Chapter 16
Modeling Spatial Dynamics of Ecosystem Processes and Services

Sarah E. Gergel and Tara Reed

OBJECTIVES

Understanding and predicting rates of ecosystem processes (e.g., soil erosion, nutrient flux) across large heterogeneous landscapes is an enduring challenge in ecosystem and landscape ecology and underpins the knowledge base for managing ecosystem services. Many current problems in ecosystem services management (e.g., maintenance of water quality and reduction of soil erosion) occur over broad spatial scales and across ecosystem boundaries and thus are influenced by landscape pattern (Syrbe and Walz 2012). When scaling up, ecosystem ecologists and watershed hydrologists have often used fine-scale plot experiments to infer rates of ecosystem processes at broader scales (Schindler 2012). This approach can present difficulties as the results of fine-scale studies may not reflect the heterogeneity evident in a larger area (McClain et al. 2003). Because collection of ecosystem data at broad scales is often difficult and costly and many ecosystem services are difficult to measure directly, modeling is a vital tool for addressing both basic and applied questions in this realm. In this lab, you will examine several fundamental issues of modeling landscape-level ecosystem processes and services in order to:

1. Gain an appreciation for the need and challenges associated with examining ecosystem processes and associated ecosystem services at broad spatial scales;
2. Learn to conceptualize how ecosystem dynamics can be modeled at the scale of a landscape;

S.E. Gergel (✉)
University of British Columbia, Vancouver, BC, Canada
e-mail: sarah.gergel@ubc.ca

T. Reed
University of Wisconsin - Green Bay, Green Bay, WI, USA

S.E. Gergel, M.G. Turner (eds.), *Learning Landscape Ecology*,
DOI 10.1007/978-1-4939-6374-4_16

3. Examine the implications of heterogeneity in rates of ecosystem processes; and
4. Explore a variety of important spatial assumptions that may affect spatial assessments of ecosystem services.

In Parts 1 and 2, we focus on the flux of phosphorus through an agricultural watershed using a very simple landscape model that enables one to easily incorporate and explore the impact of spatial heterogeneity on results. In Part 3, a series of synthesis questions helps you consider additional landscape ecological concepts important to understanding ecosystem services. Part 4 inspires you to build your own simple ecosystem service model using information provided for an urban landscape or even explore an entirely new situation. These exercises require a spreadsheet **ecosys.xls** that will constitute your modeling environment which can be downloaded from book web site.

NOTE: Before you proceed, save an extra backup copy of the model that you DO NOT manipulate in case you accidentally irreversibly alter the model.

INTRODUCTION

Eutrophication, or the enrichment of aquatic systems by excessive input of nutrients, constitutes the major threat to water quality (Schindler 2012; Howarth and Paerl 2008). Phosphorus (P) is often the limiting nutrient to algal productivity in freshwater systems (Carpenter 2008; Schindler 2012). As a result, phosphorus enrichment can lead to toxic algal blooms and increases in hazardous protozoa (Schindler 1977) which can threaten a variety of ecosystem goods and services provided by watersheds, including fisheries production, drinking water supplies, and recreation (Carpenter et al. 1998). Nuisance algal blooms can also reduce habitat diversity in shallow waters and deplete oxygen in bottom waters causing massive fish die-offs (Kaufman 1993). Additionally, the water may smell and taste foul and even cause skin irritation.

The most ubiquitous cause of eutrophication is non-point source pollution (USEPA 1990). **Non-point source pollution** refers to material entering aquatic systems from diffuse sources, such as runoff from agricultural fields; this is in contrast to point sources, such as a sewage treatment outflow pipe. Agricultural areas, particularly during storm events, can contribute significantly to non-point source phosphorus pollution (Omernick et al. 1991; Osborne and Wiley 1988; Correll et al. 1999). **Riparian buffer strips**, bands of uncultivated vegetation adjacent to surface waters, slow phosphorus flow and can be used to mitigate fertilization of water bodies in agricultural areas (Hoffmann et al. 2009). Wetlands also play a pivotal role in the biogeochemistry of landscapes (Verhoeven et al. 2006). Such types of biogeochemical “hotspots” (sensu McClain et al. 2003) are essential to consider when understanding nutrient fluxes in landscapes.

In this lab, we present an ecosystem model of a hypothetical agricultural landscape surrounding a canal. The canal leads to a nearby lake used by the public for swimming and boating. The model represents the flow of phosphorus from fertilized agricultural fields, through the riparian buffer strip, and then into the canal during a large storm event. While the model presents a highly simplified version of riparian and P dynamics (Hoffmann et al. 2009), it provides a useful introduction to modeling ecosystem processes at the scale of a landscape. This model is designed to address questions such as: *How much phosphorus can farmers apply to their fields without causing severe algal blooms?* as well as *At a given phosphorus application level, how much phosphorus must be retained by the buffer strip to maintain low phosphorus levels in the canal?*

Part 1. Conceptualizing Landscape-Level Ecosystem Models: Phosphorus Loading in an Agricultural Landscape

Open the file **ecosys.xls** using Excel© spreadsheet software. The spreadsheet has been configured to represent a model agricultural landscape. The brown cells on the landscape represent farmed lands. After fertilizer is applied, some P flows downhill towards the canal, represented by blue cells. The green cells represent vegetated buffer strips. The number in each cell represents the total amount of P available to leave that cell, after within cell uptake and processing is taken into account. Each cell in the model landscape represents one hectare (ha), a 10,000-m^2 area. The model approximates P flow across an agricultural landscape during a single storm event using the following simple parameters.

MODEL INPUT

Storm flow volume (m^3/ha) [G6] is the total amount of stream flow in each cell in the canal for the duration of the storm event.

Buffer absorption capacity (kg/ha) [G10] represents the ability of the buffer strip to prevent the passage of P to the next cell, expressed as the total amount of P that could be retained by the buffer cell. Riparian buffers stop the flow of P in a variety of ways, including: uptake by plants, trapping of soil to which the phosphorus is bound, and soil adsorption and immobilization. Here, we combine all the mechanisms into one equation for simplicity, representing the sum total of the buffer strips' ability to prevent P from entering the canal. In our idealized landscape, values for this parameter range from 20 to 40 kg/ha (Peterjohn and Correll 1984; Osborne and Kovacic 1993).

Amount of phosphorus applied (kg/ha) [G15] refers to the amount of P in the fertilizer applied to each individual cell in the model. This model assumes that fertilizer is evenly applied throughout the field. In practice, the amount of P applied through fertilizer is highly variable, ranging from 50 to 200 kg/ha (Nowak et al. 1996).

Transfer Coefficient [G12]. Our model assumes that farmers are not applying fertilizer in the rain and that 60% of the P in the cell runs off one pixel to another during a storm. This percentage is a simplification, in a real agricultural field the amount of P runoff would vary with vegetation, slope and especially rainfall intensity.

MODEL OUTPUT

Total phosphorus loading (kg) [G19] is the sum total of phosphorus entering the canal waters.

In-stream phosphorus concentration (mg/m^3) [G22] is the resulting concentration of phosphorus in the canal surface water after the total phosphorus is thoroughly mixed throughout the water column. The total concentration was multiplied by 1,000,000 to convert kg to mg, shown as "=(G19*10^6)" in the equation. We then divided by the number of cells in the stream (75 cells) times storm flow to find the mg/m^3, shown as "/(G6*75)." When the in-stream P concentration exceeds 75 mg/m^3 the system is at risk for algal blooms (Lathrop et al. 1998).

Exploring the Model—How Does it Work?

Agricultural Fields. The brown cells on the spreadsheet represent farmed areas. These fields slope down to the stream running down the middle of the spreadsheet. The number in each cell represents the amount of phosphorus "left over" after uptake within the cell is accounted for; that is, the amount available to leave the cell and flow downhill to the next cell.

Select cell **N4**. Note the equation for the amount of P that leaves this cell. It is composed of two parts. The first part of the equation: "(M4 + $G$15)" calculates the amount of phosphorus entering the cell. **M4** is the amount flowing in from the adjacent upstream cell. "$G$15" is the amount of fertilizer applied directly to the cell by the farmer (an input parameter you can alter). The sum of these numbers is the total amount that entered the cell. However, not all of this phosphorus flows to the adjacent downhill cell during a storm, as some is taken up by plants, adsorbed to soil, or leached into groundwater before it reaches cell **O4**. Thus, the 0.6 multiplier (or transfer coefficient), accounts for the fact that only 60% of the P that entered the cell can be washed into the next cell (i.e., 40% is taken up). This is an oversimplification. In reality, soil cannot bind an infinite amount of P. The model also assumes that flow is unidirectional, downhill towards the canal. This is another simplification. Flow is likely to be much more complex in a natural landscape.

Buffer Strips. Next examine the buffer strips (the green areas) along the banks of the canal. Select cell **T22**.

Q1 Write the formula for cell **T22** and explain in words what it means. (*NOTE:* These cells contain the Excel© equivalent of an "IF THEN" statement to prevent the program from printing negative numbers. These statements read: IF(x<y, print this if true, print this if false). For your answer, describe what the equation in the "print this if false" section means).

Drainage canal. Eventually, some P may make its way into the canal. Notice the differences in loading values for nearshore stream cells due to the variable width of the buffer at different locations.

Q2 Write the formula and explain in words how the output parameter **in-stream phosphorus concentration** is calculated.

Now, select cell **V15**. Enter a value of five into the cell. Repeat for cells **V4**, **V10**, **V11**, **V12**, and **V22**. Did the **in-stream phosphorus concentration** increase? By how much?

You just simulated several "cow patties" produced by a small herd of cows wading in the canal.

Part 2. Heterogeneity in Ecosystem Processes

In this section, you will manipulate different components of the model to gain familiarity with how it can be used to explore alternative scenarios involving spatial variation in parameters and rates.

EXERCISE 1: Phosphorus Application Rates

As with all simulation models, important simplifying assumptions have been made for this model. Notice that all agricultural areas, for example, have the same amount of P applied to each cell. In reality, the amount applied to each cell could vary for several reasons. For example, a farmer might determine that a certain area of the field needs more fertilizer than other areas due to soil type. Also, different fertilizer application techniques might result in uneven P application throughout a watershed.

Q3 Consider that two farmers live on opposite sides of the creek and simulate the effect of different farming practices on the landscape. Implement this by changing the formulas in the cells, or by summing total P runoff for different sides of the landscape under alternative P application rates.
(a) Explain your modification.
(b) What effect does this heterogeneity in fertilizer application have on the in-stream phosphorus concentration?

Q4 Another difference in P movement could be due to differences in crop type. For example, hay production requires less P than corn (Newman 1997). Describe how you would change the model to incorporate differences in crop type. What equation would you change? How would the equation be changed?

EXERCISE 2: Topographic Heterogeneity and Transfer Rates

Additional factors may cause heterogeneity in ecosystem processes (McClain et al. 2003; Hoffmann et al. 2009). Consider the importance of heterogeneity in the rates of P movement across the landscape caused by topography. Erosion of P-containing sediment is often greater in areas of steep slopes, particularly during rain events.

Change the model to account for slope differences throughout the landscape. The easiest way to do this is by changing the amount of P leaving an individual cell, thereby simulating a reduction or increase in the processing of P in that cell. Right now the processing rate is 40% of the inputs (i.e., 60% exits the cell), but this might vary depending on whether the slope is gentle or steep.

Q5 Describe the changes you made, and the effects on P loading and concentration. What other factors might you expect to influence the movement of P (other than the transport across buffers)?

EXERCISE 3: Variation in Buffer Strip Width vs. Application Rates

You probably noticed earlier that the width of the buffer strip is important in determining P loading into the canal in this model. For the sake of managing water quality in the surrounding surface waters, a land manager or farmer may be interested in the relative importance of buffer strip width versus the amount of fertilizer applied in influencing total P inputs.

Q6 *For the modeling scenario examined here*, does it appear that individual farmer behavior (i.e., application rates) or buffer width is more important in maintaining low concentrations of in-stream phosphorous? Answer in light of the constraints of the model and the range of parameters given.

Continue to manipulate the model, changing parameters at will. *Be certain that you understand all the model parameters and how all model formulas were derived.*

Part 3. Synthesis of Spatial Approaches to Ecosystem Services

Many of the same challenges you examined for understanding ecosystem processes at broad scales (e.g., heterogeneity, scaling up, terrain) are equally important when considering ecosystem services. Ecosystem services refer to the benefits humans receive from nature (Daily 1997). A wide of variety of definitions of ecosystem services exist and are vigorously debated (as in de Groot et al. 2002). Our goal in this section is to explore ways that spatial arrangement and spatial heterogeneity can impact ecosystem services (Syrbe and Walz 2012) at the scale of a broad landscape.

Each of the synthesis questions below is based around a key paper (or two) in the ecosystem services literature. Your instructor may wish to assign one question/one paper to different teams to explore in detail. Alternatively, you may wish to explore these questions (more quickly, during class) as thought exercises.

SYNTHESIS

Q7 Consider the ecosystem processes you just modeled and which ones are related to ecosystem services. How would you distinguish a service vs. a process? Is this distinction important? Why or why not? (*HINTS*: see Haines-Young and Potschin 2010 or Keeler et al. 2012)

Q8 Are there any ecosystem services for which spatial heterogeneity or spatial arrangement might NOT be important to consider? Explain your reasoning.

Q9 The primary dynamic explored in the previous modeling exercise is that of trade-offs: whereby management for one ecosystem service can negatively impact the provisioning of another. Food production affecting freshwater provisioning is a "classic" ES trade-off of great concern. Another type of interaction is a synergy whereby managing for one particular service helps augment another service. Using your knowledge of ecology, explain a few potential ecosystem service synergies (*HINTS*: see Bennett et al. 2009 or Qiu and Turner 2013).

Q10 Spatial characteristics of ecosystem services are important for a multitude of reasons and can be another way to organize or classify ecosystem services. Consider Costanza (2008) (reproduced in Table 16.1 here) which outlines five spatial characteristics potentially important to consider. Which of these five categories were already represented in the ecosys.xls model? Consider a spatial characteristic NOT represented in the model and explain how you might incorporate it.

Q11 Another important spatial consideration for ecosystem services is that of access which is influenced not only by *where* in the landscape services are produced but also by regulations, roads, as well as characteristics, abilities, and preferences of people who may wish to access various services. Some example ES might include bird-watching or harvesting wild foods (fish, berries, mushrooms, wild rice). Consider how one would model an ecosystem service with access considerations incorporated. Explain the type of spatial information you might incorporate and how you would link the new information to ecosystem processes, services, and access.

Q12 The long-term dynamics of ecosystems and the impact of landscape history have been of interest to landscape ecology for some time. It is appreciated that ignoring landscape history and/or baseline conditions can be problematic for truly understanding ecosystems. How might ignoring landscape history and prior conditions impact ecosystem services? How might incorporating landscape history improve our understanding of ES? (*HINTS*: see Tomscha and Gergel 2016; Sutherland et al. 2016; Renard et al. 2015).

Table 16.1 Categorization of ecosystem services based on spatial characteristics (adapted from Costanza 2008)

Spatial characteristics	Ecosystem service
Global (independent of proximity)	Climate regulation
	Carbon sequestration (NEP)
	Carbon storage
	Cultural/existence value
Local (depends on proximity)	Disturbance regulation/storm protection
	Waste treatment
	Pollination
	Biological control
	Habitat/refugia
Directional flow (from point of production to point of use)	Water regulation/flood protection
	Water supply
	Sediment regulation/erosion control
	Nutrient regulation
In situ (point of use)	Soil formation
	Food production/non-timber forest products
	Raw materials
User movement related (flow of people to unique natural features)	Genetic resources
	Recreation potential
	Cultural/aesthetic

Part 4. Constructing Your Own Model

Now that you have been introduced to the fundamentals of a simple landscape model and explored its parameters and possibilities, you have the basic tools to design your own landscape model. Next, you will use the same basic concept of combining cells of landscape elements (in a spreadsheet) to build your own landscape-level ecosystem model. You might also wish to incorporate your spatial understanding of ecosystem services (from Part 3) into your next model.

(*NOTE:* At this point, we switch our focus to urban landscapes, but those interested in continuing with ecosystem services in an agricultural setting, but with a more sophisticated and realistic modeling environment, are encouraged to explore Chapter 19.)

EXERCISE 4: Basic Modeling Version

Your task is to build a model to answer a specific question regarding the dynamics of P runoff in an urban landscape. Your urban environment is a city, such as Chicago or Seattle. In Excel©, you will model a city using a set of cells representing different elements of the urban environment (Table 16.2). Each element has its own level of phosphorus runoff and/or absorption. Using your imagination, create a city that

Table 16.2 Parameters for a simple spatial model of phosphorus flux through an urban watershed

Land cover type	Amount of phosphorus produced (g/20 m^2)	Phosphorus absorption capacity (g/20 m^2)	Simplified transfer coefficient (proportion)
Lawn (heavily fertilized)	30	–	0.60
Lawn (slightly fertilized)	4	–	0.60
City park (slightly fertilized)	4	–	0.60
Residential homes	70	–	1
Apartments	30	–	1
Commercial district	20	–	1
Industrial district	40	–	1
Construction site	200	–	1
Road	0	0	1
Runoff treatment wetland	–	40	0.60
Forest	–	50	0.60

contains at least a small proportion of all of the provided urban elements. Your city is adjacent to a small river which receives urban storm-water runoff.

Design and then manipulate your model specifically to answer at least *one* of the following questions:

1. City parks tend to be sinks for phosphorus although they may be slightly fertilized. What proportion of the city must be occupied by parks to maintain in-stream P levels below 75 mg/m^3? How does the spatial arrangement of the parks affect the proportion of the city that parks must occupy to maintain in-stream P levels below 75 mg/m^3?
2. What proportion of the stream must be bordered by runoff treatment wetlands in order to reduce in-stream P concentrations by 10%? By 50%? To eliminate phosphorus input altogether? What proportion of the stream must be bordered by treatment wetlands to maintain in-stream P levels below 75 mg/m^3?
3. Keeping the total area occupied by housing constant, what effect does varying the proportions of residential housing in apartments vs. homes (e.g., 30/70, 50/50, 90/10) have on P runoff to the stream? What proportions would you recommend to maintain in-stream P levels below 75 mg/m^3?
4. Consider your urban landscape from the perspective of one (or more) terrestrial ecosystem services provided by urban trees and vegetation (Escobedo et al. 2011). For example, urban parks are important for a variety of recreational purposes, greenspace has been linked to human health outcomes and well-being, and urban vegetation affects a variety of wildlife species in positive and negative ways. Redesign the provided urban model to address one or more of these terrestrial ecosystem services.

Model Parameters. You are provided with the following parameter estimates (Table 16.2) and in the spreadsheet. Notice, however, that the resolution of the runoff and absorption estimates is different than for the model you examined in Parts 1 and 2. You will probably want to adjust the scale of your model from the 1-ha resolution used in the agricultural model as city lot sizes are rarely that large. Here, we have provided the model parameters in units of g/20 m^2. For an urban landscape, 20 m^2 cells roughly approximate the minimum size (or spatial grain) of the landscape elements you will model. Building on this cell size, you could combine 1 residential housing pixel with 1 lawn pixel to represent one residence.

To incorporate both urban and agricultural areas in your landscape you can use values from Part 1 but will need to do some conversions (remember 1 ha = 10,000 m^2). You may adjust the grain size further as appropriate for your model and the questions you are trying to address, but be sure to choose an appropriate grain size for your model, and adjust the runoff and absorption capacity values accordingly. Lastly, you can assume that all processes that contribute to phosphorus runoff and/or absorption have been taken into account with the parameters given.

Transfer coefficients. In addition to the absorption capacity of a land cover type, the amount of P transferred to the next cell may also be diminished by a transfer coefficient. This reflects that some land-cover types are less permeable to runoff than others such that more runoff moves from one cell to the next. In the agricultural model, we used a transfer coefficient of 0.6, meaning that only 60% of the P in a cell was available to move out to the next cell. In this section, only wetland areas and forests have values for absorption capacity. We have, however, included transfer coefficients to account for soil permeability in lawns and parks, which we examine next.

Building Your Model. Switch to the second page of the spreadsheet file by clicking on the tab labeled **Urban Landscape** at the bottom of the spreadsheet. Again, here are all the elements with which to build your urban landscape, identical to those in Table 16.2. Click on the cells in the **Equations** column to view the equations, which incorporate transfer coefficients in some cases, for different land-cover types. The cells in the example column can be cut and pasted into the spreadsheet to build your urban landscape.

(*NOTE:* These equations represent P flow only from left to right. Unless you want to rewrite some of the equations to represent flow in the opposite direction, place your river, stream, or canal on the right-hand boundary of your landscape. Be sure to examine each cell to see which other cells are referenced).

Construct your model in the same general form as the model in Part 1. For simplicity, you may assume that flow is unidirectional, downhill towards the canal. Thus, as before, the phosphorus values in each cell represent the amount leaving that cell. This includes the runoff entering from the adjacent upstream cell plus or minus the runoff/absorption estimate for that land cover type, and in some cases, a transfer coefficient. *Remember that the number in each cell should represent the total phosphorus available to leave the cell, after any within cell uptake or processing or reduction due to the transfer coefficient.* The concentration in the water can be calculated by the amount of P flowing into the stream cell multiplied by the total volume of water that flowed through the stream during the storm event. When your model construction and manipulation are finished, complete the write-up portion of the lab.

EXERCISE 5: Advanced Modeling Version

Your task is to model any landscape-level ecosystem process of your choosing. You will use the basic concept of landscape element blocks in Excel©, but you are free to design those elements using your own knowledge, experience, and imagination. As in the basic version (above), *your model must be designed to answer a clearly defined question* (or set of related questions), but you will choose the question yourself. Be sure that you have a clear understanding of the underlying assumptions of your model throughout the building process, and be able to state those assumptions clearly.

Be sure to explicitly determine the appropriate grain size of your model. Also consider whether the values in each cell represent amount *entering* or *leaving* a given cell. If you have more than 1 day to complete this assignment, we recommend that you spend some time researching the literature and use realistic parameters to construct your model. Keep in mind that you must be able to manipulate your model to address your initial question. When the model and manipulation are finished, complete the write-up that follows.

Modeling Hints

1. Consider using the **Format**, then **Cell**, then **Patterns** commands on your spreadsheet's pull-down menu to assign different colors identifying different landscape elements.
2. Learn how to use the **$** symbol when cutting and pasting. For example, if you wanted to copy a formula "**=$F$6+5**" from one cell to a cell in the next column over, the **$F** preserves the column reference, while **$6** preserves the row reference; thus, the formula would remain **=$F$6+5** when copied and pasted. Otherwise, the formula typed as "**=F6+5**" becomes **=G6+5** when copied one cell to the right or becomes **=F7+5** when copied to the cell below.

WRITE-UP

Include the following sections in your report:

1. **Introduction**
   (a) State the question(s) your model addresses.
   (b) Provide some context for why this question is important.

2. **Description of Model**
   (a) State the underlying assumptions of your model.
   (b) Describe your model. Define the spatial and temporal scale of your model. (For the advanced version, list and explain all model parameters).
3. **Simulations and Results**
   (a) Clearly describe each "simulation experiment" with the model and summarize the results.
   (b) Answer the question(s) your model was designed to address.
4. **Discussion**
   (a) What are the implications of heterogeneity in rates of ecosystem processes in your model scenario?
   (b) Within the realm of the ecosystem process that you have modeled, what are the limitations of your model? Why?
   (c) What additions/modifications would you make to your model to address the limitations listed above?
   (d) When would considering the spatial arrangement of landscape elements or the role of landscape heterogeneity not matter to your results?
   (e) When would sampling at broad scales not be important?
   (f) How would a longer temporal scale effect your results?
5. **Literature Cited** (not included in page limits)
6. **Appendix** (not included in page limits)
   (a) If required, a copy of the answers to the exploratory questions posed in Parts 1 and 2 of this chapter
   (b) Print out of the Excel© file containing *YOUR* model

Your instructor will determine page lengths depending on the amount of time you have to complete your assignment. Consider giving oral presentations of your results.

REFERENCES AND RECOMMENDED READINGS[1]

*Bennett EM, Peterson GD, Gordon LJ (2009) Understanding relationships among multiple ecosystem services. Ecol Lett 12(12):1394–1404. *A carefully considered framework for examining interactions among ecosystem services, with examples from a variety of landscape types.*

Carpenter SR (2008) Phosphorus control is critical to mitigating eutrophication. Proc Natl Acad Sci 105(32):11039–11040

Carpenter SR, Caraco NF, Correll D et al (1998) Non-point pollution of surface waters with phosphorus and nitrogen. Ecol Appl 8(3):559–568

Correll DL, Jordan TE, Weller DE (1999) Effects of precipitation and air temperature on phosphorus fluxes from Rhode River watersheds. J Environ Qual 28:144–154

*Costanza R (2008) Ecosystem services: multiple classification systems are needed. Biol Conserv 141:350–352. *A practical, brief overview of why and spatial characteristics of ecosystem services matter.*

---

[1] *NOTE:* An asterisk preceding the entry indicates that it is a suggested reading.

Daily G (1997) *Nature's services: societal dependence on natural ecosystems*. Island Press, Washington, DC, p 392

de Groot R, Wilson MA, Boumans RM (2002) A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol Econ 41(3):393–408

Escobedo FJ, Kroeger T, Wagner JE (2011) Urban forests and pollution mitigation: analyzing ecosystem services and disservices. Environ Pollut 159(8):2078–2087

Haines-Young R, Potschin M (2010) The links between biodiversity, ecosystem services and human well-being. In: Raffaelli DG, Frid CLJ (eds) *Ecosystem ecology: a new synthesis*. Cambridge University Press, Cambridge, pp 110–139

Hoffmann CC, Kjaergaard C, Uusi-Kämppä J et al (2009) Phosphorus retention in riparian buffers: review of their efficiency. J Environ Qual 38(5):1942–1955

*Howarth R, Paerl HW (2008) Coastal marine eutrophication: control of both nitrogen and phosphorus is necessary. Proc Natl Acad Sci 105(49):103. *A review of eutrophication problems globally with an emphasis on nitrogen fluxes with an emphasis on terrestrial, aquatic and marine interactions, as well as contrasts between N and P.*

Kaufman L (1993) Catastrophic change in species-rich freshwater ecosystems. Bioscience 42:846–858

Keeler BL, Polasky S, Brauman KA et al (2012) Linking water quality and well-being for improved assessment and valuation of ecosystem services. Proc Natl Acad Sci 109(45):18619–18624

Lathrop RC, Carpenter SR, Stow CA et al (1998) Phosphorus loading reductions needed to control blue-green algal blooms in Lake Mendota. Can J Fish Aquat Sci 55(5):1169–1178

*Likens GE, Bormann RH (1995) *Biogeochemistry of a forested ecosystem*. Springer, New York. *The Hubbard Brook Ecosystem Study, began in 1963, has been foundational to the study of ecosystem processes at the scale of large watersheds and was been a pioneering scientific acheivement in broad-scale whole ecosystem experiments.*

*Lovett GM, Jones CG, Turner MG et al (eds) (2005) *Ecosystem function in heterogeneous landscapes*. Springer, New York, p 489. *Consider the very helpful book review by Carol Wessman describing the chapters and flow and of this exceptionally synthetic volume. Ecology, 88(3), 2007, pp. 803–804.*

*McClain ME, Boyer EW, Dent CL et al (2003) Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. Ecosystems 6(4):301–312. *Highly-cited classic paper examining spatial and temporal heterogeneity in ecosystem processes.*

Newman EI (1997) Phosphorus balance of contrasting farm systems, past and present. Can food production be sustainable? J Appl Ecol 34:1334–1347

Nowak P, Shepard S, Weiland C (1996) *Utilizing a needs assessment in water quality program implementation for the Lake Mendota watershed*. The Farm Practices Inventory (FPI) Report #2. Available via Environmental Resources Center, University of Wisconsin

Omernick JM, Abernathy AR, Male LM (1991) Stream nutrient levels and proximity of agricultural and forest land to streams: some relationships. J Soil and Water Conserv 36:227–231

Osborne LL, Kovacic DA (1993) Riparian vegetated buffer strips in water quality restoration and stream management. Freshw Biol 29:243–258

Osborne LL, Wiley MJ (1988) Empirical relationships between land use/landcover and stream water quality in an agricultural watershed. J Environ Manage 26:9–27

Peterjohn WT, Correll DL (1984) Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology 65:1466–1475

Qiu J, Turner MG (2013) Spatial interactions among ecosystem services in an urbanizing agricultural watershed. Proc Natl Acad Sci USA 110(29):12149–12154

Renard D, Rhemtulla JM, Bennett EM (2015) Historical dynamics in ecosystem service bundles. Proc Natl Acad Sci 112(43):13411–13416

*Running SW, Nemani RR, Peterson DL et al (1989) Mapping regional forest evapotranspiration and photosynthesis by coupling satellite data with ecosystem simulation. Ecology 70:1090–1101. *Landscape-level simulation model of annual evapotranspiration and net photosynthesis in a mountainous region by some of the original leaders in developing spatial ecosystem models linked to remotely-sensed data.*

Schindler DW (1977) Evolution of phosphorus limitation in lakes. Science 195:260–262

Schindler DW (2012) The dilemma of controlling cultural eutrophication of lakes. Proc R Soc Lond B Biol Sci 283(1827):1–12

*Sklar FH, Costanza R (1991) The development of dynamic spatial models for landscape ecology: a review and prognosis. In: Turner MG, Gardner RH (eds) *Quantitative methods in landscape ecology*. Springer, New York, pp 239–288. *A classic overview of spatial modeling as approached by both the social and natural sciences.*

Sutherland I, Bennett EB, Gergel SE (2016) Recovery trends for multiple ecosystem services reveal non-linear responses and long-term tradeoffs from temperate forest harvesting. For Ecol Manage 374:61–70

*Syrbe RU, Walz U (2012) Spatial indicators for the assessment of ecosystem services: providing, benefiting and connecting areas and landscape metrics. Ecol Indic 21:80–88. *Extremely thoughtful piece exploring how ecosystem services flow across large regions. Also introduces exciting ideas about how to link landscape metrics to ecosystem service provisioning.*

*Tallis H, Polasky S (2009) Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. Ann N Y Acad Sci 1162(1):265–283. *Overview of one of the earliest spatial models of ecosystem services, InVest, with some example applications. Further development of this software continues at a rapid pace.*

Tomscha SA, Gergel SE (2016) Ecosystem service trade-offs and synergies misunderstood without landscape history. Ecol Soc 21(1):43

USEPA (1990) *The quality of our nation's water*. U. S. Environmental Protection Agency 440/4-90-005. Washington, DC

USEPA (1997) *Index of watershed indicators*. U. S. Environmental Protection Agency -841-R-97-010. Washington, DC

Verhoeven JT, Arheimer B, Yin C et al (2006) Regional and global concerns over wetlands and water quality. Trends Ecol Evol 21(2):96–103