Other funding mechanisms should also be pursued to facilitate synthesis research by individuals and smaller groups, recognizing a point mentioned above—that the initial identification and development of synthesis questions and problems may be equally or more likely to happen in small informal groups than in large collaborations. In any case, the need for synthesis research is too important and too urgent to rely on one funding model, even though that model has proven to be successful.

Four key challenges emerge for future development of synthesis in coastal science. The entire environmental science community and particularly those studying coastal systems need to (1) agree on what is meant by synthesis research and how it is done, (2) develop an efficient system to fund and reward excellence in synthesis research, (3) improve mutually supporting linkages between synthesis research and coastal management, and (4) develop and support curricula to provide effective vehicles for teaching synthesis science. We hope this essay will help to address the first of these challenges by providing an initial definition of synthesis research, a list of steps required to conduct it, and a description of synthesis methods with examples of their applications (Table 2). Although we may have wandered out on an intellectual limb in our attempt to advance these ideas on synthesis science, our disclaimer is that this essay is intended as a starting point. We have described many examples of synthesis in coastal research; however, it was impossible to be comprehensive, and many excellent case studies have been omitted. Hopefully, others will correct our mistakes and provide improved and clarified perspectives. We echo comments of our predecessors that cultural and operational barriers to synthesis need to be breached and resources to support this research need to be redoubled. We endorse the formation and operation of environmental science synthesis centers around the world; however, support for synthesis research by individuals and small collaborative teams is equally important. Monitoring programs are valuable resources that link synthesis research to environmental management, but initiatives are needed to promote use of these data both to advance synthesis science and to enhance coastal management. The development of diverse open-source simulation models (physics, biogeochemistry, ecology, and fisheries) represents an essential step for linking synthesis science to management. Research institutions and management agencies must share responsibility and support for the construction, evolution and continued maintenance of these models. Perhaps most importantly, a core of courses is needed to teach the fundamental principles of synthesis science and its application to interesting and important problems. Institutionally sponsored programs must continue to provide graduate students with opportunities to experience synthesis research in large multi-disciplinary groups. The future of environmental science depends on our commitment to these lofty goals.

Acknowledgments We are grateful for the support of our colleagues and students for the ideas that we have gathered and developed in this essay. We are, of course, indebted to H.T. Odum for the inspiration and mentorship that brought us together in graduate school and launched us into this career-long collaboration of ideas and enthusiasm. Scott Nixon, Bob Christian, and Wayne Gardner provided valuable comments on an earlier version of this essay. We are particularly indebted to Jeremy Testa and Eva Bailey for their continued technical and intellectual support. Finally, we thank the agencies that have provided funding support for our synthesis science over many years, including the National Oceanic and Atmospheric Administration (Maryland Sea Grant Program, Center for Sponsored Coastal Ocean Research), the US Environmental Protection Agency (Chesapeake Bay Program), the US National Science Foundation, the Maryland Department of Natural Resources, and the Maryland Department of the Environment.

References

Andelman, S.J., C.M. Bowles, M.R. Willig, and R.B. Waide. 2004. Understanding environmental complexity through a distributed knowledge network. *BioScience* 54: 240–246.

Andersen, T., J. Carstensen, E. Hernandez-Garcia, and C.M. Duarte. 2008. Ecological thresholds and regime shifts: Approaches to identification. *Trends in Ecology & Evolution* 24: 49–57.

Artioli, Y., J. Friedrich, A. Gilbert, A. McQuatters-Gollop, L. Mee, J. Vermaat, F. Wulff, C. Homborg, L. Palmeri, and F. Pollehne. 2008. Nutrient budgets for European seas: A measure of the effectiveness of nutrient reduction policies. *Marine Pollution Bulletin* 56: 1609–1617.

Baird, D., and R.E. Ulanowicz. 1989. The seasonal dynamics of the Chesapeake Bay ecosystem. *Ecological Monographs* 59: 329–364.

Ball, W., D. Brady, M. Brooks, R. Burns, B. Cuker, D. Di Toro, T. Gross, W.M. Kemp, L. Murray, R. Murphy, E. Perlman, M. Piasecki, and J. Testa. 2008. Prototype system for multidisciplinary shared cyberinfrastructure: Chesapeake Bay Environmental Observatory (CBEO). *Journal of Hydrologic Engineering* 13: 960–970.

Banas, N.B., J.N. Hickey, and J. Ruesink. 2007. Tidal exchange, bivalve grazing, and patterns of primary production in Willapa Bay, Washington, USA. *Marine Ecology Progress Series* 341: 123–139.

Berman, T., and D.A. Bronk. 2003. Dissolved organic nitrogen: A dynamic participant in aquatic ecosystems. *Aquatic Microbial Ecology* 31: 279–305.

Billen, G., and J. Garnier. 1997. The Phison River plume: Coastal eutrophication in response to changes in land use and water management in the watershed. *Aquatic Microbial Ecology* 13: 3–17.

Billen, G., J. Garnier, A. Ficht, and C. Cun. 2001. Modeling the response of water quality in the Seine River estuary to human activity in its watershed over the last 50 years. *Estuaries* 24: 977–993.

Boesch, D.F., J. Burger, C. D'Elia, D. Reed, and D. Scavia. 2000. Scientific synthesis in estuarine management. In *Estuarine science: A synthetic approach to research and practice*, ed. J.E. Hobbie, 507–526. Washington, DC: Island Press.

Borer, E.T., E. Seabloom, J. Shurin, K. Andersono, C. Blanchette, B. Broitman, S. Cooper, and B. Halpern. 2005. What determines the strength of a trophic cascade? *Ecology* 86: 528–537.

Box, G.E.P., and G.M. Jenkins. 1976. *Time series analysis: Forecasting and control (revised edition)*. San Francisco: Holden-Day.

Boynton, W.R., and W.M. Kemp. 2000. Influence of river flow and nutrient loading on selected ecosystem processes and properties in Chesapeake Bay. In *Estuarine science: A synthetic approach to research and practice*, ed. J.E. Hobbie, 269–298. Washington, DC: Island Press.

Boynton, W.R., and S.W. Nixon. 2012. Budget analysis of estuarine ecosystems. In *Estuarine ecology*, 2nd ed, ed. J. Day, B. Crump, A. Yanez, and W.M. Kemp. New York: Wiley.

Boynton, W.R., W.M. Kemp, and C.W. Keefe. 1982. A comparative analysis of nutrients and other factors influencing estuarine phytoplankton production. In *Estuarine comparisons*, ed. V. Kennedy, 67–90. New York: Academic.

Boynton, W.R., J.H. Garber, R. Summers, and W.M. Kemp. 1995. Input, transformations and transport of nitrogen and phosphorus in Chesapeake Bay and selected tributaries. *Estuaries* 18: 285–314.

Boynton, W.R., J. Hagy, J. Cornwell, W.M. Kemp, S. Greene, M. Owens, J. Baker, and R. Larsen. 2008. Nutrient budgets and management actions in the Patuxent River estuary, Maryland. *Estuaries and Coasts* 31: 623–651.

Breitburg, D.L., D. Hondorp, L. Davias, and R. Diaz. 2009. Hypoxia, nitrogen, and fisheries: Integrating effects across local and global landscapes. *Annual Review of Marine Science* 1: 329–349.

Brown, J., J. Gillooly, A. Allen, V. Savage, and G. West. 2004. Toward a metabolic theory of ecology. *Ecology* 85: 1771–1789.

Burnham, K.P., and D.R. Anderson. 2001. Kullback–Leibler information as a basis for strong inference in ecological studies. *Wildlife Research* 28: 111–119.

Caffrey, J.M. 2004. Factors controlling net ecosystem metabolism in U.S. estuaries. *Estuaries* 27(1): 90–101.

Carpenter, S.R., E.V. Armbrust, P.W. Arzberger, F.S. Chapin III, J.J. Elser, E.J. Hackett, A.R. Ives, P.M. Kareiva, M.A. Leibold, P. Lundberg, M. Mangel, N. Merchant, W.W. Murdock, M.A. Palmer, D.P.C. Peters, S.T.A. Pickett, K.K. Smith, D.H. Wall, and A.S. Zimmerman. 2009a. Accelerate synthesis in ecology and environmental sciences. *BioScience* 59: 699–701.

Carpenter, S.R., E.V. Armbrust, P.W. Arzberger, F.S. Chapin III, J.J. Elser, E.J. Hackett, A.R. Ives, P.M. Kareiva, M.A. Leibold, P. Lundberg, M. Mangel, N. Merchant, W.W. Murdoch, M.A. Palmer, D.P.C. Peters, S.T.A. Pickett, K.K. Smith, D.H. Wall, and A.S. Zimmerman. 2009b. The future of synthesis in ecology and environmental sciences. NSF Workshop report. Arlington, VA. 9–10 December 2008. pp. 1–18.

Carstensen, J., D. Conley, J. Andersen, and G. Aertebjerg. 2006. Coastal eutrophication and trend reversal: A Danish case study. *Limnology and Oceanography* 51: 398–408.

Cerco, C., and M. Noel. 2007. Can oyster restoration reverse cultural eutrophication in Chesapeake Bay? *Estuaries and Coasts* 30: 331–343.

Cerco, C., and M. Noel. 2010. Monitoring, modeling, and management impacts of bivalve filter feeders in the oligohaline and tidal fresh regions of the Chesapeake Bay system. *Ecological Modeling* 221: 1054–1064.

Christensen, V., and C.J. Walters. 2004. Ecopath with ecosim: Methods, capabilities and limitations. *Ecological Modelling* 172: 109–139.

Christensen, N.L., A.M. Bartuska, J.H. Brown, S. Carpenter, C. D'Antonio, R. Francis, J.F. Franklin, J.A. MacMahon, R.F. Noss, D.J. Parsons, C.H. Peterson, M.G. Turner, and R.G. Woodmansee. 1996. The report of the Ecological Society of America Committee on the scientific basis for ecosystem management. *Ecological Applications* 6: 665–691.

Clark, J., S. Carpenter, M. Barber, S. Collins, A. Dobson, J. Foley, D. Lodge, M. Pascual, R. Pielke, W. Pizer, C. Pringle, W. Reid, K. Rose, O. Sala, W. Schlesinger, D. Wall, and D. Wear. 2001. Ecological forecasts: An emerging imperative. *Science* 293: 657–660.

Cloern, J.E. 2007. Habitat connectivity and ecosystem productivity: Implications from a simple model. *American Naturalist* 169: E21–E33.

Cloern, J.E., C. Grenz, and L. Lucas. 1995. An empirical model of the phytoplankton chlorophyll: Carbon ratio—the conversion factor between productivity and growth rate. *Limnology and Oceanography* 40: 1313–1321.

Cloern, J., K. Hieb, T. Jacobson, B. Sanso, E. Lorenzo, M. Stacey, J. Largier, W. Meiring, W. Peterson, T. Powell, M. Winder, and A. Jassby. 2010. Biological communities in San Francisco Bay track large-scale climate forcing over the North Pacific. *Geophysical Research Letters* 37: L21602. doi:10.1029/2010GL044774.

Conley, D.J., J. Carstensen, R. Vaquer-Sunyer, and C.M. Duarte. 2009. Ecosystem thresholds with hypoxia. *Hydrobiologia* 629: 21–29.

Cooper, S.R., and G. Brush. 1991. Long-term history of Chesapeake Bay anoxia. *Science* 254: 992–996.

Cornwell, J.C., W.M. Kemp, and T. Kana. 1999. Denitrification in coastal ecosystems: Methods, environmental controls, and ecosystem level controls, a review. *Aquatic Ecology* 33: 41–54.

Cronin, T.M., and C. Vann. 2003. The sedimentary record of climatic and anthropogenic influence on the Patuxent estuary and Chesapeake Bay ecosystems. *Estuaries* 26: 196–209.

Day, J.W., J.-Y. Ko, J. Rybczyk, D. Sabins, R. Bean, G. Berthelot, C. Brantley, L. Cardoch, W. Connor, J.N. Day, A. Englande, S. Feagley, E. Hyfield, R. Lane, J. Lindsey, J. Mistich, E. Reyes, and R. Twilley. 2004. The use of wetlands in the Mississippi Delta for wastewater assimilation: A review. *Ocean and Coastal Management* 47: 671–691.

de Leiva Moreno, J., V. Agostini, J. Caddy, and F. Carocci. 2000. Is the pelagic-demersal ratio from fishery landings a useful proxy for nutrient availability? A preliminary data exploration for the semi-enclosed seas around Europe. *ICES Journal of Marine Science* 57: 1091–1102.

de Young, B., M. Barange, G. Beaugrand, R. Harris, R.I. Perry, M. Scheffer, and F. Werner. 2008. Regime shifts in marine ecosystems: Detection, prediction and management. *Trends in Ecology & Evolution* 23: 402–408.

Deegan, L.A. 1993. Nutrient and energy transport between estuaries and coastal marine ecosystems by fish migration. *Canadian Journal of Fisheries and Aquatic Science* 50: 74–79.

Di Toro, D., N. Thomas, C. Herdendorf, R. Winfield, and J. Connolly. 1987. A post audit of a Lake Erie eutrophication model. *Journal of Great Lakes Research* 13: 801–825.

Diaz, R., and R. Rosenburg. 2008. Spreading dead zones and consequences for marine ecosystems. *Science* 321: 926–929.

Duarte, C.M. 1991. Seagrass depth limit. *Aquatic Botany* 40: 363–377.

Duarte, C.M., N. Marba, D. Krause-Jensen, and M. Sanchez-Camacho. 2007. Testing the predictive power of seagrass depth limit models. *Estuaries and Coasts* 30: 652–656.

Duarte, C.M., D. Conley, J. Carstensen, and M. Sanchez-Camacho. 2009. Return to Neverland: Shifting baselines affect eutrophication restoration targets. *Estuaries and Coasts* 32: 29–36.

Estes, J.A., M.T. Tinker, T.M. Williams, and D. Doak. 1998. Killer whale predation on sea otters linking oceanic and nearshore ecosystems. *Science* 282: 473–476.

Flener, P., and U. Schmid. 2008. An introduction to inductive programming. *Artificial Intelligence Review* 29: 45–62.

Folke, C., S.R. Carpenter, B.H. Walker, M. Scheffer, T. Elmqvist, L.H. Gunderson, and C.S. Holling. 2004. Regime shifts, resilience and biodiversity in ecosystem management. *Annual Review of Ecology and Systematics* 35: 557–581.

Ford, E.D., and H. Ishii. 2001. The method of synthesis in ecology. *Oikos* 93: 153–160.

Garnier, J., P. Servais, G. Billen, M. Akopian, and N. Brion. 2001. Lower Seine River and estuary (France) carbon and oxygen budgets during low flow. *Estuaries* 24: 964–976.

Gauch, H.G. 2003. *Scientific method in practice*. Cambridge: Cambridge University Press.

Getzels, J.W., and M. Csikszentmihalyi. 1964. *Creative thinking in art students: An exploratory study. (Cooperative Research No. E-008)*. Chicago: University of Chicago Press.

Graham, M.H., and P.K. Dayton. 2002. On the evolution of ecological ideas: Paradigms and scientific progress. *Ecology* 83: 1481–1489.

Graybill, J.K., S. Dooling, V. Shandas, J. Withey, A. Greve, and G. Simon. 2006. A rough guide to interdisciplinarity: Graduate student perspectives. *BioScience* 56: 757–763.

Gunderson, L.H., and S.S. Light. 2006. Adaptive management and adaptive governance in the everglades ecosystem. *Policy Science* 39: 323–334.

Gunderson, L.H., S.R. Carpenter, C. Folke, P. Olsson, and G. Peterson. 2006. Water RATs (resilience, adaptability, and transformability) in lake and wetland social–ecological systems. *Ecology and Society* 11: 16–25.

Habib, E., B. Larson, W. Nuttle, V. Rivera-Monroy, B. Nelson, E. Meselhe, and R. Twilley. 2008. Effect of rainfall spatial variability and sampling on salinity prediction in an estuarine system. *Journal of Hydrology* 350: 56–67.

Hackett, E.J., and D.R. Rhoten. 2009. The Snowbird Charrette: Integrative interdisciplinary collaboration in environmental research design. *Minerva* 47: 407–440.

Hackett, E.J., J.N. Parker, D. Conz, D. Rhoten, and A. Parker. 2006. *Ecology transformed: NCEAS and changing patterns of ecological research*. Tempe: School of Human Evolution and Social Change, Arizona State University.

Hagy, J.D., W.R. Boynton, C.W. Keefe, and K.V. Wood. 2004. Hypoxia in Chesapeake Bay, 1950–2001: Long-term changes in relation to nutrient loading and river flow. *Estuaries* 27: 634–658.

Hanninen, J., I. Vuorinen, and P. Hjelt. 2000. Climatic factors in the Atlantic control oceanographic and ecological changes in the Baltic Sea. *Limnology and Oceanography* 45: 703–710.

Harris, L.A., C. Duarte, and S. Nixon. 2006. Allometric laws and prediction in estuarine and coastal ecology. *Estuaries and Coasts* 29: 340–344.

Hedges, L.V., and I. Olkin. 1985. *Statistical methods for meta-analysis*. Orlando, FL: Academic.

Henriksen, P. 2009. Long-term changes in phytoplankton in the Kattegat, the Belt Sea, the Sound and the Western Baltic Sea. *Journal of Sea Research* 61: 114–123.

Hetland, R., and S. DiMarco. 2008. How does the character of oxygen demand control the structure of hypoxia on the Texas-Louisiana continental shelf? *Journal of Marine Systems* 70: 49–62.

Hjerne, O., and S. Hansson. 2002. The role of fish and fisheries in the Baltic Sea nutrient dynamics. *Limnology and Oceanography* 47: 1023–1032.

Hobbie, J.E. 2000. Estuarine science: The key to progress in coastal ecological research. In *Estuarine science: A synthetic approach to research and practice*, ed. J.E. Hobbie, 1–16. Washington, DC: Island Press.

Hopkinson, C., and J. Vallino. 1995. The relationships among man's activities in watershed and estuary: A model of runoff effects on patterns of estuarine community metabolism. *Estuaries* 18: 596–621.

Hoppema. 1991. The oxygen budget of the western Wadden Sea, The Netherlands. *Estuarine, Coastal and Shelf Science* 32: 483–502.

Houde, E. D. 2011. *Managing the Chesapeake's Fisheries: A work in progress*. College Park: Maryland Sea Grant College. Publication number: UM-SG-CP-2011-01.

Howarth, R., G. Billen, D. Swaney, A. Townsend, N. Jaworski, K. Lajtha, J. Downing, R. Elmgren, N. Caraco, T. Jordan, F. Berendse, J. Freney, V. Kudeyarov, P. Murdoch, and Z. Zhao-Liang. 1996. Regional nitrogen budgets and riverine N and P fluxes for the drainages to the North Atlantic Ocean: Natural and human influences. *Biogeochemistry* 35: 75–139.

Howarth, R.W., D. Swaney, E. Boyer, R. Marino, N. Jaworski, and C. Goodale. 2006. The influence of climate on average nitrogen export from large watersheds in the northeastern United States. *Biogeochemistry* 79: 163–186.

Humborg, C., K. Fennel, M. Pastuszak, and F. Fennel. 2000. A box model approach for a long-term assessment of estuarine eutrophication, Szczecin Lagoon, southern Baltic. *Journal of Marine Systems* 25: 387–403.

Jones, B.F. 2009. The burden of knowledge and the "death of the Renaissance Man": Is innovation getting harder? *Review of Economic Studies* 76: 283–317.

Jordan, T.E., and I. Valiela. 1982. A nitrogen budget of the ribbed mussel, *Geukensia demissa*, and its significance in nitrogen flow in a New England salt marsh. *Limnology and Oceanography* 27: 75–90.

Jordan, S.J., J. Stoffer, and J.A. Nestlerode. 2011. Wetlands as sinks for reactive nitrogen at continental and global scales: A meta-analysis. *Ecosystems* 14: 144–155.

Josefson, A.B., and B. Rasmussen. 2000. Nutrient retention by benthic macrofaunal biomass of Danish estuaries: Importance of nutrient load and residence time. *Estuarine, Coastal and Shelf Science* 50: 205–216.

Justic, D., N.N. Rabalais, and R.E. Turner. 2003. Simulated responses of the Gulf of Mexico hypoxia to variations in climate and anthropogenic nutrient loading. *Journal of Marine Systems* 42: 115–126.

Kemp, W.M., and M. Brooks. 2009. Food webs, trophic efficiency and nutrient enrichment. In *Experimental ecosystems and scale: Tools for understanding and managing coastal ecosystems*, ed. J. Petersen, V. Kennedy, W. Dennison, and W. Kemp, 195–202. New York: Springer.

Kemp, W.M., and E.B. Goldman. 2008. *Thresholds in the recovery of eutrophic coastal ecosystems*. College Park: Maryland Sea Grant. Publication number: TS-2008-01. http://www.mdsg.umd.edu/store/reports/thresholds/.

Kemp, W.M., and J.M. Testa. 2012. Metabolic balance between ecosystem production and consumption. In *Treatise on estuarine and coastal science*, ed. E. Wolanksy and D. McLusky. Oxford: Elsevier.

Kemp, W.M., E.M. Smith, M. Marvin-DiPasquale, and W.R. Boynton. 1997. Organic carbon-balance and net ecosystem metabolism in Chesapeake Bay. *Marine Ecology Progress Series* 150: 229–248.

Kemp, W.M., M. Brooks, and R. Hood. 2001. Nutrient enrichment, habitat variability and trophic transfer efficiency in simple models of pelagic ecosystems. *Marine Ecology Progress Series* 223: 73–87.

Kemp, W.M., W. Boynton, J. Adolf, D. Boesch, W. Boicourt, G. Brush, J. Cornwell, T. Fisher, P. Glibert, J. Hagy, L. Harding, E. Houde, D. Kimmel, W.D. Miller, R.I.E. Newell, M. Roman, E. Smith, and J.C. Stevenson. 2005. Eutrophication of Chesapeake Bay: Historical trends and ecological interactions. *Marine Ecology Progress Series* 303: 1–29.

Kemp, W.M., J.M. Testa, D.J. Conley, D. Gilbert, and J.D. Hagy. 2009. Temporal responses of coastal hypoxia to nutrient loading and physical controls. *Biogeosciences* 6: 2985–3008.

Kimmel, D.W., L. Miller, E.H. Harding, and M. Roman. 2009. Estuarine ecosystem response captured using a synoptic climatology. *Estuaries and Coasts* 32: 403–409.

Krause-Jensen, D., and K. Sand-Jensen. 1998. Light attenuation and photosynthesis of aquatic plant communities. *Limnology and Oceanography* 43: 396–407.

Kuhn, T.S. 1970. *The structure of scientific revolutions*. Chicago: University of Chicago Press.

Latimer, J.S., and S.A. Rego. 2010. Empirical relationship between eelgrass extent and predicted watershed-derived nitrogen loading for shallow New England estuaries. *Estuarine, Coastal and Shelf Science* 90: 231–240.

Lawton, J.H. 1999. Are there general laws in ecology? *Oikos* 84: 177–192.

Lehrter, J.C., and J. Cebrian. 2010. Uncertainty propagation in an ecosystem nutrient budget. *Ecological Applications* 20: 508–524.

Leopold, A.C. 1978. The act of creation: Creativity process in science. *BioScience* 28: 436–440.

Levin, P.S., M.J. Fogarty, S.A. Murawski, and D. Fluharty. 2009. Integrated ecosystem assessments: Developing the scientific basis for ecosystem-based management of the ocean. *PLoS Biology* 7 (1): e1000014. doi:10.1371/journal.pbio.1000014.

Levins, R. 1966. The strategy of model building in population biology. *American Scientist* 54: 421–431.

Likens, G.E. 1998. Limitations to intellectual progress in ecosystem science. In *Successes, limitations, and frontiers in ecosystem science*, ed. M.L. Pace and P.M. Groffman, 247–271. New York: Springer.

Liu, E.T. 2005. Systems biology, integrative biology, predictive biology. *Cell* 121: 505–506.

Lucas, L.V., J. Koseff, S. Monismith, and J. Thompson. 2009. Shallow water processes govern system-wide phytoplankton bloom dynamics: A modeling study. *Journal of Marine Systems* 75: 70–86.

Madden, C.J., and W.M. Kemp. 1996. Ecosystem model of an estuarine submersed plant community: Calibration and simulation of eutrophication responses. *Estuaries* 19(2B): 457–474.

Malone, T.C., W. Boynton, T. Horton, and C. Stevenson. 1993. Nutrient loadings to surface waters: Chesapeake Bay case study. In *Keeping pace with science and engineering*, ed. M.F. Uman, 8–38. Washington, DC: National Academy Press.

Mantua, N.S., Y. Hare, J.W. Zhang, and R. Francis. 1997. A Pacific Interdecadal Climate Oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* 78: 1069–1085.

Marcus, W., C. Nielsen, and J. Cornwell. 1993. Sediment-budget based estimates of trace metal inputs to a Chesapeake estuary. *Environmental Geology* 22: 1–9.

McConnell, W.J., J.D.A. Millington, N.J. Reo, M. Alberti, H. Asbjornsen, L.A. Baker, N. Brozovic, L.E. Drinkwater, S.A. Drzyzga, J. Fragoso, D.S. Holland, C.A. Jantz, T.A. Kohler, H.D.G. Maschner, M. Monticino, G. Podesta, R.G. Pontius Jr., C.L. Redman, D. Sailor, G. Urquhart, and J. Liu. 2011. Research on Coupled Human and Natural Systems (CHANS): Approach, challenges, and strategies. Meeting report of a symposium on complexity in human—nature interactions across landscapes. *Bulletin of the Ecological Society of America* 218–228.

Megrey, B.A., J.S. link, G.L. Hunt Jr., and E. Moksness. 2009. Comparative marine ecosystem analysis: Applications, opportunities and lessons learned. *Progress in Oceanography* 81: 2–9.

Micheli, F. 1999. Eutrophication, fisheries, and consumer-resource dynamics in marine pelagic ecosystems. *Science* 285: 1396–1398.

Miller, W.D., and L. Harding. 2007. Climate forcing of the spring bloom in Chesapeake Bay. *Marine Ecology Progress Series* 331: 11–22.

Monbet, Y. 1992. Control of phytoplankton biomass in estuaries: A comparative analysis of microtidal and macrotidal estuaries. *Estuaries* 15: 563–571.

Morris, J.T. 1991. Effects of nitrogen loading on wetland ecosystems with particular reference to atmospheric deposition. *Annual Review of Ecology and Systematics* 22: 257–279.

Morrison, G., A. Janicki, D. Wade, J. Martin, G. Vargo, and R. Johansson. 1997. Estimated nitrogen fluxes and nitrogen–chlorophyll relationships in Tampa Bay, 1985–1994. In *Tampa Bay Area Scientific Information Symposium 3*, ed. S.F. Treat. Tampa, FL: Tampa Bay Estuary Program.

Moslemi, J.M., K. Capps, M.S. Johnson, J. Maul, P. McIntyre, A. Melvin, T. Vadas, D. Vallano, J. Watkins, and M. Weiss. 2009. Training tomorrow's environmental problem solvers: An integrative approach to graduate education. *BioScience* 59: 514–521.

Murawski, S.A., J. Steele, P. Taylor, M.J. Fogarty, M.P. Sissenwine, M. Ford, and C. Suchman. 2010. Why compare marine ecosystems? *ICES Journal of Marine Science* 67: 1–9.

Murphy, R., W.M. Kemp, and W. Ball. 2011. Long-term trends in Chesapeake Bay seasonal hypoxia, stratification and nutrient loading. *Estuaries and Coasts*. doi:10.1007/ss12237-011-9413-7.

Musante, S. 2004. A new approach to combat invasive species: Project-based training for graduate students. *BioScience* 54: 893.

Myers, R.A., and B. Worm. 2003. Rapid worldwide depletion of predatory fish communities. *Nature* 423: 280–284.

Naeem, S. 2002. Ecosystem consequences of biodiversity loss: The evolution of a paradigm. *Ecology* 83: 1537–1552.

Nixon, S.W. 1988. Physical energy inputs and the comparative ecology of lake and marine ecosystems. *Limnology and Oceanography* 33: 1005–1025.

Nixon, S.W., and B.A. Buckley. 2002. “A strikingly rich zone”—nutrient enrichment and secondary production in coastal marine ecosystems. *Estuaries* 25: 782–796.

Nixon, S.W., S. Granger, and B. Nowicki. 1995. An assessment of the annual mass balance of carbon, nitrogen and phosphorus in Narragansett Bay. *Biogeochemistry* 31: 15–61.

Nixon, S.W., J.W. Ammerman, L.P. Atkinson, V.W. Berounksy, G. Billen, W.C. Boicourt, W.R. Boynton, T.M. Church, D.M. DiToro, R. Elmgren, J.H. Garber, A.E. Giblin, R.A. Jahnke, N.J. P. Owens, M.E.Q. Pilson, and S.P. Seitzinger. 1996. The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. *Biogeochemistry* 35: 141–180.

Nixon, S.W., R. Fulweiler, B. Buckley, S. Granger, B. Nowicki, and K. Henry. 2009. The impact of changing climate on phenology, productivity, and benthic–pelagic coupling in Narragansett Bay. *Estuarine, Coastal and Shelf Science* 82: 1–18.

NRC (National Research Council). 1990. *Managing troubled waters: The role marine environmental monitoring*. Washington, DC: National Academies Press.

O’Donnell, J.H., H.G. Dam, W.F. Bohlen, W. Fitzgerald, P.S. Gray, A. E. Houk, D.C. Cohen, and M.M. Howard-Strobel. 2008. Intermittent ventilation in the hypoxic zone of western Long Island Sound during the summer of 2004. *Journal of Geophysical Research* 113: 1–13.

Odum, H.T. 1971. *Environment, power and society*. New York: Wiley.

Odum, H.T. 1988. Self-organization, transformity, and information. *Science* 242: 1132–1139.

Odum, H.T. 1994. *Ecological and general systems: An introduction to systems ecology*. Niwot: University Press of Colorado.

Odum, H.T., and E.C. Odum. 2001. *A prosperous way down: Principles and policies*. Boulder: University of Colorado Press.

Ottersen, G., D.O. Hjermann, and N.C. Stenseth. 2006. Changes in spawning stock structure strengthen the link between climate and recruitment in heavily fished cod (*Gadus morhua*) stock. *Fisheries Oceanography* 15: 230–243.

Paerl, H.W. 2009. Controlling eutrophication along the freshwater-marine continuum: Dual nutrient (N and P) reductions are essential. *Estuaries and Coasts* 32: 593–601.

Paerl, H.W., L. Valdes, A. Joyner, M.F. Piehler, and M.E. Lebo. 2004. Solving problems resulting from solutions: Evolution of a dual nutrient management strategy for the eutrophing Neuse River estuary, North Carolina. *Environmental Science and Technology* 38: 3068–3073.

Pauly, D., V. Christensen, J. Dalsgaard, R. Froese, and F. Torres. 1998. Fishing down the food webs. *Science* 279: 860–863.

Pennisi, E. 2000. Integrating the many aspects of biology. *Science* 287: 419–421.

Peters, R.H. 1984. *The ecological implications of body size*. Cambridge: Cambridge University Press.

Peters, R.H. 1991. *A critique of ecology*. Cambridge: Cambridge University Press.

Petersen, C.G.J. 1918. The sea bottom and its production of fish food: A survey of the work done in connection with valuation of Danish waters from 1883–1917, p. 1–82. Reports from the Danish Biological Station.

Petersen, J.K., J. Nahsen, M. Laursen, P. Clausen, J. Carstensen, and D. Conley. 2008. Regime shift in a coastal marine ecosystem. *Ecological Applications* 18: 497–510.

Philippart, C., J. Beukema, G. Cadee, R. Dekker, P. Goedhart, J. van Iperen, M. Leopold, and P. Herman. 2007. Impacts of nutrient reduction on coastal communities. *Ecosystems* 10: 95–118.

Pickett, S.T.A. 1988. Space-for-time substitution as an alternative to long-term studies. In *Long-term studies in ecology*, ed. G.E. Likens, 110–135. New York: Springer.

Pickett, S.T.A. 1999. The culture of synthesis: Habits of mind in novel ecological integration. *Oikos* 87: 479–487.

Pitcher, T.J., D. Kalikoski, K. Short, D. Varkey, and G. Pramod. 2009. An evaluation of progress in implementing ecosystem-based management of fisheries in 33 countries. *Marine Policy* 33: 223–232.

Platt, J.R. 1964. Strong inference. *Science* 146: 347–353.

Popper, K.R. 1968. *The logic of scientific discovery*, Revisedth ed. New York: Harper and Row.

Rabalais, N.N., R.J. Diaz, L.A. Levin, R.E. Turner, D. Gilbert, and J. Zhang. 2010. Dynamics and distribution of natural and human-caused hypoxia. *Biogeosciences* 7: 585–619.

Rhoten, D., and A. Parker. 2004. Risks and rewards of an interdisciplinary research path. *Science* 306: 2046.

Rhoten, D., E. O’Connor, and E. Hackett. 2009. The act of collaborative creation and the art of integrative creativity: Originality, disciplinarity and interdisciplinarity. *Thesis Eleven* 96: 83–108.

Riley, G.A. 1946. Factors controlling phytoplankton populations on Georges Bank. *Journal of Marine Research* 6: 54–73.

Risgaard-Petersen, N., T. Dalsgaard, S. Rysgaard, P.B. Christensen, J. Borum, K. McGlathery, and L.P. Nielsen. 1998. Nitrogen balance of a temperate eelgrass *Zostera marina* bed. *Marine Ecololgy Progress Series* 174: 281–291.

Savage, C., P.R. Leavitt, and R. Elmgren. 2010. Effects of land use, urbanization, and climate variability on coastal eutrophication in the Baltic Sea. *Limnology and Oceanography* 55: 1033–1046.

Savchuk, O.P. 2005. Resolving the Baltic Sea into seven subbasins: N and P budgets for 1991–1999. *Journal of Marine Systems* 56: 1–15.

Schubel, J., and H. Carter. 1977. Suspended sediment budget for Chesapeake Bay. In *Estuarine processs*, ed. M. Wiley, 48–62. New York: Academic.

Scully, M.E. 2010a. The importance of decadal-scale climate variability to wind-driven modulation of hypoxia in Chesapeake Bay. *Journal of Physical Oceanography* 40: 1435–1440.

Scully, M.E. 2010b. Wind modulation of dissolved oxygen in Chesapeake Bay. *Estuaries and Coasts* 33: 1164–1175.

Seitzinger, S.P. 1988. Denitrification in freshwater and coastal marine ecosystems: Ecological and geochemical significance. *Limnology and Oceanography* 33: 702–724.

Seitzinger, S.P., S. Nixon, and M. Pilson. 1984. Denitrification and nitrous oxide production in a coastal marine ecosystem. *Limnology and Oceanography* 29: 73–83.

Sill, D.J. 2001. Integrative thinking, synthesis, and creativity in interdisciplinary studies. *The Journal of General Education* 50: 288–311.

Silliman, B.R., J. van de Koppel, M. Bertness, L. Stanton, and I. Mendelssohn. 2005. Drought, snails, and large-scale die-off of southern U.S. salt marshes. *Science* 310: 1803–1806.

Smith, N.P. 1994. Water, salt, and heat balances of coastal lagoons. In *Coastal lagoon processes*, ed. B. Kjerfve, 69–102. New York: Elsevier.

Smith, S.V., and M.J. Atkinson. 1994. Mass balances of nutrient fluxes in coastal lagoons. In *Coastal lagoon processes*, ed. B. Kjerfve, 133–156. New York: Elsevier.

Smith, S.V., R.W. Buddemeier, F. Wulff, and D.P. Swaney. 2005. C, N, P fluxes in the coastal zone. In *Coastal fluxes in the Anthropocene*, ed. C.J. Crossland, H.H. Kremer, H.J. Lindeboom, M. Crossland, and M.D.A. Le Tissier, 95–143. Berlin: Springer.

Steckbauer, A., C.M. Duarte, J. Carstensen, R. Vaquer-Sunyer, and D. J. Conley. 2011. Ecosystem impacts of hypoxia: Thresholds of hypoxia and pathways to recovery. *Environmental Research Letters* 6: doi:10.1088/1748-9326/6/2/025003

Steward, J.S., and E.F. Lowe. 2010. General empirical models for estimating nutrient load limits for Florida’s estuaries and inland waters. *Limnology and Oceanography* 55: 433–445.

Stige, L.C., G. Ottersen, K. Brander, K.-S. Chan, and N. Stenseth. 2006. Cod and climate: Effect of the North Atlantic Oscillation on recruitment in the North Atlantic. *Marine Ecology Progress Series* 325: 227–241.

Swaney, D., D. Scavia, R. Howarth, and R. Marino. 2008. Estuarine classification and response to nitrogen loading: Insights from simple ecological models. *Estuarine, Coastal and Shelf Science* 77: 253–263.

Testa, J.M., and W.M. Kemp. 2008. Regional, seasonal, and interannual variability of biogeochemical processes and physical transport in a partially stratified estuary: A box-modeling analysis. *Marine Ecology Progress Series* 356: 63–79.

Turekian, K., J. Cochran, L. Benninger, and R. Aller. 1980. The sources and sinks of nuclides in Long Island Sound. In *Estuarine physics and chemistry: Studies in Long Island Sound*, ed. B. Saltzman, 129–164. New York: Academic.

Turner, R.E. 1977. Intertidal vegetation and commercial yields of Penaeid shrimp. *Transactions of the American Fisheries Society* 106: 411–416.

Twilley, R.R., R. Chen, and T. Hargis. 1992. Carbon sinks in mangroves and their implications to carbon budget of the tropical coastal ecosystems. *Water, Air, and Soil Pollution* 64: 265–288.

Twilley, R.R., V. Rivera-Monroy, R. Chen, and L. Botero. 1998. Adapting an ecological mangrove model to simulate trajectories in restoration ecology. *Marine Pollution Bulletin* 37: 8–12.

Ulanowicz, R.E. 1997. *Ecology, the ascendant perspective*. New York: Columbia University Press.

Ulanowicz, R.E. 2009. *A third window: Natural life beyond Newton and Darwin*. West Conshohocken, PA: Templeton Foundation Press.

Vallino, J., C. Hopkinson, and R. Garritt. 2005. Estimating estuarine gross production, community respiration and net ecosystem production: A nonlinear inverse technique. *Ecological Modelling* 187: 281–296.

van Beusekom, J.E.E., and V.N. de Jonge. 1998. Retention of phosphorus and nitrogen in the Ems Estuary. *Estuaries* 21: 527–539.

Vollenweider, R.A. 1976. Advances in defining critical loading levels of phosphorus in lake eutrophication. *Memorie-Istituto Italiano de Idrobilogia* 33: 53–83.

Von Bertalanffy, L. 1972. The history and status of general systems theory. *The Academy of Management Journal* 15(4): 407–426.

Wake, M.H. 2008. Integrative biology: Science for the 21st Century. *BioScience* 58: 349–353.

Walters, C.J. 1986. *Adaptive management of renewable resources*. New York, NY: McGraw Hill.

Walters, C. 1997. Challenges in adaptive management of riparian and coastal ecosystems. *Conservation Ecology* 1: 1–12. http://www.consecol.org/vol1/iss2/art1/.

Wang, P.F., J. Martin, and G. Morrison. 1999. Water quality and eutrophication in Tampa Bay, Florida. *Estuarine, Coastal and Shelf Science* 49: 1–20.

Webster, D. 2006. *New World Dictionary*. Indianapolis: Wiley.

Webster, I., and G. Harris. 2004. Anthropogenic impacts of the ecosystems of coastal lagoons: Modeling fundamental biogeochemical processes and management implications. *Marine and Freshwater Research* 55: 67–78.

Weijerman, M., H. Lindeboom, and A. Zuur. 2005. Regime shifts in marine ecosystems of the North Sea and Wadden Sea. *Marine Ecology Progress Series* 298: 21–39.

West, G., J. Brown, and B. Enquist. 1997. A general model for the origin of allometric scaling laws in biology. *Science* 2767: 122–126.

Williams, M.R., T. Fisher, W.R. Boynton, C. Cerco, W.M. Kemp, K. Eshelman, S.-C. Kim, R. Hood, D. Fiscus, and G. Radcliffe. 2006. An integrated modeling system for management of the Patuxent River estuary and basin, Maryland, USA. *International Journal of Remote Sensing* 27: 3705–3726.

Wofsy, S.C. 1983. A simple model to predict extinction coefficients and phytoplankton biomass in eutrophic waters. *Limnology and Oceanography* 28: 1144–1155.