The Multiscale Integrated Model of Ecosystem Services (MIMES): Simulating the interactions of coupled human and natural systems

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ABSTRACT
In coupled human and natural systems ecosystem services form the link between ecosystem function and what humans want and need from their surroundings. Interactions between natural and human components are bidirectional and define the dynamics of the total system. Here we describe the MIMES, an analytical framework designed to assess the dynamics associated with ecosystem service function and human activities. MIMES integrates diverse types of knowledge and elucidates how benefits from ecosystem services are gained and lost. In MIMES, users formalize how materials are transformed between natural, human, built, and social capitals. This information is synthesized within a systems model to forecast ecosystem services and human-use dynamics under alternative scenarios. The MIMES requires that *multiple* ecological and human *dynamics* be specified, and that outputs may be understood through different temporal and spatial lenses to assess the effects of different actions in the short and long term and at different spatial scales. Here we describe how MIMES methodologies were developed in association with three case studies: a global application, a watershed model, and a marine application. We discuss the advantages and disadvantage of the MIMES approach and compare it to other broadly used ecosystem service assessment tools.

INTRODUCTION

The historical goal of natural resource management was to maximize economic benefits harnessed from nature, or as Gifford Pinchot put it "to manage the system in order to provide the greatest goods, for the greatest number; and for the longest run"(Pinchot 1910). In this command-and-control vision of the world, human systems and natural ones are largely separate and the outcomes of targeted human actions in the natural world can be calculated and executed for maximal gain. The legacy of this thinking, along with continued growth of the human population, has led to the strain, near collapse, or total collapse of much of the world's natural resources (Vitousek et al. 1997, Foley et al. 2005) including widespread degradation of habitat. Earth's sixth mass extinction, and loss of many of the ecosystem functions that humans rely upon are all well documented (Estes et al. 2011). The current state of the world has challenged both scientists and decision-makers to reconsider how we understand the structure, organization, and functional capacity of planetary systems. In response, a new paradigm for understanding the world is emerging. In contrast to the idea of natural and human systems as isolated, there is now recognition that each subsystem is characterized via its embeddings within the other. In this view, the coupling of the natural and human spheres is a major driver of overall system state. Conceptions that adopt this viewpoint include Social Ecological Systems (SES) and Coupled Human and Natural Systems (CHANS) and are characterized by reciprocal relationships, nonlinearities, and emergent behavior (Liu et al. 2007, Zvoleff et al. 2014) .

The evolution of CHANS has developed along two somewhat distinct paths. One thrust has been towards immediate utility and transportability. For example, the Cumulative Human Impact Analysis and the INtegrated Valuation of Ecosystem Services and Tradeoffs (INVEST) software are now widely employed to assess the effects of human activities and services provided by ecosystems (Halpern et al. 2008, Daily et al. 2009). Results from these examples enrich our ability to characterize CHANS and can provide guidance in developing ecosystem-based management (EBM) approaches. For example, InVEST highlights areas where ecosystem function may be especially threatened as a result of multiple impacts whose effects are additive or interactive (Verutes et al. 2014). Though an important step in operationalizing CHANS, this existing body of work lacks a critical feature necessary for a full understanding of coupled systems' behavior. Namely, these approaches fail to explicitly account for the *dynamic* character of CHANS despite the fact that concepts such as sustainability and adaptation (often stated goals of EBM) require a dynamic perspective. These core concepts are based upon the principles that Earth is made up of human and natural elements that *interact* and have *feedbacks*, characteristics unique to time-evolving systems (Liu et al. 2007).

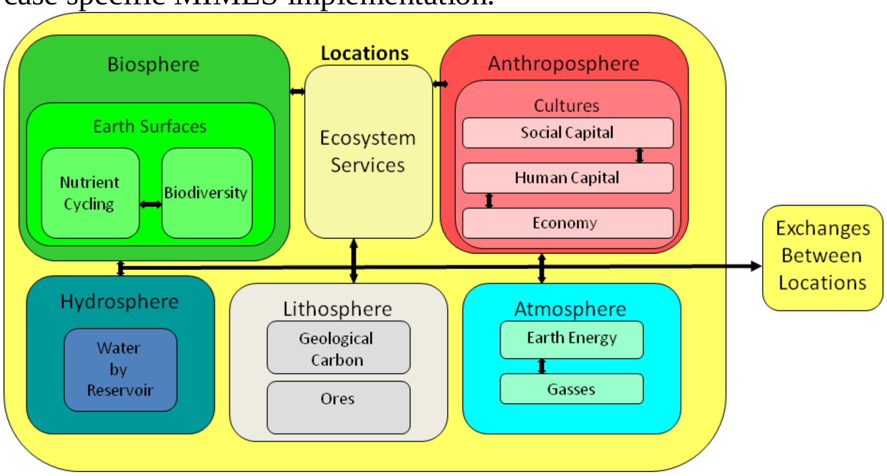
A second, more limited body of work related to CHANS is also emerging. Its goals are to develop the principles and theoretical underpinnings necessary to understand the unique properties and behavior of these systems (Liu et al. 2007). This means establishing CHANS as objects of formal study and developing a field of scientific inquiry that (1) poses and tests hypotheses about the fundamental nature and behavior of CHANS and (2) produces knowledge and scenario-building tools that can be applied in such domains as landscape and ocean planning, international development, and urban renewal. Important theoretical work on this front include the work of the Resilience Alliance (Gunderson and Holling 2002), Kai Lee's *Compass and Gyroscope* (Lee 1993), and Eleanor Ostrom and colleagues' efforts to identify the various elements and interactions of coupled systems (eg.,Anderies et al. 2004). More recently, social-ecological system models have been designed to help decision making in resource management, to deal with uncertainty in natural and social systems, to examine the role of co-evolutionary processes in the dynamics of social-ecological systems, and to understand the implications of microscale human decision making for sustainable resource management and conservation (Schlüter et al. 2012). Despite these landmark contributions, the development of the science to understand CHANS is still humbled by the scale and complexity of these systems and a formalized theoretical framework to guide CHANS research does not yet exist. In this paper, we introduce a framework and methods for computationally assembling and exploring the dynamics of CHANS termed Multiscale Integrated Model of Ecosystem Services (MIMES). We argue that MIMES helps formalize understanding of coupled systems behavior and provides a framework to develop CHANS theory. In addition, MIMES case studies are providing a set of standardized sampling units necessary to test CHANS-theory in the future. We proceed with a detailed description of how the MIMES approach has developed over the past eight years with the support of a number of research groups. Using three case studies, we illustrate sequential phases of MIMES development from (1) initial conception, including guiding principles, overarching framework, and methodologies, to (2) development of the theoretical approach for a specific case study to provide proof of concept, and (3) application to a real-world case study. (When appropriate, additional case studies that have contributed to each development phase are also described). We close the paper with a discussion of how MIMES compares to some other commonly used ecosystem service assessment tools.

MIMES ANCESTRY AND GUIDING PRINCIPLES

The early origins of MIMES can be found in such models as CELLS developed at Louisiana State University in the 1980s and 1990s (Sklar et al. 1985, Costanza et al. 1986, Costanza et al. 1988, Martin et al. 2000, Reyes et al. 2000, Martin et al. 2002). More recent ancestry of the approach hails in part to the Polygon-Based Systems model (Boumans and Sklar 1990), the Patuxent Landscape Model (Costanza et al. 2002), and the Global Unified Metamodel of the BiOsphere (GUMBO; (Boumans et al. 2002)). GUMBO was developed to address the recommendations of a working group at the National Center for Ecological Analysis and Synthesis in Santa Barbara, CA. Its purpose was to simulate the integrated earth system and assess the dynamics and values of ecosystem services. A synthesis of several existing dynamic global models, GUMBO integrated natural and social scientific information at an intermediate level of complexity and was the first global model to include dynamic feedbacks among human activities (such as those that advance technological methods of resource acquisition), economic and ecosystem services production, and human wellbeing ,within a dynamic system. GUMBO included sub-models to simulate carbon, water, and nutrient fluxes as well as human economic and social dynamics across eleven biomes, which together encompass the entire surface of the planet. The dynamics of eleven major ecosystem goods and services for each biome were simulated and evaluated. Four scenarios, originally designed by Costanza (2000) were applied to GUMBO which combined alternative assumptions about technology and natural resource policies. For technology the alternative states included a technology-optimistic and a technology-skeptical option; for natural resource policies the alternatives were to invest more heavily in social and natural capital or to invest more in built and human forms of capital.

Foundational concepts originally introduced in GUMBO and subsequently translated into the MIMES framework include the conception of *spheres* which are a set of interactions to organize and connect similar model elements; forms of *capital* to describe how human and natural components of the system contribute to the wellbeing of people*; production* and *impact functions* which are the set of rules for generating natural and human processes including those that produce ecosystem service flows and those that direct human behaviors which feedback into the system; *demand profiles* to describe the relative strength by which multiple ecosystem services are desired by different human user groups; and finally, *scenarios* to describe the set of parameters to be altered across various runs of the model. These foundational concepts are described sequentially and in more detail below.

Spheres—In MIMES similar system elements are grouped together into individual *spheres*, each of which represent a set of processes that generate natural and human system flows (Boumans et al. 2002, Andrade et al. 2010). After the relevant spheres are developed for case study, they are coupled to one another allowing for exchange, interaction, and feedbacks to occur across the whole system. Once coupled, the MIMES architecture is complete and reflects a full encompassing of the suite of dynamics underlying CHANS biophysical, climatological, and human processes. Operationally, developing the model through these spheres helps to formalize understanding and organize modeled interactions within and across a set of five distinct areas (Figure 1): the *hydrosphere* which captures flows related to water, the *lithosphere* which focuses on geological flows, the *atmosphere* which is concerned with flows of gases and particulates; the *biosphere* in which biological processes are generated; and the *anthroposphere* which is characterized by human flows and activities. The protocol for coupling spheres requires the production of an interaction matrix, which is designed to negotiate bidirectional information flows among the sub-models and prevent interoperational issues such as mismatch in units and concept definitions. Strict implementation of this matrix allows model and sub-model formulation for each of the spheres to be flexible and facilitates the cooperative development of a case specific MIMES implementation.



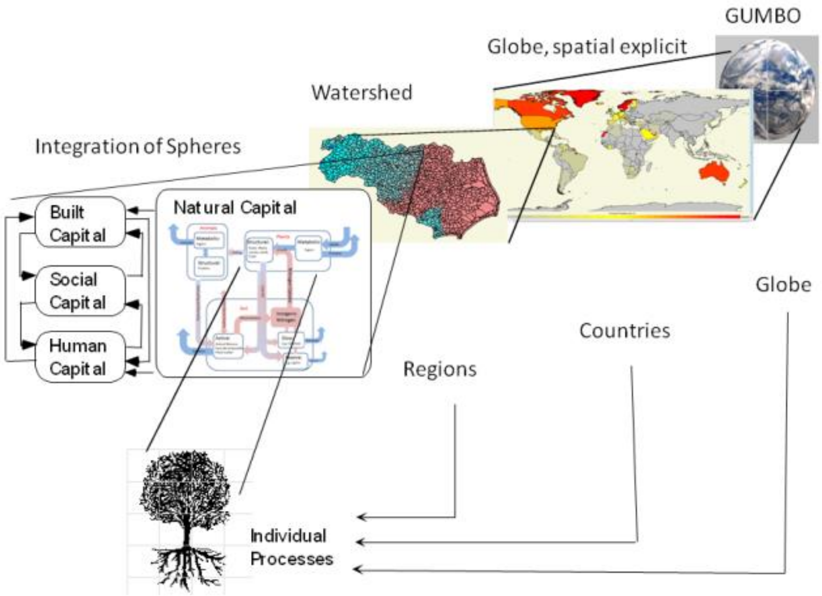
Forms of Capital— In MIMES, capital is defined by system elements that contribute to the goods and services, which affect human wellbeing. Four types of capital are recognized: built capital, human capital, social capital, and natural capital. The first three are associated with the human system and can take the form of physical construction and infrastructure (built capital); knowledge and education (human capital), and social institutions such as families and neighborhoods (social capital). In contrast, natural capital refers to the natural entities, structures and processes that contribute to human wellbeing (Vemuri and Costanza 2006).

Production Functions— Benefits produced from market forms of capital appear in the form of economic services. For example, the presence of a skilled and healthy labor force is a function of human capital and meets demands such as housing construction and childcare. Similarly, services produced by social capital are norms and rules established as a consequence of strong social relationships to meet the demand for stable and safe societies. Not all forms of human capital are reflected as market values, but most are, or have been. In contrast, ecosystem services are derived from nature without the interference of a market (Millennium Ecosystem Assessment 2005). Examples include the provisioning of clean water and healthy soils. Similarly, wild fish can be harvested for food or recreational opportunities and coastal dunes can protect shore communities. In some sense, these services have become marketized (through, for example, bottled water and the pricing of agricultural real estate), but their provisioning by nature has historically been taken for granted. Whereas the idea of economic services has strongly informed classical and neo-classical economic doctrines, recognition of ecosystem services in economic theory has only recently begun to take hold. For example, the integration of natural capital forms into economic thinking has led to the development of ecosystem service classification systems to match the same rigor as those derived for built capital; these include The Economics of Ecosystem Services and Biodiversity (TEEB 2010) and the Common International Classification of Ecosystem Services (CICES 2013). Methodologically, the generation of production functions in MIMES is governed by a *make table* which defines the suite of services for the system and identifies the system elements necessary to produce those services.

Demand Profiles—The diversity and abundance of ecosystem services demanded by humans from the ecosystem is essential for modeling how people invest in human, social, and built capital. Human user groups, however, vary in their demographic, social, religious, and economic character, and therefore demand profiles in the anthroposphere must incorporate a multitude of perspectives. In MIMES human groups are defined as part of the anthroposphere and these groups may be characterized, for example, by differences in economic incentives (*e.g.* industrial vs artisanal fishing sectors), cultural identify (*e.g.* different Native American tribes), or nationality. Methodologically, demand profiles must be set for each human user group and are generated through the *use table*, which defines the users and demand profiles of services.
Data on demand profiles based on cultural preferences can be sourced through anthropological databases like the Human Relations Area Files (HRAF; http://www.yale.edu/hraf/index.html), or sampled through surveys based on con-joint analyses (Jordan et al. 2010).

Impact Functions—Impact functions describe the effects that economic production has on the structure and functioning of ecosystems. These functions are the core concern of many ecosystem service models and organizations such as the US EPA, World Health Organization, and World Resources Institute. Typically, scenarios that incorporate Best Management Practices (BMP; i.e. *how* an action is conducted) are parameterized through these impact functions. Although they can be project specific, impact functions typically include such general parameters such as depletion rates, pollution levels, and land-cover changes. Methodologically, the *impact table* characterizes human generated impacts and defines the impact levels caused by different types of human activities on system elements. Information relevant to the impact table is the core concern of organizations such as the US EPA and international counterparts, such as the Food and Agriculture Association of the United Nations (FAO,) World Resources Institute, and World Health Organization,

*Scenarios—*Scenarios allow decision makers to choose among different investments of natural and human capital. We have developed MIMES to perform scenario analyses and to envision outcomes in the integrated management of resources at the global, regional, and local scales (Figure 2). The model was created to provide a "thinking space" that can help experts reach consensus on knowledge integration and form opinions on the alternatives that are most desirable or sustainable. This integration, applied to a place-based case study, allows stakeholders to play out scenarios that forecast how different actions effect quality of life and the distribution of benefits in the future.

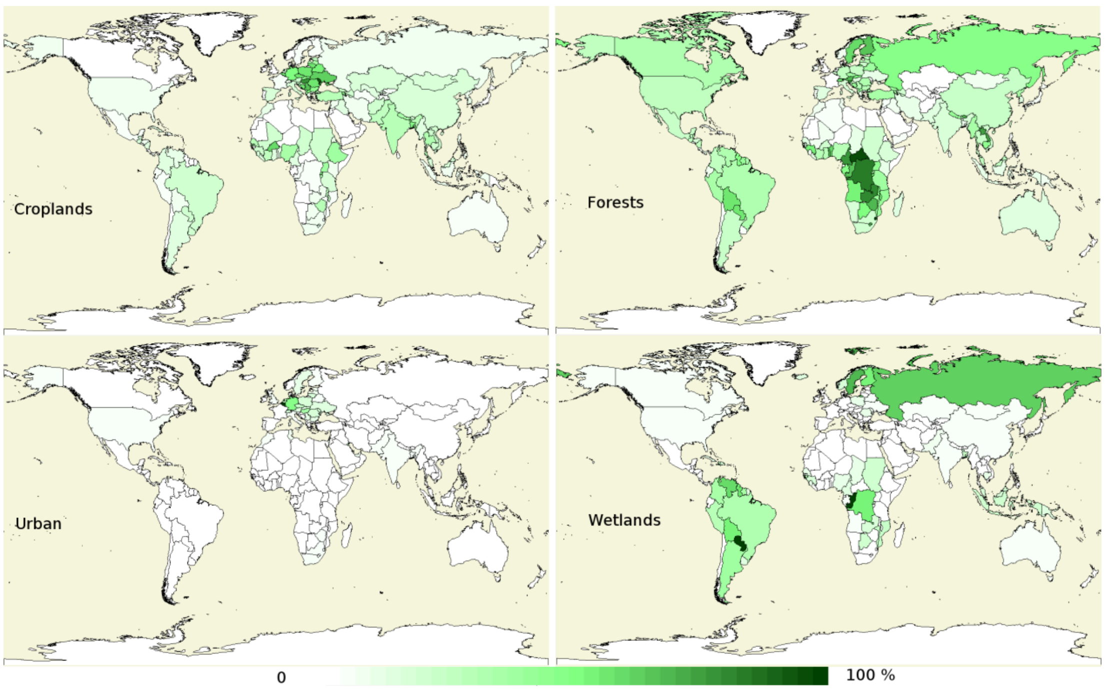


INCORPORATING SPATIAL FLOWS: THE GLOBAL MIMES CASE STUDY

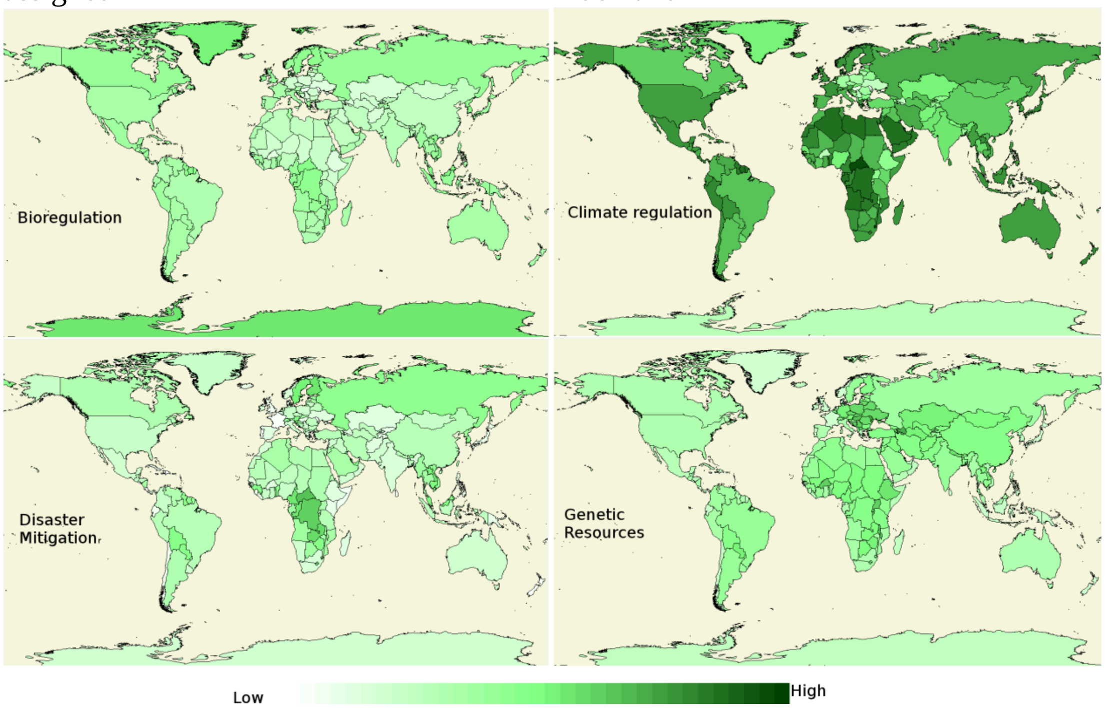
In 2007, a group of applied scientists and modelers gathered at the University of Vermont to discuss GUMBO and future modeling efforts. Although GUMBO demonstrated the feasibility of dynamic modeling of CHANS systems, meeting participants recognized that the approach was severely limited, both in its utility to support real-world decision making and its ability to analyze empirical patterns in coupled systems' behavior. The group identified a set of key needs for developing the approach, chief among which was to incorporate spatial dimensions into the framework. Participants envisioned that a refined approach could be applied with flexibility to a variety of case studies including terrestrial, marine, and watershed systems and could be utilized to explore relevant management scenarios, for instance by simulating emerging carbon trading and carbon offset systems; exploring payment for ecosystem services options; and understanding the system-wide effects related to climate change, land-use change, and restoration efforts. The goal of the refined approach would be to help evolving institutions gain insight into the dynamics, spatial patterns, and value of ecosystem services; nurture collaborations among managers, researchers, and implementing partners; and to support the redesign of national-accounting frameworks.

In response to this feedback, MIMES developers turned to Simile, a declarative modeling software used to construct spatially explicit systems dynamic models (Muetzelfeldt 2004). By spatializing the approach, MIMES became capable of simulating CHANS as a collection of locations that exchange material flows (*e.g* movement of water and air) and individuals (both from human non-human animal populations) through movement from migration and travel patterns. In MIMES, spatial units were designed to be flexible both in number and configuration such that the simulated behavior of a CHANS case study could be executed across cells, grids, rasters, or polygons, where different scales could represent different human or ecological units.

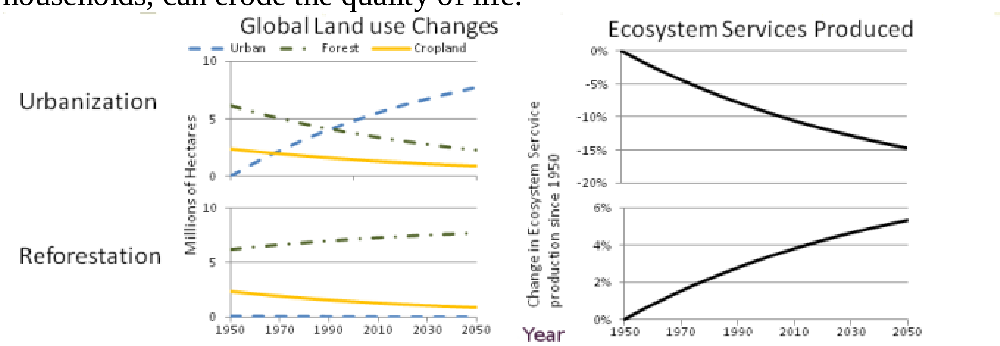
The global implementation of MIMES was the first case study to test the capabilities of this dynamic and spatially explicit approach and to produce ecosystem service tradeoff results (Figure 3). Whereas GUMBO is globally averaged, MIMES is spatially explicit and scalable to render the dynamics for ecosystem-service values in a spatially explicit form. It allows the analysis of tradeoff decisions considering human-natural interdependence at the global and national scale.



Land covers are assigned production profiles, while economic sectors (including households) are assigned demand profiles.



The value of the ecosystem services are sector-specific prices, emerging as a result of mismatches in production and demand, multiplied by the amounts of services produced. Large supplies in ecosystem services can improve quality of life, whereas high prices, in particular for households, can erode the quality of life.



Methods for Global MIMES

In the global MIMES model the anthroposphere includes the country-specific population dynamics and production dynamics of 10 general economic sectors (agriculture, fisheries, forestry, households, manufacturing, mining, research and education, tourism, transportation, and other services). In executing the simulations, initial country-specific levels of sector-specific capital investment (United Nations Statistics Division 2003) are updated based on scenarios for yearly investment decisions.

For Global MIMES, economic production in the anthroposphere is expressed in the following equation:

1 $${}_{1}^{n}Y = K^{b_1}L^{b_2}\prod ECS_{3}^{ib}\prod ES_{i}^{jb}$$

Economic production for each of the sectors (${}_1^{n}Y, \text{eq } 1$) is calculated with the use of a Cobb Douglas equation where inputs are: invested built capital (K), available labor (L), intermediate production from the other economic sectors (ECS), and available ecological services (ES, which are estimated from the ecological production functions in the biosphere). Each term is raised to a power set by a demand profile parameter (b_1 to b_m) and the sum of all the demands is normalized to 1 ($\sum b_{1\rightarrow j} = 1$). Production from the economic and ecological systems are the dynamic inputs that together form a make table. Parameters specifying the demand profile are characterized in a use table and informed by the Central Product Classifications (United Nations Statistics Division 2003). The make and use tables are the case specific parameters informing the economics in a MIMES.

Land-cover change dynamics in global MIMES are derived through the following equation:

2: $$\frac{dA_i}{dT} = A_{(i)t} - max(0, min(\varepsilon + Pl + Ecl + CCl, Ac))$$

Process-based land cover change dynamics ($\frac{dA}{dt}$) are caused by population changes, investment strategies, and global climate change for 240 different countries and districts. Each country or district contains a distribution of 11 land covers (A_{1-11}), which are the producers of 12 ecosystem services and 3 ecosystem goods (Figure 3). *Pl* represents land cover loss due to human population growth, *Ecl* are changes due to economic impacts, *CCl* are due to climate change, and ε is the error component. *Ac* sets the maximum of the land cover that can be changed due to either regulatory or physical restraints. Production of ecosystem services per unit land cover are kept constant and were sourced from the benefits-transfer database Ecosystem Valuation Toolkit (http://esvaluation.org).

Pressure-specific change parameters are two-dimensional arrays that assure that the total area in a country remains the same under different scenarios of land-cover change. The dynamics are either provided by time series datasets or calculated within the model to represent scenarios in population change, economic development, and climate change. No models were implemented in the MIMES global implementation, to represent the hydrosphere, lithosphere, or atmosphere.

Results and Discussion for Global MIMES

After the implementation of global MIMES, the next step was to use the model to look at different scales and ecological and socioeconomic systems. Here we present two additional examples: a watershed model for the Albemarle-Pamlico watershed in North Carolina and a marine model for the Massachusetts coastal waters, both in the eastern United States. MIMES applications preferably follow discussions involving local and regional stakeholders. Through these discussions, choices are made for the appropriate content and complexity of the ecological and economic models. Frequent interactions among those who have a stake in the study and those whose expertise is to program the models ensure that the appropriate information will be available in the decision tool.

PROOF OF CONCEPT: THE ALBEMARLE-PAMLICO WATERSHED

The First MIMES Watershed application emerged as a place-based demonstration project initiated by the US Environmental Protection Agency (EPA) in 2008. The geographical focus of this application was the Albemarle-Pamlico watershed system; the largest estuarine lagoon system (and second largest estuary) in the U.S. The Albemarle-Pamlico extends across portions of the states of North Carolina and Virginia where the watershed and estuary support a unique assemblage of natural resources including an abundant and diverse freshwater fish assemblage which generate more than four billion dollars in fisheries and tourism annually. More than three million people live in this watershed and many habitats and waters are affected by human activities with the most impaired river basins being the Neuse and Tar-Pamlico River basins. For example, the Neuse River estuary has experienced harmful algal blooms, outbreaks of toxic microorganisms, and fish kills from nitrogen overload for more than 30 years. For this case study, the EPA was interested in developing the methodology to substantiate their long-term plans for exploring alternative future associated with local management scenarios carried out at the state level in eastern North Carolina and Virginia (Figure 4).

Methods for Albemarle-Pamlico MIMES

The MIMES Albemarle-Pamlico project was designed to examine the coupling between socioeconomic, climatic, and biological processes in the region, while recognizing the dependence of ecosystem services on human factors. The EPA identified three research goals for the demonstration project: 1) mapping and monitoring, 2) modeling, and 3) decision support for the Albemarle-Pamlico watersheds and estuary in North Carolina and Virginia. At the start of the project, associated data collection, analysis, and modeling activities were already in progress for these watersheds (Rashleigh and Keith 2010).

The Albemarle-Pamlico Watershed consists of about 80,000 km^2 of land and water in 36 and 16 counties in North Carolina and Virginia, respectively. Six major freshwater river basins flow into the sounds: the Pasqotank, Roanoke, and Chowan Rivers flow into Albemarle Sound; the Tar-Pamlico and Neuse Rivers flow into the Pamlico Sound; and the White Oak River flows into Bogue Sound (additional description of site can be found in (Rashleigh and Keith 2010). Land cover in the watershed is predominantly forest (45%), wetlands (14%), and cultivated cropland and pasture (26%); with urban land cover accounting for less than 7% or the area. The region features a variety of habitat types, including a type of southeastern shrub bogs called pocosin, pine savannah, hardwood swamp forest, bald cypress swamp, salt marsh, brackish marsh, freshwater marsh, beds of submerged aquatic vegetation, and beaches.

For the MIMES watershed model of the Albemarle-Pamlico, we created an executable model to inform watershed and coastal EBM and local decision-making. The spatial units for the study area consist of subwatershed polygons delineated by HUC12 boundaries (USDA-NRCS 2010). Each is assigned a distribution of land uses (Fry et al. 2011) and soil types (U.S. Department of Agriculture) so that subwatershed specific values are generated for parameters that inform hydrological dynamics such as permeability, water-holding capacity, and infiltration (Figure. 4).

In addition to the land cover change and economic production dynamics used in the global model, we added biosphere dynamics to the watershed model to simulate the effect of ecosystem functioning and capture long-term trends in ecosystem services production by land cover type. This complex representation of the biosphere allows changes in ecosystem production to occur even when land cover remains constant, allowing decision makers to understand trends in the ecosystem health of different habitats. The biosphere dynamics are represented by flows of nutrients (carbon, nitrogen, and phosphorous) among six reservoirs. Uptake of nutrients into the system happens through the growth of autotrophic organisms that are able to photosynthesize

and sequester carbon from the air (first reservoir). Growth rates of autotrophs in the model are bounded by daily temperatures, the availability of water (for example, as a function of droughts and flooding), and the availability of nutrients according to the following equation:
3.

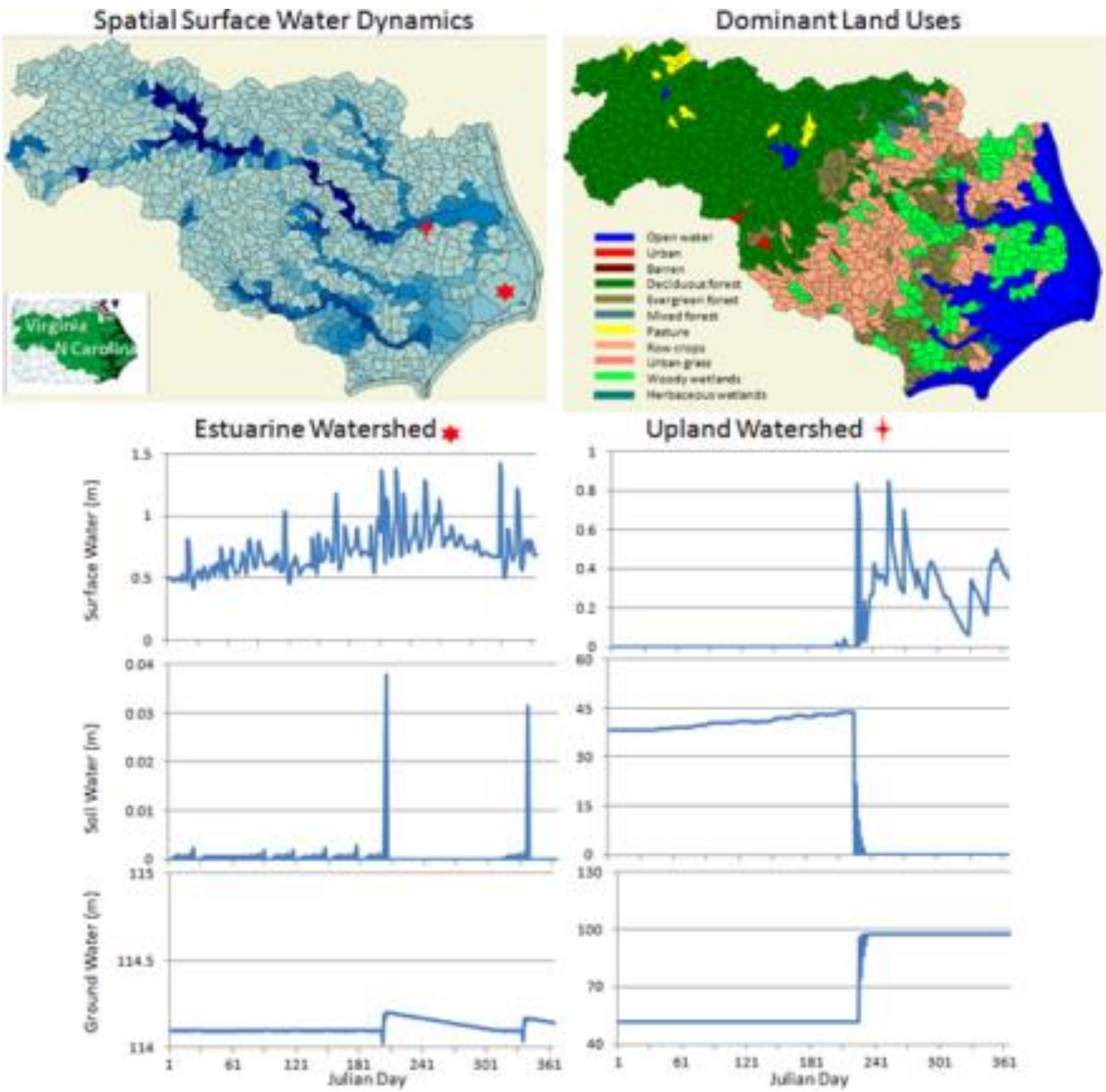
$$\frac{d(Autotrophs)}{d(t)} = Autotrophs_t * GrMax * \min(C_{lf}, N_{lf}, P_{lf}, Flood_{lf}, Drought_{lf}, T_{lf})$$

where, GrMax is the maximum growth rate, and $C_{lf}, N_{lf}, P_{lf}, Flood_{lf}, Drought_{lf}, T_{lf}$ are limitations experienced by autotrophs due to the availability of atmospheric carbon, soil nitrogen, soil phosphorous, flooding conditions, drought conditions, and temperatures. Limitations are ratios of growth rate and fluctuate between 0 (no growth) and 1 (no limitation). When autotrophs grow, they combine C with N and P at land cover specific ratios to create new biomass and sequester carbon. This biomass can be burned or harvested, with nutrients leaving the system; it can be consumed (mostly by animals but also by fungi, known as the second reservoir); or it can die and be added to the soil organic matter (SOM contains litter, humus, and other dead organic matter; the third reservoir). Consumers also die. And when they do, their nutrients can follow similar fates. Dynamics regulating the state of SOM are known as soil formation. Because the first three reservoirs are alive or contain living organisms, they respire and return carbon back into the atmosphere. Nutrients residing within SOM are mineralized to flow into the mineral portion of the soil where they are dissolved (fourth reservoir) and available for plant uptake. Dissolved minerals are either taken up by plants or absorbed into soil particles (fifth reservoir). Absorbed minerals dissolve back into the dissolved reservoir based on their specific equilibrium constants, or they are suspended during erosional events (sixth and final reservoir). Dissolved minerals can enter or leave locations through hydrological flows, while absorbed minerals only enter or leave locations as suspended materials in response to erosional events.

Dynamics to represent the hydrosphere in Albamarle-Pamlico were adapted from the Patuxent Landscape Model (Voinov et al 1999) and were coupled to the land cover dynamics and economic production. This hydrology follows the schemes of vertical and horizontal water movement. Vertically it assumes that water is fluxed from rainfall onto the surface water (rivers, lakes and surface pools), into a soil unsaturated zone (soil moisture available to plants) and onward into a soil saturated zone (ground water). Water in surface water (average water depth in meters) and soil moisture flux back into the atmosphere through evapo-transpiration which is defined as a vegetation-mediated process in the model. Horizontal water movements occur when surface water flows down the elevation gradient due to head differences (differences between sub-watersheds lowest elevations and their water depths) and friction experienced in flow. Sub-watersheds with outlets into the ocean exchange surface water flows due to head differences with the daily average ocean tidal level derived from hourly predictions of tide based on 8 tidal constituents.
4.

$$Waterlevel_t = \sum_1^8 Amplitude_{1-8} * \cos(Speed_{1-8,t} + Phase_{1-8})$$

The description of the users in the Albemarle Pamlico watershed (Anthroposphere) followed the economic sector classifications set by the North American Industry Classification System (NAICS) used by the Bureau of Economic Analyses to help U.S. federal statistical agencies collect, analyze, and publish U.S. economics data (U.S. Department of Commerce 1997). The make table estimates the means of production in the economic sectors using data and classifications from the North American Product Classification System.



Results and Discussion for Albemarle-Pamlico MIMES

The MIMES framework for the Albemarle-Pamlico watershed proved a successful catalyst for EPA research. The production of the HYGEIA model (Boumans et al. 2014) led to a refocus of landscape effects, highlighting human health over economic outcomes. The Albemarle-Pamlico implementation of MIMES, with its highly complex Anthroposphere, is not parameterized, and, as such, is not an executable model ready to replace the EPA legacy models. It serves more as a general reference and resource for future model development. This situation is by design, with the intention of creating models that are conceptually beyond the current state-of-the-art to identify underdeveloped areas of understanding. The promise of MIMES is the incorporation of the Anthroposphere and the computation of dynamic terrestrial processes on the watershed and their influence on water quality and quantity, a direct computation of ecosystem services. Several models based on the Albemarle-Pamlico concept have been constructed with stakeholders, including simulations of the Manawatu watershed in New Zealand (van den Belt et al. 2013), and the Snohomish watershed in Washington State USA (Boumans and Christin 2014).

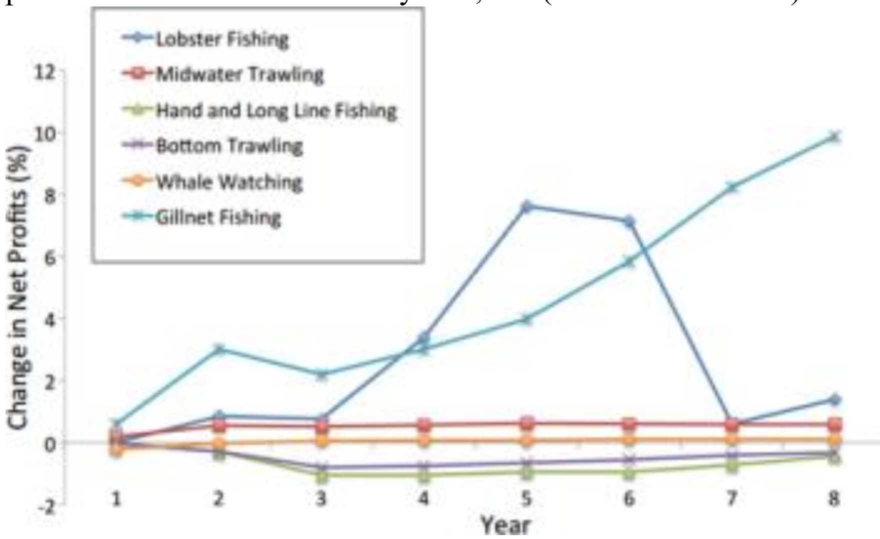
MIMES IN PRACTICE: A CASE STUDY FOR THE MASSACHUSETTS OCEAN

The Massachusetts marine model is the first MIMES application to be developed as a collaborative spatial tool for decision-making. It was created as one of a suite of research and implementation projects to help bring the Commonwealth of Massachusetts into compliance with a new state law, the Massachusetts Oceans Act of 2008 (MOA). While much of the proximate motivation for the development and passage of MOA in 2009 had to do with plans for the siting and construction of offshore wind energy fields in state and adjacent federal waters, to date the legislation represents a first in the nation example of integrative ocean management. By considering how to best manage the entire suite of activities associated with coastal and near shore ocean waters in Massachusetts, the MOA is an example of how EBM may be realized in the real world.

The ocean-planning process in Massachusetts brought together much of the available information to map the distribution of the ecosystem's natural features and human uses including the aggregation of more than 100 spatial data layers. The planning process also resulted in a qualitative analysis to understand the compatibility of human uses within the system. While these activities exemplify how natural resource management in the state is being developed to meet the standards outlined in the U.S. National Ocean Policy, including the goals of sustainability and EBM, in Massachusetts there still remains an urgent need to look beyond overlapping data layers and come to grips with the more complex and counterintuitive aspects of system dynamics. In response to this need, the MIMES case study for the Massachusetts Ocean was initiated as part of a pilot project with the goal of developing of a computational basis for EBM decision-making under MOA. The pilot project consisted of two parallel efforts one led by researchers at the Bren School for the Environment (UCSB); the other led by the MIMES team. While the Bren School team focused on the specific tradeoffs associated with particular configurations for a designated number of offshore wind turbine pylons (White et al. 2012a), the MIMES model sought to demonstrate the feasibility of a spatially explicit analysis of ecosystem service tradeoffs for specified wind-farm developments and area surrounding those development. The collaborative group that developed the MIMES model included researchers from Boston University, the Gund Institute for Ecological Economics, the New England Aquarium, the Stellwagen Bank National Marine Sanctuary, and SeaPlan, an organization that serves as a forum for regional stakeholders. Detailed methods and results from the Massachusetts MIMES case study can be found in Altman et al (Altman et al. 2014), below we present a summary of this work.

Methods for Massachusetts Ocean MIMES

The focal study area for the Massachusetts Marine MIMES model includes 3,900 km^2 of coastal and marine waters located strategically around the town of Gloucester, Massachusetts, an important fishing community whose economy and character have been tied to marine resources for centuries (Figure 5). In the Massachusetts Ocean model, a time series of observed chlorophyll *a* concentration (remotely sensed from within the study area) was used to set the baseline for seasonal primary production dynamics; population dynamics of marine species are modeled through logistic growth function, habitat type, and bottom disturbance by mobile bottom-tending fishing gear. Values for modeled fish species are initiated and bounded by the outputs of a regional ATLANTIS model based upon the 45-year trawl survey data base of the Northeast Fisheries Science Center (NOAA/NMFS, (Link et al. 2010) For further information on parameters for the natural subsystem, see (Altman et al. 2014).



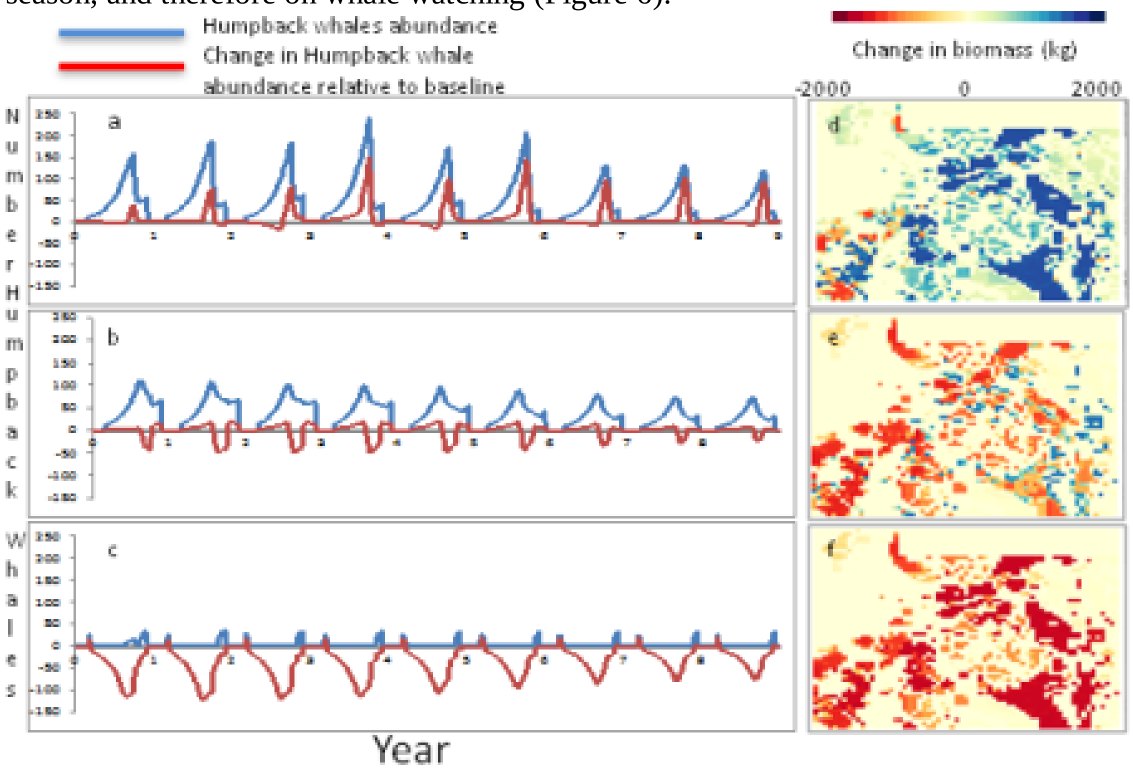
For the Massachusetts model, essential habitat features were characterized using spatial data layers from a variety of sources, including datalayers found in MORIS, the Massachusetts Ocean Resource Information System (www.mass.gov/czm/mapping/index.htm). In addition, spatial information on bathymetry, slope, sediment type (from the backscatter values of a multibeam sonar survey) and a variety of other spatial data (Altman et al. 2014). These features were integral to modeling species distributions, upwelling dynamics, and resulting human behavioral and economic processes.

For the *make table*, the marine model accounts for contributions of the ecosystem to human activities but omits economic contributions. Trends in production of ecosystem services are modeled in the other spheres as described below. In the marine model, human groups are defined by the activities in which they engage while on the water. The choice in human activities, derived from stakeholder interactions, includes the various fishing techniques (tradeoffs among fisheries), industrial users (shipping, liquefied natural gas terminals, pipelines, and wind generators), recreational users (whale watching and recreational fishing), and those whose stake rests in the ` of biodiversity. Meta-analyses and stakeholder inputs provided the demand profiles.

Results and Discussion for Massachusetts Ocean MIMES

Several MIMES scenarios were developed to explore the impacts of different management decisions on ecosystem services, such as fisheries and conservation. The dynamic and spatially explicit models revealed tradeoffs and helped forecast the outcomes of alternative processes. Here we discuss the output for two scenarios: the development of offshore wind turbines and increased fishing for forage species.

Tradeoffs measured across the study area for offshore wind energy development can affect productivity of human-use sectors, though sector members may not experience gains and losses equally (Martin and Hall-Arber 2008, Altman et al. 2014). To understand the effects of spatial scale on tradeoffs, we described changes in species populations and human-activity dynamics within wind areas, focusing our attention on changes associated with development at the largest spatial scale and with other human-use sectors granted unrestricted access to these areas.
MIMES model outputs were also generated for different intensities of foraging fishing in the study area. The species, which included northern sand lance and Atlantic herring, are an important source of food for fish and whales in the region. The study showed that intense harvesting of forage fish would have an effect on whale biomass, especially in the early and late season, and therefore on whale watching (Figure 6).



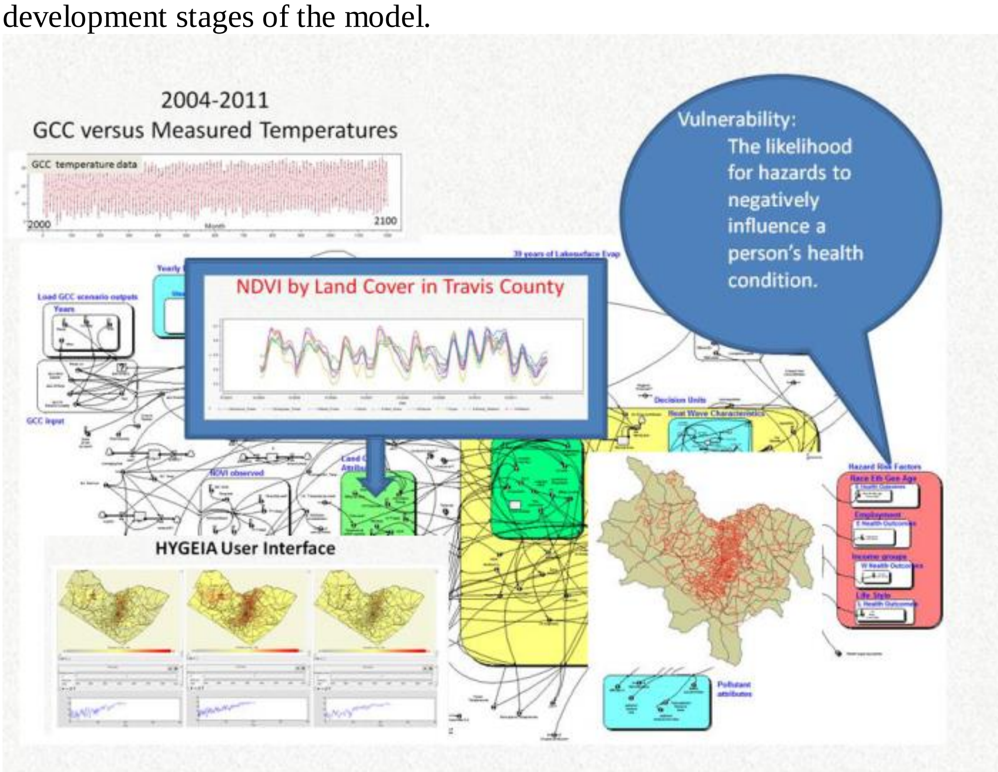
Intense fishing would also have an effect on the valuable ground fishery in the region, which has been under intense harvest pressure for decades. A decline in food base for these species would have the consequence of putting them at even greater risk of population collapse. Models such has MIMES can help decision makers anticipate the effects of different policies, as opposed to continually trying to manage the consequences of policies after they have been enacted.

DISCUSSION

Over the course of its development, the MIMES approach has evolved into an analytical tool that can capture the dynamics and feedbacks of multiple ecosystem service productions and demands simultaneously. A baseline scenario (or most likely outcome given past conditions) is created through calibration against known states of the modeled system, and is used for comparison against alternatives. Calibrations and sensitivity analyses of the base-case scenarios are also used to inform confidence levels in a particular model (Boumans et al. 2001). When played out under various scenarios, MIMES tells the story of CHANS, with the generation and flow of ecosystem services supporting the human enterprise in space and time. MIMES projects the potential for gains and losses under alternative management scenarios in a landscape organized and scaled to match the human experience. Model outcomes are movies of changing landscapes under "what-if " conditions, showing the tradeoffs in economic services and human well being benchmarked against stakeholder preferences in service distributions.

Like programs such as InVEST, ARIES, and Tradeoff Optimization, MIMES has been developed to describe a landscape populated with spatially explicit ecosystem service production functions, yet there are distinct differences from these approaches. ARIES employs a Bayesian framework and relies on the data itself to inform functional relationships rather than defining the relationships *a priori* as with deterministic models (Villa et al. 2014). InVEST is useful for understanding the consequences of alternative decisions when little information exists about a system (or when it is otherwise necessary to rely on more generalized functional relationships); however, in its current state of development the tool provides limited insight into the time evolution of these tradeoffs (Guerry and H. 2014). Tradeoff Optimization explores multiple ecosystem services and identifies optimal and suboptimal spatial configurations of human activities in a marine system (White et al. 2012b). In contrast, MIMES operates like a dynamic Geospatial Information System, addressing the links between natural and human capital and allowing users to integrate site-specific information with spatial data. In this regard, it is ideally suited to examine tradeoffs under various economic, policy, and climate scenarios in space and over time.

Outputs from MIMES applications are multiple, complex, and can be as baffling as the real world (Figure 7). The benefits of this complex nature are that an implementation can be used to execute different kinds of scenarios, even those which were not anticipated during the initial development stages of the model.



One cost is the challenge of training researchers and programmers to develop the infrastructure and scenarios for a successful model. Through verification and calibration, MIMES serves well as a thinking space and platform for reaching scientific consensus and new discoveries in system behavior. Researchers can reproduce the results and sample the processes in the model to make sense of causal relationships. Such opportunities might not occur in the real world, where events may not repeat themselves, and even if they did, observation of such events could be very costly, and irreversible. Models such as MIMES allow for testing management scenarios that would be socially unacceptable—and present opportunities for conservation offence, alerting managers and stakeholders to potentially unsustainable practices, such as the opening of new fisheries.

Within the modular framework of MIMES, spatial scales can be bridged when local applications are nested in regional applications and regional applications again are nested in the global application. In practice, the computational and labor resources, together with a fully developed scientific agreement on how information travels across scales, are not available to attempt this implementation. There are three critical features of MIMES that make it a useful framework for addressing ecosystem services at multiple scales: 1) The MIMES approach can engage a wide diversity of collaborators and experts, including those more knowledgeable in ecology and economics than in mathematics and modeling, 2) online resources allow investigators from around the world to work collaboratively, and 3) groups have been developed to work on related problems, for example ocean planning in Massachusetts. These core groups can serve as experts for other projects. In the end, the goal is not complete a single working model for a given case study, but to engage people in a process through which understanding is both organized and formalized. From this understanding a model is developed that can be used, updated, and optimized into the future.

In MIMES, sub-models representing different spheres of the ecosystem are constructed to follow the conventions of an interaction matrix for plug-and-play capabilities (Voinov et al. 2004). Modeled interactions can be amended over time to incorporate additional inquiry objectives or to make use of new scientific developments in light of the original objectives. MIMES developers benefit from an international collective for access to suites of established dynamic ecological and economic simulation models and databases. Efforts are underway to organize the collaborative through a general accessible cloud server. Model representations of the interaction between ecosystems and the economic sectors range from linear relationships set by databases to complex nonlinear couplings between hydrological, ecological and economic states. The library of modules available through MIMES includes models from a range of disciplines and perspectives, and demonstrates that this experience can be synthesized into a workable integrated model. Modules continue to be developed in the process of building the knowledge consensus, expanding into increasingly varied examples and systems along the way. An important feature of this cumulative, comparative approach is that it lays the groundwork for the recognition of transcendent principals that may be operating in coupled human and natural system dynamics. In this way, the modeling of CHANS within a standardized but dynamic framework could eventually give rise to a coherent body of theory for these systems. Without such a tool, it is hard to imagine this science developing in time to be useful.

Once MIMES case studies are built they can be used for a variety of purposes. Most are designed to try out management scenarios and explore potential futures in economic, social, and ecological terms over time and in space; they can also be used as a thinking space and platform for experimentation with alternative hypotheses. This dual use in MIMES aims to keep an open communication channel between the decision makers and the scientists. Access to the stored information in the model and its history of use can range from simply looking at maps, graphs, to creating movies of alternative scenarios. Scientists can update MIMES applications with the latest data and understandings, while decision makers can ask new questions that might challenge the content of the models. The success of a MIMES case study will set the pace on how often these interchanges occur.

Types of results that MIMES is able to generate include spatial and temporal information on social equity (economic losers and winners); ecological integrity (the ability of the system to produce services, to sustain the human enterprise without fundamental change in system state, and to recover from catastrophic perturbation); economic efficiency (capital utilization, value added, and the price and value of economic output); the contribution of the ecosystem services to economic production; and the perceived scarcity of ecosystem services for each of the economic sectors (calculated as shadow prices to forecast trends in "willingness to pay").

Although a lack of data can be an enormous hindrance to the study of CHANS, MIMES makes it possible to integrate and make the most of any and all data that are available. Today a vast amount of information on system properties is available from high-resolution observation platforms (satellites, sensor arrays, and surveys), large-scale monitoring projects, and small-scale research initiatives. Advanced computer technologies allow for the integration and analysis of these different types of information and provide new ways for people to communicate results in real time over large distances. With these technologies comes the expectation that decision support tools should assist in exploring the likely consequences of any particular choice (Sharma et al. 2006). Very little of this potential has been realized.

In Coupled Human And Natural Systems (CHANS), adaptation is the process that occurs when human needs change to match the supply of ecosystem services. When adaptation is successful, quality of life is minimally impacted because needs were reshaped. Adaptation often involves substitution for services that were lost. Recently, these substitutes have relied upon the availability of fossil carbon deposits that are nonrenewable. For example when fish catch in coastal areas declined, the fisheries economic sector opted for larger boats and associated propulsion systems so that fish could be caught further away from the coast (Alexander et al. 2009). Ignoring the limited availability of these deposits, they offer a less than perfect substitution due to their deferred environmental costs (i.e. further destabilization of the fishery, plus CO2 emissions that aggravate global climate change). Poor substitutability tends to undervalue the contributions of the ecosystems. Designing adaptation strategies requires a clear understanding of the tradeoffs that are made concerning the substitutability of the services. MIMES facilitates the discovery and dissemination of tradeoff insights. For example, in the Massachusetts Bay case study, there was a tradeoff between forage fishes (Atlantic herring, sand lance) provisioning a reduction fishery, vs. the same fishes feeding whales and supporting the whale-watch industry. The modeling exercise revealed that the maximum total allowable catch for a sustainable fishery (calculated using current, though antiquated means) was much greater than the catch that could be made without disrupting the feeding habits of humpback whales, the major species supporting the whale-watching industry. These asymmetric impacts (fishery hurts whale-watching more than a healthy whale population impacts the fishery) mean that the herring fishery will need to be curtailed or substitute target species, a situation amplified by the importance of forage fishes in supporting directly competing fisheries.

Planning for sustainable futures requires the most sophisticated and spatially explicit approaches available, including dynamic modeling of ecosystem services and the scaling of information on local ecosystem services to the watershed, national, and global scales. To be truly useful and to allow better ecosystem management, such an approach must be easily transferable to managers, policy makers, and the informed public.

CONCLUSIONS

The search for desirable and sustainable solutions requires understanding the production of multiple, coupled ecosystem services. By comparing what is lost and what is gained among alternative decisions, we can evaluate tradeoffs and better understand the consequences to human wellbeing. Such tradeoffs can be estimated through a multitude of emergent properties in the social, economic, and environmental domains operating as one integrated system (Daily 1997, Schoolman et al. 2012). The vast majority of natural resource management decisions are rarely conceived with CHANS in mind or evaluated in ways that consider the full range of ecosystem services and their behavior over the long term. The MIMES model was designed to be a practical tool to support sustainable and ecosystem-based management planning on the ground. At its core, MIMES guides users to associate information on CHANS through successive cycles of observation, stakeholder engagement, mediated modeling, and model run updates. This iterative flow is a key feature of the adaptive management process and also supports stakeholder investment into the data and insights made available through the model.

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Figure Legends

Figure 1. The basic MIMES structure includes the percentage of the earth surface at each location that is in each of eleven basic surface-use types. Multiple interconnected locations arranged as either a regular grid or polygons represent the spatial pattern of the system. The spatial resolution of MIMES can easily be varied for specific applications.

Figure 2. Outline of the MIMES hierarchy for integrated management of resources at the global, regional, and local scales. Models at the various scales provide "thinking spaces" through integration of knowledge.

Figure 3. Demonstration of the Global MIMES application applied to 240 countries outlined by country polygons from the GLC2000 dataset on Land Covers (Bartholome and Belward 2005). Spatial distribution of land uses (4 out of 11 displayed in 3a) and the associated ecosystem services (4 out of 12 displayed in 3b) as provided for 240 countries (greener colors indicate higher values). Figure 3c displays a matrix on Land use changes (left) and trends in ecosystem services (right) under Urbanization and Reforestation scenarios.

Figure 4. (a) Spatial displays of the Surface Water and the Dominant Land Uses generated within the MIMES graphical user interface for the Albemarle Pamlico Watershed. A movie on the spatial dynamics for hydrology outputs is available as supporting information. The MIMES watershed implementation uses biophysical and anthropogenic forcing to simulate changing land use distributions within sub-watersheds. Land use attributes and hydrological parameters are also used to estimate the contributions of ecosystem services to local economic activity. Stars indicate the watershed locations of the hydrological output graphs in figure 3b. (b) Sample hydrographs for two out of 949 of the subwatersheds modeled in the Albemarle Pamlico MIMES application. Hydrographs are shown for an estuarine and an upland watershed. The estuary shows tidally influenced surface waters, mostly saturated soils (groundwater), and occasional periods of slightly unsaturated conditions (soil water). The upland is an example of a subwatershed in transition from dryland (no surface water) to riverine controlled flooded land. Restricted runoff conditions cause the saturation of the soil causing it to join the groundwater in the saturated zone.

Figure 5. MIMES scenarios reveal the impacts of wind turbines on other human uses in Massachusetts Bay. In this case, the relative change in net profits from baseline conditions with no wind turbines, across an eight-year model run within the largest area of wind development under full-use scenarios. For the human activities displayed, each point is the average annual change in net profits from the baseline.

Figure 6. Examples of MIMES-generated scenario results associated with the Massachusetts Ocean MIMES case study examining the effects of changing fishing rates for northern sand lance and Atlantic herring, the primary prey sources for humpback whales in the region. Under baseline conditions Atlantic herring are fished at intermediate levels and there is no targeted fishing on sand lance. Time series plots show humpback whale abundance (blue line) and change in abundance relative to baseline conditions (red line) for three scenarios (panels a, b, and c): 1. fishing pressure on Atlantic herring is decreased (panels a and d), 2. fishing is increased on Atlantic herring (panels b and e), and 3. fishing pressure is increased on both northern sand lance and Atlantic herring (panels c and f). Difference maps (panels d, e, and f) show snapshots of the daily change output generated by the simulation in biomass for humpback whales during the migration season when these marine mammals are present in the study area (red tones indicate biomass losses and blue tones indicate biomass gains).

Figure 7.

Outputs from MIMES applications are multiple, complex, and can be as baffling as the real world. This is demonstrated by a collection of screenshots from a regular model run output made for the HYGEIA Model (Boumans et al. 2014) supper imposed upon the model diagram. The benefits of this complex nature are that an implementation can be used to execute different kinds of scenarios, even those unanticipated during the development of the model.

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