Landscape and Urban Planning 91 (2009) 78–87

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Connecting the ecological-economic dots in human-dominated watersheds: Models to link socio-economic activities on the landscape to stream ecosystem health

Bongghi Hong[a,*], Karin E. Limburg[b], Jon D. Erickson[c], John M. Gowdy[d], Audra A. Nowosielski[e], John M. Polimeni[f], Karen M. Stainbrook[g]

[a] Department of Environmental and Forest Biology, SUNY College of Environmental Science and Forestry, 144 Illick Hall, 1 Forestry Drive, Syracuse, NY 13210, USA
[b] Department of Environmental and Forest Biology, SUNY College of Environmental Science and Forestry, 249 Illick Hall, 1 Forestry Drive, Syracuse, NY 13210, USA
[c] Rubenstein School of Environment and Natural Resources, University of Vermont, 344 Aiken Center, Burlington, VT 05405, USA
[d] Department of Economics, Rensselaer Polytechnic Institute, 3208 Sage Hall, Troy, NY 12180, USA
[e] Formerly of Department of Economics, Rensselaer Polytechnic Institute, Troy, NY 12180, USA
[f] Department of Pharmacy Practice, Albany College of Pharmacy, 106 New Scotland Avenue, Albany, NY 12208, USA
[g] Watershed Assessment Associates, 28 Yates St., Schenectady, NY 12305, USA

ARTICLE INFO

Article history:
Received 6 June 2008
Received in revised form
25 November 2008
Accepted 30 November 2008
Available online 10 January 2009

Keywords:
Urbanization
Economy
Land use change
Ecosystem condition
Interdisciplinary
Hudson River Valley

ABSTRACT

We present an interdisciplinary modeling framework to investigate how human socio-economic activities influence the spatial pattern of urbanization, and how consequent changes in land use affect water quality and stream ecosystem condition. The framework is composed of three submodels considering (1) the social and economic structures based upon a social accounting matrix, (2) land use change and urban sprawl based upon a binary logit regression, and (3) stream ecosystem condition in the catchment area based upon the NAWQA (National Water Quality Assessment) dataset. We applied our integrated model to Dutchess County, New York, USA, as a case study. Our study, in spite of its limitations and uncertainties, demonstrates the importance of a quantitative holistic approach in linking human and natural systems and estimating tradeoffs between economic benefits and environmental quality.

1. Introduction

Increasing urban- and suburbanization are important causes of worsening water quality conditions and loss of habitats for some fish species in the USA (Hatt et al., 2004). About three quarters of the USA population reside in cities and suburbs, and pressure to convert forest and agricultural lands to urban uses is increasing (McKinney, 2002). The spread of urban area alters runoff patterns and increases sediment, nutrient, and toxicant loading through increased impervious surfaces, leading to stream degradation, loss of ecosystem function and reduced biodiversity (Paul and Meyer, 2001). Land use change driven by urban development has large impacts on water resources and biodiversity, both locally and globally (Sala et al., 2000; Vörösmarty et al., 2000).

A large body of literature, including the results from the NAWQA (National Water Quality Assessment) Program (Meador and Goldstein, 2003), has shown that there is a close link between land use characteristics and stream ecosystem condition (Jones et al., 2001; Wickham et al., 2003; Brown et al., 2005). Here, ecosystem condition, sometimes referred to as ecosystem health, is defined as the status of the system's biotic integrity, including resistance and/or resilience to change in the face of anthropogenic disturbance (Rapport, 1992), and includes physical and chemical environmental quality (e.g., stream temperature, conductivity, and element concentration), as well as biotic condition (e.g., fish and macroinvertebrate diversity). As the proportion of land occupied by urban areas increases, stream ecosystem condition typically declines, as indicated by increasing stream water conductivity and nitrate concentration and declining species richness of fishes (Brown et al., 2005; Limburg et al., 2005; McKinney, 2002).

* Corresponding author. Tel.: +1 315 470 6804; fax: +1 315 470 6934.
E-mail addresses: bohong@syr.edu (B. Hong), KLimburg@esf.edu (K.E. Limburg), Jon.Erickson@uvm.edu (J.D. Erickson), gowdyj@rpi.edu (J.M. Gowdy), naudra@juno.com (A.A. Nowosielski), polimenj@acp.edu (J.M. Polimeni), kstainbrook@gmail.com (K.M. Stainbrook).

0169-2046/$ – see front matter
doi:10.1016/j.landurbplan.2008.11.012

Estimating future stream ecosystem condition is difficult because urban development is a complex social/economic phenomenon, mostly driven by demographic and economic factors (Benitez and Fisher, 2004; Li et al., 2003; Verburg et al., 2004). Thus, to estimate the future trend of stream ecosystem condition and plan for environmental mitigation, we need to understand how human social and economic activities affect the spatial pattern of urbanization, and in turn, how expanding urban areas alter stream water quality and biotic condition. However, establishing links between human activities and ecosystem condition has met with a number of obstacles. Social and natural phenomena have been traditionally studied by separate disciplines with their own terminologies and methodological approaches (Alberti et al., 2003). The available data collected by each discipline often have different boundaries and scales (Turner, 2000; Veldkamp and Verburg, 2004). For example, demographic and economic data are generally available at politically meaningful scales such as county or town planning units, or statistically meaningful scales such as census tracts and blocks, whereas water quality and other ecological data are collected at ecologically meaningful scales (e.g., watersheds). Moreover, we have substantial gaps in our understanding within each discipline itself, and some feel that the uncertainties may simply be too large to make any meaningful estimation (e.g., Nilsson et al., 2003).

Despite these obstacles, it is often necessary and desirable to incorporate the best available scientific knowledge into the decision making process, in order to choose among various development options to minimize adverse environmental impacts. Modeling is a means to integrate our knowledge and illustrate potential outcomes despite our imperfect understanding of complex systems. Gaps in our understanding may be assessed through uncertainty analysis and used to highlight areas where further research is required.

In this study, our primary goal was to develop an integrated, quantitative assessment framework, implemented as a set of software tools running in MATLAB (http://www.mathworks.com/), estimating how human socio-economic activities influence the spatial pattern of urbanization, and how consequent changes in land use affect water quality and stream ecosystem condition (Fig. 1). The framework is composed of three submodels simulating the social and economic structures (socio-economic submodel), land use change and urban sprawl (land use submodel), and stream ecosystem condition in the catchment area (ecosystem assessment submodel). An interdisciplinary team of researchers in the fields of ecology, environmental science and economics worked together and learned the languages and concepts of each other's disciplines. The three submodels previously developed by each discipline were linked together as an integrated model and applied to Dutchess County, New York, USA, an urbanizing area located in the lower Hudson River watershed, using a highly relevant economic impact scenario for this region of increased employment in a semiconductor industry. In this paper we synthesize the results of our multidisciplinary case study linking quantitative models describing social and natural systems and illustrating both positive and negative aspects of regional economic growth. Our work would help decision makers and local planners make better land use decisions. We demonstrate our findings and discuss the significance and limitations of our current modeling approach.

2. Model description

The following three sets of research questions were explored: (1) how much does human social and economic activity create demand for new land for development? (2) where in the landscape does the land use change in response to the demand for new land? and (3) to what extent does land use change alter stream ecosystem condition? The pursuit of these research questions recently resulted in three different analytical frameworks: a socio-economic model described in Nowosielski (2002) and Nowosielski and Erickson (2007), a land use change model described in Polimeni (2002, 2005) and Polimeni and Erickson (2007), and an ecosystem assessment described in Stainbrook (2004), Limburg et al. (2005), Limburg and Stainbrook (2006), and Stainbrook et al. (2006). In this study, we developed explicit links among these frameworks, integrating them as three submodels of an integrated assessment model. The model takes an economic impact scenario from the user, runs three submodels consecutively, and reports estimated changes in the economy, land use, and stream ecosystem condition. Each submodel has its own graphical user interface that allows the user to view and change model inputs, assumptions, economic impact scenarios, and reporting options. Model inputs and their descriptions are given in Table 1.

The socio-economic submodel is based upon a social accounting matrix (SAM) providing an expanded view of economic activity and interconnections among industries, household income groups, and social institutions in the region (Pyatt and Round, 1985). A SAM can be viewed as an extended input–output transaction table representing the sales and purchases of the sectors in the economy, expressed as real dollar flows among different sectors. The socio-economic submodel constructs the SAM mostly from a regional economic database ("IMPLAN"—Impact Analysis for Planning, see http://www.implan.com) and uses it to calculate the Leontief inverse matrix, which shows the direct and indirect requirements from each sector of the economy to deliver a dollar's worth of product to final consumers. The model creates a vector representing the final demand from a user-specified economic impact scenario, and multiplies it by the Leontief inverse matrix to obtain a total impact vector. Finally, the model calculates overall economic impacts on the households and estimates the number of new households required to meet the additional demand by various economic sectors. The user may specify the proportion of commuters working inside the region but residing elsewhere.

The land use submodel is based upon a binary logit regression model (e.g., McMillen, 1989) estimating development potential of vacant tax parcels in the simulated region. The model creates a vector of 0–1 dependent variables by assuming that tax parcels with vacant, agricultural, and private forest properties have the potential of being converted into residential use in the near future. The independent variable matrix is constructed from various parcel-specific information selected by the user, including population, income, land assessment value, and distance to central business district. After the development potential in each vacant tax parcel is estimated from the binary logit regression, the model calculates the number of households that can be built within each vacant tax parcel by excluding areas where development may be restricted (hydric soils, wetlands, steep slope area, and protected lands) and by considering zoning regulation for minimum lot size. Finally, using new household demand estimated by the socio-economic submodel, the land use submodel estimates development of vacant tax parcels within the simulated region in response to the economic impact scenario. To accomplish this, the model considers the current employment status and allocates the available vacant lands to potential newcomers (people moving in to take new jobs resulting from the impact scenario) by randomly selecting vacant parcels in proportion to the estimated development potential until all the households required for the newcomers are distributed over the simulated region. The user may choose the independent variables to be used by the binary logit regression model, specify assumptions about the current employment status in the simulated region, select possible restrictions to development, and specify the number of Monte Carlo iterations. The user may also specify the proportion

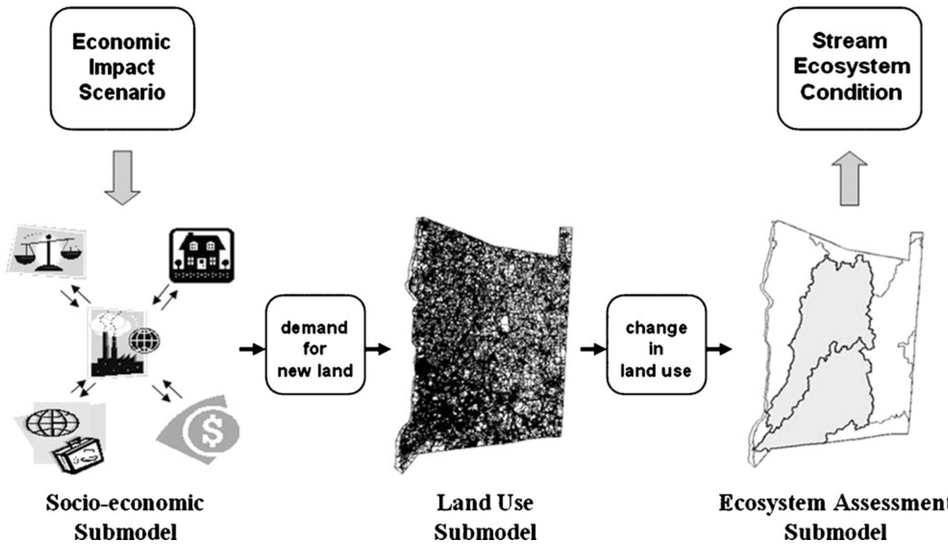

Fig. 1. Schematic of current integrated modeling framework.

of newcomers moving within a certain distance from the impact location.

The ecosystem assessment submodel is based upon a series of multiple linear regression models estimating stream condition variables from land use characteristics (percent use of urban, agricultural, forest, rangeland, wetlands, and water). The submodel currently uses an extensive dataset obtained from NAWQA Program website (http://water.usgs.gov/nawqa/). The NAWQA dataset may be filtered based on user-specified latitudinal and longitudinal range restrictions before the regression for each ecosystem condition variable is constructed, in order not to use data from outside the ecoregion of interest. The submodel overlays urbanized vacant lands (simulated by the land use submodel) onto the National Land Cover Data (NLCD) grid map, to estimate the change in land use

Table 1
Input data for integrated assessment model.

Submodel	Name	Detail
Socio-economic submodel	Sector code	Economic sector codes and labels
	Regional purchase coefficients	Regional purchase coefficients of all commodities within a county
	Byproducts	Industry by commodity byproduct matrix for all industrial sectors
	Industry gross inputs	Commodity by industry gross input matrix
	Household gross inputs	Commodity by household gross input matrix
	Total industry output	Total outputs of all industrial sectors within a county
	Total household output	Total outputs of all household sectors within a county
	Regional commodity supply	Total locally produced commodity supply available in a region
	Social accounting matrix C	Occupation by industry matrix representing division of factor payments between different occupation categories
	Social accounting matrix D	Household by industry matrix representing non-labor inputs industries buy from households
	Social accounting matrix E	Household by occupation matrix representing division of factor payments between different household categories
	Social accounting matrix F	Household by household matrix showing transfers between households
	Household income distribution	Income distribution of all household groups within a county
	Impact conversion factors	Conversion factors from dollars to employment or value added
Land use submodel	Tax parcel data	Exported GIS attribute table containing tax parcel information such as parcel ID, property, area, *x* and *y* coordinates, and minimum lot size
	Property code	Tax parcel classification code (0 = residential; 1 = vacant; 2 = agricultural; 3 = private forest; -9999 = others)
	Parcel ID	Grid map containing ID of vacant tax parcels
	Hydric soils	Grid map showing location of hydric soils
	Wetlands	Grid map showing location of wetlands
	Steep area	Slope grid map (15 = 15–25%; 25 = greater than 25%; otherwise 0)
	Protected lands	Grid map showing location of protected lands
	Impact location	Grid map containing location of simulated economic impact
Ecosystem assessment submodel	Ecosystem condition data	NAWQA dataset containing measurements of ecosystem condition variables in streams and rivers of major US watersheds
	Sampling site description	Description of sampling sites (NAWQA study units) where measurements of ecosystem condition variables were made
	Subbasin ID	Grid map containing ID of all subbasins within a county
	Subbasin code	Subbasin names and codes linked to subbasin ID grid map
	Subbasin connectivity table	Square matrix indicating how subbasins are hydraulically connected
	Land use	NLCD (National Land Cover Data) land use grid map
	Land use code	Description of NLCD land use classification system
	Sampling location	Grid map containing outlet positions of all subbasins

characteristics within each subbasin in response to the economic impact scenario. Land use change can be estimated at three different spatial scales: local, subbasin, or whole watershed. At the local scale, calculation of percent land use is made using only the subbasin grid cells within the user-specified distance from the outlet position, whereas at the subbasin scale all the subbasin grid cells are used. At the whole watershed scale, the subbasin connectivity table provided by the user is applied to calculate the percent land use from all the grid cells that are hydraulically connected upstream of the corresponding subbasin. Once the land use characteristics are estimated, they become inputs to the regression model to assess the change in ecosystem condition driven by the economic impact scenario. The user may choose the ecosystem condition variables to be assessed, set the latitudinal and longitudinal restrictions applied to filter the NAWQA dataset, and specify the spatial scale for estimating land use.

3. Study site and economic impact scenario

The integrated assessment model was applied to Dutchess County (2077 km^2), New York, USA, located in the lower Hudson River watershed (Fig. 2). Dutchess County has two major watersheds, Wappinger (547 km^2) and Fishkill (521 km^2) Creek watersheds, which together contribute approximately 2.6% of the total freshwater to the Hudson watershed (Stainbrook, 2004). The Wappinger and Fishkill Creek watersheds are predominantly forested with glaciated soils, and streams flow southwest toward the Hudson River. County land use intensity follows a development gradient from the rural (and largely unzoned) northeast toward the largest urban centers located in the southwestern part of the county along the Hudson River. This rural-suburban-urban gradient made this site a good location for applying the integrated assessment model to investigate how the stream condition would change with increasing urban development.

Dutchess County's economy through the early 20th century was principally agrarian. Development was steady since the end of the

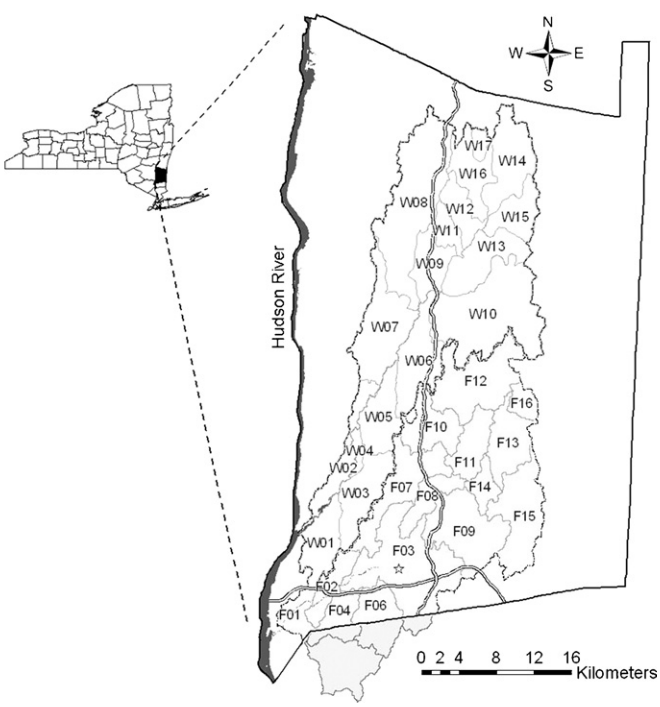

Fig. 2. Map of Dutchess County, New York. Subbasins beginning with "W" and "F" are within Wappinger and Fishkill Creek watersheds, respectively. The central location of the economic impact scenario (semiconductor industry) is shown with a star sign.

Second World War, and job growth increased in industrial sectors. The computer industry, located in the southern part of the Fishkill Creek watershed (Fig. 2), became a major employer in the county. Through workshops with state and county planners, representatives of non-governmental organizations, and technical advisers from academia and local research institutes, growth of the semiconductor industry was identified as a priority concern. In particular, a new semiconductor plant would employ approximately 1000 people when operational. Following these considerations, we applied our model using the economic impact scenario of 1000 new jobs in the semiconductor industry as a case study, to determine what changes are anticipated in the socio-economy, spatial land use pattern, and stream ecosystem condition in this region.

4. Model parameterization and assumptions

We identified 203 industrial sectors, 11 occupation categories (disaggregated according to their skills), and 9 household groups (disaggregated according to income categories) as endogenous economic components within the county. The input data necessary for creating a SAM for this study (Table 1) were obtained from IMPLAN. The main modification for the Dutchess County SAM was disaggregation of IMPLAN's single labor income row into eleven occupation categories using Bureau of Labor Statistics data from the 2000 census and following the procedure outlined by Rose et al. (1988).

Tax parcel data and grid maps were obtained from the Dutchess County Environmental Management Council. Independent variables for the binary logit regression model were prepared by exporting the GIS attribute table of the 2001 Dutchess County tax parcel map and combining it with population and income variables obtained from 1990 and 2000 census block data (http://www.census.gov/). A total of 12 independent variables were prepared: population density in 2000, change in population from 1990 to 2000, mean household income, change in mean household income, median household income, change in median household income, per capita income, change in per capita income, land assessment value per area in 2001, total assessment value, distance to the nearest central business district, and a "neighborhood index," which was calculated as the total number of residential parcels divided by the total number of residential and vacant parcels in a census block; it estimates the developmental pressure on a vacant parcel in relation to its neighboring parcels.

Data for ecosystem condition variables (Table 1) were obtained from the NAWQA database and included 8459 measurements of 24 variables (water temperature, specific conductance, dissolved oxygen, pH, dissolved Ca, Mg, Na, K, Cl, SO_4, F, SiO_2, Fe, Mn, alkalinity, dissolved residue, NH_4, NO_2, NO_3, organic N, total N, dissolved P, PO_4, and total P) measured during 1992–1996 from 213 NAWQA sampling sites across the USA. The data also include biological community samples, composed of 667 and 421 measurements of fish and stream macroinvertebrate species abundance, respectively, that were used to calculate Shannon's diversity indices. The fish abundance data were also used to calculate a fish Index of Biotic Integrity (IBI), calibrated for the mid-Atlantic region by Daniels et al. (2002). The Wappinger and Fishkill Creek watersheds were divided into 17 and 15 subbasins, respectively (Fig. 2). Subbasins outside the county boundary were not considered in this analysis. The 2001 NLCD grid map was used to estimate current land use characteristics. All the grid maps used in this study had a 30 × 30 m resolution.

After the integrated assessment model was parameterized, an economic impact scenario of 1000 new semiconductor jobs was used to drive the simulation. It was assumed that all the economic impacts occur inside the county and 50% of newcomers reside within 10 km from the impact location (southern Dutchess County).

All the restrictions to development (hydric soils, wetlands, steep slope, and land protection) were applied. All the ecosystem condition variables were filtered so that only the data between 37°N and 48°N latitude and 65°W and 85°W longitude were used to construct the multiple linear regression model, except for the fish and invertebrate diversities, which were not filtered because of limited sample size and problems in extrapolation. Although occurrence of individual species varies highly across geographic regions, a measure of their diversity has been shown to be related consistently to the land use pattern within the catchment area (e.g., Allan, 2004). The land use characterization was done at the whole watershed scale. One hundred Monte Carlo iterations were performed when estimating the land use change in response to the economic impact scenario, and subsequently, when estimating changes in ecosystem condition variables (each Monte Carlo output from the land use submodel is used as the input to the ecosystem assessment submodel).

5. Simulation results and validation

The socio-economic submodel estimated that new employment (1000 jobs as a direct economic impact) in the semiconductor sector would stimulate employment in other parts of the economy within Dutchess County (Fig. 3). The indirect employment effect, which includes new recruitment by other industries to meet the additional demand from the semiconductor industries, is pronounced in closely related industries such as computer and data processing, maintenance and repair, and wholesale trade. The semiconductor industries themselves are estimated to receive additional employment, resulting from interdependencies among economic sectors. Induced employment effect, calculated by accounting for the increased economic activities from expenditures of newly employed people, is pronounced mostly in the service and health-related sectors, including eating and drinking, food stores, and doctors and hospitals. Overall, a total of 2292 new jobs were estimated (1000 direct, 602 indirect, and 690 induced) as a result of this scenario.

The output from the socio-economic submodel was used as input to the land use submodel. A stepwise regression analysis indicated that all 12 independent variables for the binary logit regression model significantly explained the spatial development pattern in Dutchess County. Thus, the land use submodel used all 12 variables to create a map of development potential, which shows that there is generally high-urbanization potential in the central and western parts of the county (Fig. 4A). Vacant parcels within the Fishkill watershed have higher development potential (mean ± standard deviation = 0.34 ± 0.16) than in the Wappinger (0.30 ± 0.14). However, both watersheds showed higher development potential than the county average (0.27 ± 0.17). Because we constrained the spread of development around the location of the economic impact in this scenario, most conversion of vacant parcels into residential use is estimated to take place in the lower part of the county (Fig. 4B). Urbanized areas are estimated to increase while forested and agricultural areas are reduced (Fig. 5). More intense urbanization is estimated in the Fishkill watershed, where the semiconductor industry is located, than in the Wappinger watershed.

These estimated land use changes were used as input to the ecosystem assessment submodel. The NAWQA dataset indicated that most water quality variables, including specific conductance and sodium and chloride concentrations that have been reported to increase in urbanizing watersheds (e.g., Kaushal et al., 2005), showed positive correlations with percent urban use and negative correlations with percent forest use, whereas all stream biota variables (invertebrate and fish population diversities and fish IBI score) showed the opposite trend (Fig. 6). The correlation pattern related to agricultural land use was more complicated and inconsistent. Based on these relationships, the ecosystem assessment submodel estimated that the stream water quality would generally degrade as a result of the economic impact, and there would be slight decreases in invertebrate and fish diversities and fish IBI score (Fig. 7A). The impact was generally estimated to be higher in the Fishkill than in the Wappinger watershed (Fig. 7B), although there were large uncertainties associated with the estimation. Sodium and chloride concentrations showed relatively large increases, as well as great differences between watersheds, in response to the economic impact. Silica, iron, and manganese concentrations also increased (Fig. 7A).

Estimated changes in the stream condition were highly variable at the individual subbasin level and, since spatial constraints were imposed, were related to the distance from the impact location. Estimated urbanized area (Fig. 8A), water quality variables such as chloride concentration (Fig. 8B), and stream biota variables such as fish IBI score (Fig. 8C) generally showed greater response when closer to the impact location. Since Fishkill subbasins are generally closer to the impact location than Wappinger subbasins (Fig. 2), large changes were often estimated to occur at Fishkill subbasins. Uncertainties estimated from Monte Carlo simulation were also relatively high in subbasins close to the impact location.

Empirical assessments and validation of individual submodels were made in the previous studies (Nowosielski and Erickson, 2007; Polimeni, 2005; Stainbrook et al., 2006). A direct evaluation of our linked simulation results (prediction of stream ecosystem condition as impacted by 1000 new jobs in the semiconductor industry) is more challenging, since long-term monitoring data are generally

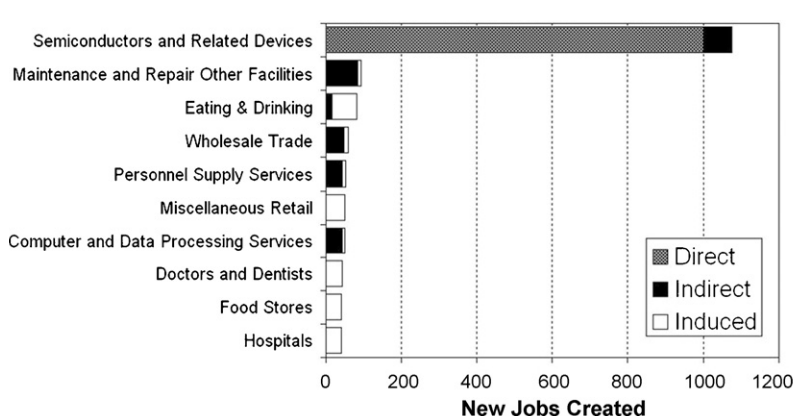

Fig. 3. Direct, indirect, and induced new jobs created by top 10 industries experiencing the greatest increase of jobs within Dutchess County in response to the economic impact.

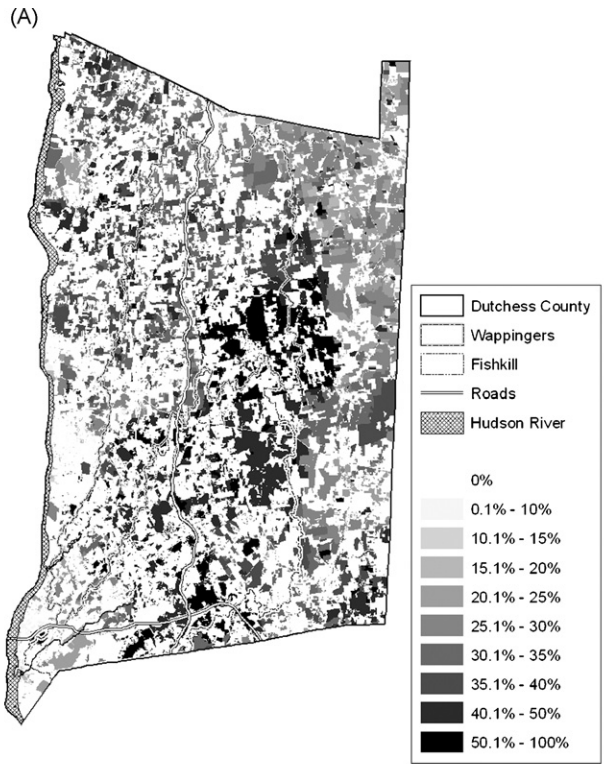

Fig. 4. (A) Relative potential of tax parcels within Dutchess County being converted into residential use in the near future, estimated using the binary logit regression model, and (B) probability of vacant parcels being converted into residential use in response to the simulated economic impact, estimated from one hundred Monte Carlo iterations (considering restrictions to development and distance to the impaction location).

not available at our study sites and our simulation results include only the estimated net effects of the economic impact scenario without imposing them on the time trend projection. At the long-term monitoring stations in the study area, the average chloride concentration increased from 20 mg/l in 1985 to 40 mg/l in 2003 (Kaushal et al., 2005), about 4% increase per year, and the specific conductance showed an annual increase of 1.0–2.2% since the 1960s (Stainbrook et al., 2006). Our simulation results indicated that the stream chloride concentration, which is estimated to be most affected by the urbanization of the watershed in our model, would show an increase of 1.5% in response to the 1000 new jobs in the semiconductor industry, and the specific conductance would increase by 0.27% (Fig. 7A). Although direct comparison is limited, this analysis suggests that our integrated assessment model produces reasonable estimation.

6. Integrated assessment

Our integrated assessment model estimated that, as a result of 1000 new jobs in the semiconductor industry, an additional 1292 jobs would be created in various economic sectors (Fig. 3), 20 km^2 of watershed area would be converted into urban use (Fig. 5), and there would be general degradation of water quality, as well as slight decreases in invertebrate and fish diversities and fish IBI score (Fig. 7A). The Fishkill Creek watershed was estimated to receive more impact than the Wappinger Creek watershed (Fig. 7B), and both the magnitude of impact and the uncertainty associated with the estimation were greater when closer to the impact location (Fig. 8). Overall, our simulation results clearly illustrate the fact that there are both positive and negative aspects to regional economic growth (Shogren et al., 2003). We believe that our work is significant because it provides quantitative estimation (including uncertainties) of the tradeoffs between economic benefits and environmental quality. Our approach also demonstrates the potential of pulling together some pre-existing secondary data sources in a fairly straightforward way, instead of linking a series of complex dynamic models that may require enormous amounts of data input (and for which such extensive data sets may be lacking). Although we focused on assessing changes in stream conditions, other ecological changes (e.g., changes in avian communities, Glennon and Porter, 2005) may be assessed in this framework, by establishing their relationships with land use and linking them to the land use submodel. More complex non-linear, threshold-based models can also be linked and tested as they are developed.

A number of studies have proposed integrated frameworks linking human activities to ecosystem condition, often including socio-economic components driving urbanization, changes in physical environment, and effects on ecosystems. In many cases, the proposed framework is represented as a conceptual diagram rather than combined quantitative models (e.g., Alberti et al., 2003). In other cases, probable outcomes are suggested from a set of scenar-

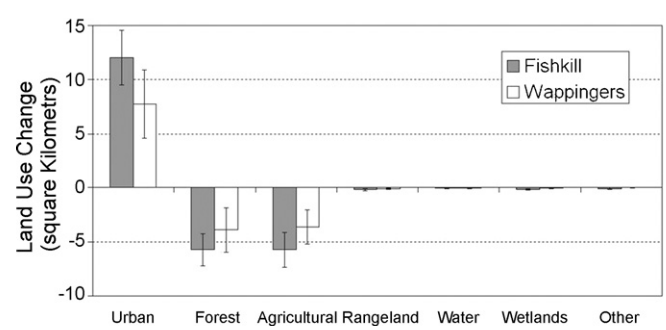

Fig. 5. Land use change within Fishkill and Wappinger Creek watersheds predicted by land use submodel. Error bars denote standard deviations of 100 Monte Carlo iterations.

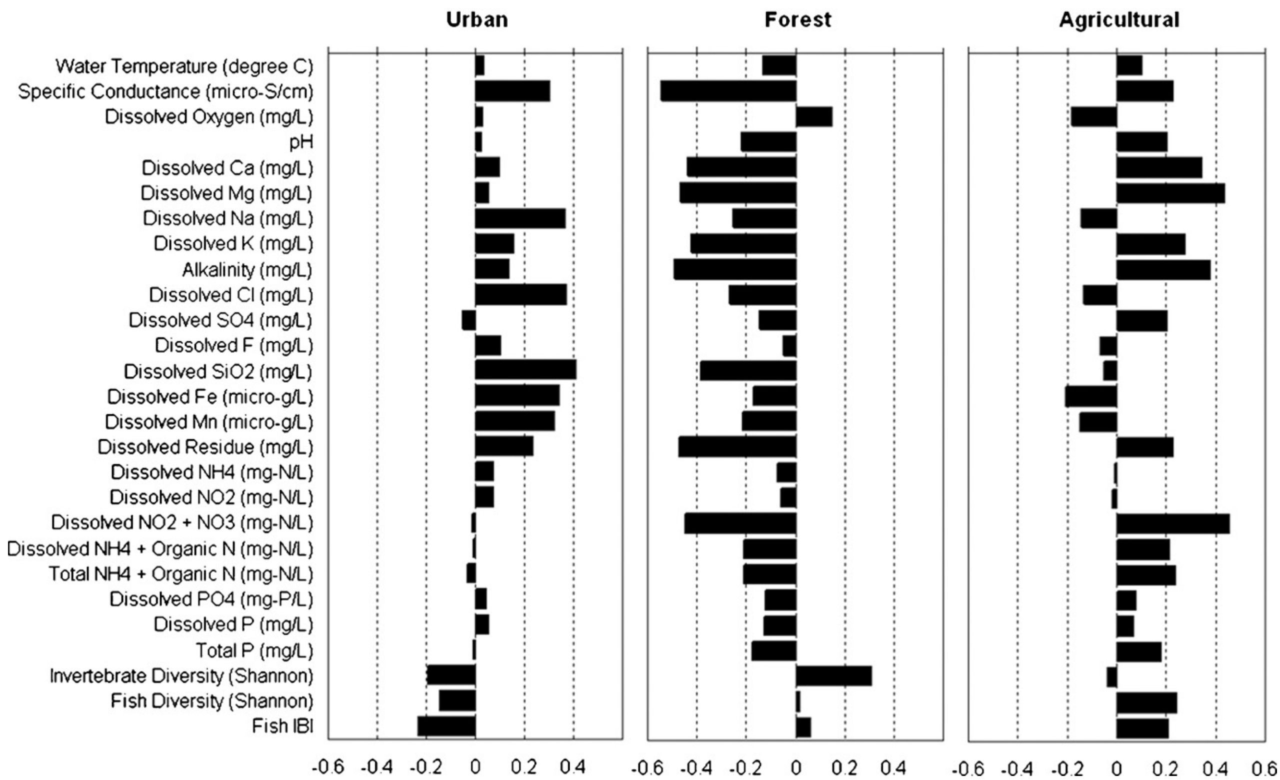

Fig. 6. Pearson's correlation coefficients between urban, forest, and agricultural land use and ecosystem condition variables derived from NAWQA database.

ios, representing plausible examples of what could happen under particular assumptions and conditions (e.g., Peterson et al., 2003). A scenario analysis is used as a surrogate for a forecasting tool in the face of uncontrollable uncertainties and unknowns (Peterson et al., 2003). There also have been attempts to provide a holistic quantitative assessment considering both human and natural systems (Costanza et al., 2002; Dalton, 2004; Farber et al., 2006; Santelmann et al., 2004).

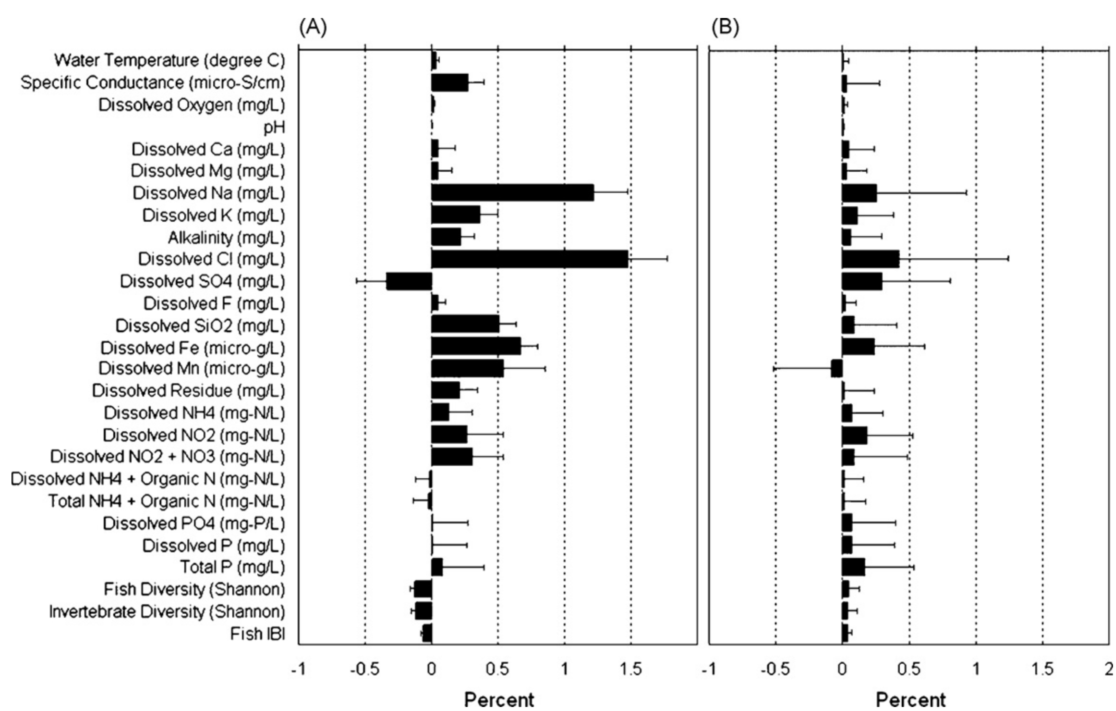

Fig. 7. (A) Predicted mean percent change in ecosystem condition variables in response to the economic impact scenario in 32 subbasins of the Dutchess County. Percent change is calculated as (prediction after economic impact − prediction before impact)/prediction before impact × 100. (B) Difference in mean percent change between Fishkill and Wappinger Creek watersheds. Positive values in (B) indicate that the change was greater in Fishkill than in Wappinger. Error bars denote standard deviations of 100 Monte Carlo iterations.

Direct assessment of economic and environmental tradeoffs is still challenging, because “ecosystem health” is often considered to be an ill-defined term and assigning economic values to environmental quality has met considerable difficulties (Simberloff, 1998). Consequently, interpretation of our results may vary depending on the preferences and priorities of different stakeholders and interest groups. Some would emphasize positive aspects such as increased regional economic activity and more employment opportunity, while others may be concerned with loss of green area and open space, water quality degradation, and reduced biodiversity. Our quantitative assessment of the impacts on the economy, landscape, and environmental quality, in conjunction with an appropriate decision making tool such as the multi-criteria decision aid (Macharis et al., 1998), may be used to integrate social and ecological criteria measured in multiple units and dimensions, demonstrate conflicts between stakeholder perspectives and priorities, and provide opportunities for compromise, alliances, and group consensus.

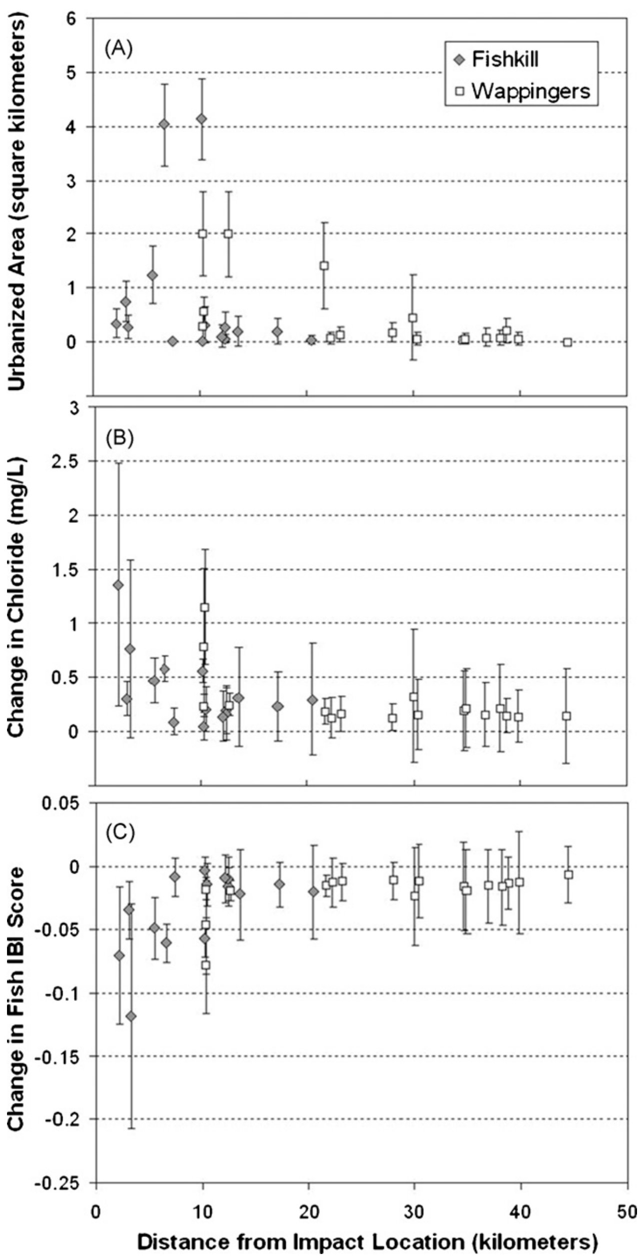

Fig. 8. Predicted urbanized area (A) and changes in stream chloride concentration (B) and fish IBI score (C) due to modeled economic impact in 32 subbasins of the Dutchess County in relation to the distance from impact location. Error bars denote standard deviations of 100 Monte Carlo iterations.

7. Limitations

Our strategy here was to link social and ecological models developed by separate disciplines and run each model in a stepwise fashion, using output from one model as input to another. This approach has been successfully adopted in other studies (e.g., Costanza et al., 2002), and has the merit of transparency, modularity, and efficiency (Voinov et al., 2004). Quantitative uncertainty analysis can identify major sources of uncertainty and pinpoint areas of modeling effort requiring improvement (Clark, 2002). However, compatibility problems may arise when connecting models with disparate temporal and spatial scales and boundaries (Turner, 2000). For example, our socio-economic submodel is spatially aggregated to the county level, whereas the land use submodel is spatially explicit. Both the land use and ecosystem assessment submodels are spatially explicit, but the former is a tax parcel-based county-level model, while the latter is a grid-based watershed-level model, and their boundaries neither overlap nor contain one other (Fig. 2).

Although linking models may be viewed as a major challenge in this type of analysis, uncertainties and unknowns currently existing in each of our modeling steps may be even greater, affecting the reliability of the assessment result (Nilsson et al., 2003). Difficulties in dynamic forecasting arise from both model structure and availability of data for model validation. The socio-economic submodel using an extended input–output transaction table, though appropriate for describing the current economic system in detail, is a snapshot in time. The linear, static nature of economic input–output modeling (Pyatt and Round, 1985) has been criticized with the advent of dynamic and general equilibrium models. Introducing dynamics to the current socio-economic submodel is challenging but essential for forecasting future trends. The binary logit regression, implemented in our land use submodel, has shown to be effective in locating areas of immediate land use change, but becomes less reliable once the time-span gets longer (Allen and Lu, 2003). There are acknowledged difficulties in forecasting future economic and land use change, even at the scale of decades (e.g., Nilsson et al., 2003). The current regression model also does not explicitly account for spatial correlation or multicollinearity of input variables. In an earlier study, Polimeni (2002, 2005) addressed this problem by grouping the input variables having similar properties (for example, mean and median household incomes) and selecting only one variable from each group, obtaining similar results to those from the stepwise logit regression presented in this paper.

The prediction by our current ecosystem assessment submodel is based on the statistical relationship between land use characteristics and various ecosystem condition variables, estimated from national-scale NAWQA database. Percent land use within watersheds may be used to estimate stream water quality and biotic community condition (Meador and Goldstein, 2003). A variation of this approach, useful in regional-scale land use planning and risk assessment, is to assign export coefficients to each land use type representing the mass of nutrients exported per unit area (Wickham et al., 2003). These empirical models have merit in that they offer a rapid and robust assessment of various aspects of ecosystem condition, including physical, chemical, and biotic characteristics (Fig. 7), using land cover databases that are now becoming available nationally (Jones et al., 2001). However, they ignore the complexity and non-linearity of watershed hydrologic systems that often display threshold or bifurcation behavior. It has often been demonstrated that stream condition is affected by the configuration of land use characteristics within a watershed, for example the amount of forest or vegetated buffer along streams (Kleppel et al., 2004) and impervious areas directly connected to streams by pipes or lined drains (Hatt et al., 2004). Moreover, different ecosystem condition variables may have different scales at which the predictive power of land use characteristics is maximized (Jones et al., 2001). To address these problems, existing process-based hydrological models linking land use characteristics, water and nutrient transport, and stream water quality have been incorporated into the integrated modeling framework, for example GEM (general ecosystem model) included in the PLM (Patuxent landscape model) project (Costanza et al., 2002), the water quality model SWAT (Soil and Water Assessment Tool) linked to the SEPMs (spatially explicit population models) (Santelmann et al., 2004), and GLEAMS (Ground Water Loading Effects of Agricultural Management Systems) used in the decision support system for non-point source pollution control planning (Djodjic et al., 2002).

Finally, feedbacks are currently missing in our modeling framework. As humans affect the environment, the environmental change in turn influences socio-economic decisions. For example, degraded environmental quality could make the land less attractive for building new houses (Alberti et al., 2003), but might lead to zoning for even more environmentally stressful activity. A number of studies reported that establishing feedback links into the modeling framework could make a substantial difference in the assessment result (Hammer et al., 2003; Settle et al., 2002).

Despite these limitations, we believe that we effectively demonstrated the importance of a quantitative, holistic approach in integrating human and natural systems and addressing both the positive and negative aspects of human socio-economic activities. Much work remains for meeting the goal of reliable forecasting of future economy, landscape, and ecosystem condition. Extensive interdisciplinary efforts bringing together distinct fields of research into a single modeling framework will be necessary to succeed in this daunting task.

Acknowledgements

This research was funded by the National Science Foundation (DEB-0238121) and the Hudson River Foundation. Our sincere thanks go to David Burns and Salvatore LiCausi at the Dutchess County Environmental Management Council, who provided tax parcel maps and other GIS data. We also thank Peter Woodbury and Dennis Swaney for reviewing an early draft of the manuscript, and Myrna Hall and Gary Lovett for helpful discussions.

References

Alberti, M., Marzluff, J.M., Shulenberger, E., Bradley, G., Ryan, C., Zumbrunnen, C., 2003. Integrating humans into ecology: opportunities and challenges for studying urban ecosystems. Bioscience 53, 1169–1179.

Allan, J.D., 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annu. Rev. Ecol. Evol. Syst. 35, 257–284.

Allen, J., Lu, K., 2003. Modeling and prediction of future urban growth in the Charleston region of South Carolina: a GIS-based integrated approach. Conserv. Ecol. 8, 2 [online] http://www.consecol.org/vol8/iss2/art2/.

Benitez, J.A., Fisher, T.R., 2004. Historical land-cover conversion (1665–1820) in the Choptank watershed, Eastern United States. Ecosystems 7, 219–232.

Brown, L.R., Gray, R.H., Hughes, R.M., Meador, M.R. (Eds.), 2005. Effects of urbanization on stream ecosystems. Am. Fish. Soc. Symp. 47. American Fisheries Society, Bethesda, MD.

Clark, M.J., 2002. Dealing with uncertainty: adaptive approaches to sustainable river management. Aquat. Conserv. 12, 347–363.

Costanza, R., Voinov, A., Boumans, R., Maxwell, T., Villa, F., Wainger, L., et al., 2002. Integrated ecological economic modeling of the Patuxent River watershed, Maryland. Ecol. Monogr. 72, 203–231.

Dalton, T.M., 2004. An approach for integrating economic impact analysis into the evaluation of potential marine protected area sites. J. Environ. Manage. 70, 333–349.

Daniels, R.A., Riva-Murray, K., Halliwell, D.B., Vana-Miller, D.L., Bilger, M.D., 2002. An index of biological integrity for northern mid-Atlantic slope drainages. Trans. Am. Fish. Soc. 131, 1044–1060.

Djodjic, F., Montas, H., Shirmohammadi, A., Bergström, L., Ulén, B., 2002. A decision support system for phosphorus management at a watershed scale. J. Environ. Qual. 31, 937–945.

Farber, S., Costanza, R., Childers, D.L., Erickson, J., Gross, K., Grove, M., et al., 2006. Linking ecology and economics for ecosystem management. Bioscience 56, 121–133.

Glennon, M.J., Porter, W.F., 2005. Effects of land use management on biotic integrity: an investigation of bird communities. Biol. Conserv. 126, 499–511.

Hammer, M., Holmlund, C.M., Almlöv, M.Å., 2003. Social–ecological feedback links for ecosystem management: a case study of fisheries in the Central Baltic Sea archipelago. Ocean Coast. Manage. 46, 527–545.

Hatt, B.E., Fletcher, T.D., Walsh, C.J., Taylor, S.L., 2004. The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. Environ. Manage. 34, 112–124.

Jones, K.B., Neale, A.C., Nash, M.S., Van Remortel, R.D., Wickham, J.D., Riitters, K.H., et al., 2001. Predicting nutrient and sediment loadings to streams from landscape metrics: a multiple watershed study from the United States Mid-Atlantic Region. Landsc. Ecol. 16, 301–312.

Kaushal, S.S., Groffman, P.M., Likens, G.E., Belt, K.T., Stack, W.P., Kelly, V.R., et al., 2005. Increased salinization of fresh water in the northeastern United States. Proc. Natl. Acad. Sci. 102, 13517–13520.

Kleppel, G.S., Madewell, S.A., Hazzard, S.E., 2004. Responses of emergent marsh wetlands in upstate New York to variations in urban typology. Ecol. Soc. 9, 1 [online] http://www.ecologyandsociety.org/vol9/iss5/art1.

Li, L., Sato, Y., Zhu, H., 2003. Simulating spatial urban expansion based on a physical process. Landsc. Urban Plann. 64, 67–76.

Limburg, K.E., Stainbrook, K.M., Erickson, J.D., Gowdy, J.M., 2005. Urbanization consequences: case studies in the Hudson Valley. In: Brown, L.R., Gray, R.H., Hughes, R.M., Meador, M. (Eds.), The Effects of Urbanization on Stream Ecosystems. Am. Fish. Soc. Symp. 47. American Fisheries Society, Bethesda, MD, pp. 23–37.

Limburg, K.E., Stainbrook, K.M., 2006. Assessing ecosystem health in Dutchess County, New York. In: Erickson, J.D., Gowdy, J.M. (Eds.), Frontiers in Environmental Valuation and Policy (Chap. 6). Edward Elgar, Cheltenham, UK.

Macharis, C., Brans, J.P., Mareschal, B., 1998. The GDSS PROMETHEE procedure. J. Decis. Syst. 7, 283–307.

McKinney, M.L., 2002. Urbanization, biodiversity, and conservation. Bioscience 52, 883–890.

McMillen, D.P., 1989. An empirical model of urban fringe land use. Land Econ. 65, 138–145.

Meador, M.R., Goldstein, R.M., 2003. Assessing water quality at large geographic scales: relations among land use, water physicochemistry, riparian condition, and fish community structure. Environ. Manage. 31, 504–517.

Nilsson, C., Pizzuto, J.E., Moglen, G.E., Palmer, M.A., Stanley, E.H., Bockstael, N.E., et al., 2003. Ecological forecasting and the urbanization of stream ecosystems: challenges for economists, hydrologists, geomorphologists, and ecologists. Ecosystems 6, 659–674.

Nowosielski, A.A., 2002. Geo-referenced Social Accounting with Application to Integrated Watershed Planning the Hudson River Valley. Doctoral Dissertation. Rensselaer Polytechnic Institute, Troy, NY.

Nowosielski, A.A., Erickson, J.D., 2007. Regional economic modeling and spatial key sector analysis. In: Erickson, J.D., Messner, F., Ring, I. (Eds.), Ecological Economics of Sustainable Watershed Management: Advances in the Economics of Environmental Resources. Elsevier Science, Amsterdam, pp. 167–182.

Paul, M.J., Meyer, J.L., 2001. Streams in the urban landscape. Annu. Rev. Ecol. Syst. 32, 333–365.

Peterson, G.D., Cumming, G.S., Carpenter, S.R., 2003. Scenario planning: a tool for conservation in an uncertain world. Conserv. Biol. 17, 358–366.

Polimeni, J.M., 2002. A Dynamic Spatial Simulation of Residential Development in the Hudson River Valley, New York State. Doctoral Dissertation. Rensselaer Polytechnic Institute, Troy, NY.

Polimeni, J.M., 2005. Simulating agricultural conversion to residential use in the Hudson River Valley: scenario analyses and case studies. Agric. Hum. Values 22, 377–393.

Polimeni, J.M., Erickson, J.D., 2007. Residential location theory, modelling, and scenario analysis of urban growth and planning. In: Erickson, J.D., Messner, F., Ring, I. (Eds.), Ecological Economics of Sustainable Watershed Management: Advances in the Economics of Environmental Resources. Elsevier Science, Amsterdam, pp. 183–210.

Pyatt, G., Round, J., 1985. Social Accounting Matrices: A Basis for Planning. The World Bank, Washington, DC.

Rapport, D.J., 1992. Evaluating ecosystem health. J. Aquat. Ecosyst. Health 1, 15–24.

Rose, A., Stevens, B.K., Davis, G., 1988. Natural Resource Policy and Income Distribution. Johns Hopkins University Press, Baltimore, MD.

Sala, O.E., Chapin III, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., et al., 2000. Global biodiversity scenarios for the year 2100. Science 287, 1770–1774.

Santelmann, M.V., White, D., Freemark, K., Nassauer, J.I., Eilers, J.M., Vaché, K.B., et al., 2004. Assessing alternative futures for agriculture in Iowa, U.S.A. Landsc. Ecol. 19, 357–374.

Settle, C., Crocker, T.D., Shogren, J.F., 2002. On the joint determination of biological and economic systems. Ecol. Econ. 42, 301–311.

Shogren, J.F., Parkhurst, G.M., Settle, C., 2003. Integrating economics and ecology to protect nature on private lands: models, methods, and mindsets. Environ. Sci. Policy 6, 233–242.

Simberloff, D., 1998. Flagships, umbrellas, and keystones: is single-species management passé in the landscape era? Biol. Conserv. 83, 247–257.

Stainbrook, K.M., 2004. Using Ecological Indicators to Detect Environmental Change in Urbanizing Watersheds: Case Study in Dutchess County, NY. Master's Thesis. SUNY College of Environmental Science and Forestry, Syracuse, NY.

Stainbrook, K.M., Limburg, K.E., Daniels, R.A., Schmidt, R.E., 2006. Long-term changes in ecosystem health of two Hudson Valley watersheds, New York, USA, 1936–2001. Hydrobiologia 571, 313–327.

Turner, R.K., 2000. Integrating natural and socio-economic science in coastal management. J. Mar. Syst. 25, 447–460.

Veldkamp, A., Verburg, P.H., 2004. Modelling land use change and environmental impact. J. Environ. Manage. 72, 1–3.

Verburg, P.H., Ritsema van Eck, J., de Nijs, T.C.M., Dijst, M.J., Schot, P., 2004. Determinants of land use change patterns in the Netherlands. Environ. Plann. B 31, 125–150.

Voinov, A., Fitz, C., Boumans, R., Costanza, R., 2004. Modular ecosystem modeling. Environ. Modell. Softw. 19, 285–304.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289, 284–288.

Wickham, J.D., Wade, T.G., Riitters, K.H., O'Neill, R.V., Smith, J.H., Smith, E.R., et al., 2003. Upstream-to-downstream changes in nutrient export risk. Landsc. Ecol. 18, 195–208.