Introduction. Methods in Ecosystem Science: Progress, Tradeoffs, and Limitations

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Ecosystem science is a relatively young field of ecology dealing with all of the organisms in an area and their relationships with the physical environment (Odum 1959). It includes plants, animals, and microorganisms, and studies the interactions among them and with the soil, water, and the atmosphere. In pursuing general patterns at the ecosystem level, and when trying to understand the mechanisms controlling these patterns, ecosystem scientists study the flow of energy and the cycling of material, including water and elements, such as carbon, nitrogen, and phosphorus. The rapid growth in ecosystem science during the last 20 years partially resulted from its unique relationship to other disciplines. Ecosystem science has articulated the role of organisms with the physical environment and emphasized the feedback of human activities with the atmosphere, rivers, and open oceans. The demands of global change research and earth-system studies are only likely to increase the importance of ecosystem studies in the future.

As ecosystem science grew and gained its identity, scientists began to develop their own methods for studying ecosystem processes. Some of these methods were developed ex novo, while some others were adapted from such disciplines as chemistry, physics, and physiology. The development of new tools fostered new concepts in ecosystem science, while new theories led to the development of new techniques in a synergistic interaction between theory and methods. For example, continuous flow mass spectrometers opened the possibility of using stable isotopes as a tool for studying water and nutrient dynamics in ecosystems. These new capabilities, in turn, stimulated a wealth of model and theoretical developments on isotopic discrimination by different ecosystem processes (see Chapters 8 and 12). The progress of ecosystem science is limited simultaneously by both theory and methods, as has been demonstrated by the benefits of introducing simulation models and remote sensing tools into ecological research (see Chapters 3 and 25). This book suggests that there are methods limitations, such as real-time root observation techniques, automated tissue grinders, or chamberless methods for flux measurements. These represent just some examples of methodological constraints, but they are not necessarily the only or the most important limitations.

The objectives of this book are to review the methods most commonly used in ecosystem science and to assess their advantages and disadvantages. Each chapter reviews the basic ecological concepts behind each method, describes the methods most commonly used and those increasing in importance, and examines tradeoffs among alternatives. The aim of the book is to help scholars explore new areas and make decisions about the best methods to answer particular ecosystem questions. Because of the breadth of ecosystem science, the book cannot possibly describe all methods in detail, but instead provides information for choosing among methods and guidance for locating detailed information about particular techniques. When good reviews of particular techniques exist, some authors have chosen to direct the reader to those reviews, and concentrate on other methods less well described.

The range of methods in ecosystem science is one of our discipline's strengths, but it also poses a challenge. Methods change quickly and are adapted to the needs of researchers locally. This local need sometimes conflicts with the need of our discipline to synthesize results across systems. If every researcher uses a different technique to measure an ecosystem process, we may be unable to compare results quantitatively across studies. This inability hinders some aspects of ecosystem science today and limits our ability to synthesize data for use by other disciplines. Another goal of this book, then, is to clarify differences and similarities among methods and suggest the extent to which results collected using different tools could be compared.

The book discusses tools to address similar questions in aquatic and terrestrial ecosystems. Differences between methods used in these two ecosystem types stem from differences in their natures and differences in the histories of the disciplines. Aquatic and terrestrial scientists have often worked in isolation as a result of the barriers imposed by the structure of institutions, such as funding agencies, universities, or scientific societies. Although structure is necessary and fosters efficiency, it sometimes leads to duplication and intellectual isolation. This book therefore attempts to present, in one volume, methods for aquatic and terrestrial ecosystems because we think that this intellectual interaction will be fruitful. Developments in one area may stimulate ideas in the other. The book attempts to cover the breadth of aquatic and terrestrial ecosystem science in a structure that is roughly parallel, but the reader will undoubtedly find gaps. For example, description of the manipulations of nutrients in terrestrial ecosystems does not have an aquatic counterpart in the book, and the analysis of animal manipulations belowground lacks a counterpart of the aboveground manipulations. Similarly, the book describes most types of manipulations of the abiotic environment but it misses some important manipulations, such as carbon dioxide.

Ecosystem science is a complex discipline spanning different spatial and temporal scales, from the square meter to the region and from minutes to centuries. As temporal and spatial scales change, not only the researcher's perspective changes but also the nature of the process and its controls change. Important controlling variables at one scale become white noise at a coarser scale, and what may have been considered constant now becomes a driving variable (Allen and Starr 1982; O'Neill et al. 1986). For example, in the case of carbon fixation, the same process can be studied at the scale of patches with a diameter of a few meters, at the landscape level, or at the regional level. Whereas differences in soil texture, through changes in water and nutrient availability, account for most of the variability in terrestrial carbon fixation at the finer levels of the hierarchy, they are overshadowed by climate variability at coarser scales (Sala et al. 1988). In contrast, while climate could be easily considered as a constant at the finer scale, it is certainly one of the major determinants of primary production patterns at the regional scale.

Important basic and applied questions in ecosystem science need to be addressed at each of these levels. The rate of primary production at the scale of a paddock or lake and its variability in space and time are critical tools when managing commercial fish stocks, herds of grazers, or forests stands. Carbon balance at the regional level is currently an important item in global negotiations for carbon trade among countries. Different tools and methods are necessary to address the same kind of questions at different scales. This book attempts to describe methods to address this nested hierarchy of ecosystem questions.

Chapters in this book do not prescribe a method or technique but emphasize tradeoffs among tools. A clear description of advantages and disadvantages will aid scientists in how to test hypotheses and answer questions. When discussing tradeoffs, the authors point out not only issues of scale but cost–accuracy or accuracy–understanding tradeoffs. Methods that yield the best results at a fine scale may not be the most appropriate at the regional scale. Similarly, the errors associated with methods sometimes are negatively associated with its costs. Consequently, the question and the accuracy needed for the estimate of the variable help to determine the best methodological option. Some chapters make a thorough analysis of the errors associated with each technique. In some cases, methods that provide estimates closest to the real value are not necessarily those that are most detailed (for example, see Chapters 2 and 4). A very detailed estimate of a large number of process components certainly yields a better understanding of the role of the different pieces. This bottom-up approach and the error inevitably associated with aggregation yield, in many cases, results that are farther away from the real value. For example, when estimating primary production from a time series of total biomass versus from time series of individual species biomass, the latter yields valuable information about the behavior of individual species but an estimate of total production that is farther from the real value than if just total values were used (see Chapters 2, 4, and 18 for examples of errors associated with aggregation). Similarly, nutrient estimates at the mouth of a river yield better estimates of the biogeochemical behavior of the watershed than could have been obtained by laboriously measuring individual units in the watershed (Howarth et al. 1996). When the purpose of the study is the accurate estimate, then integrating measurements at the questions' scale are usually preferred. In contrast, when the main purpose is mechanistic understanding of ecosystem processes, detail estimates at finer scales than the level of interest are preferred.

Ecosystem science is complex and interacts with many other disciplines, such as atmospheric science, soil science, plant and animal physiology, as well as microbiology, zoology, and botany. The nature of ecosystem questions calls for such interdisciplinary work. Consequently, ecosystem studies incorporate pieces of methods from other disciplines and adapt them to satisfy ecosystem questions, which have their own scales and their own emphasis on interactions. The multiscale nature of ecosystem science, the wealth of interactions with other disciplines, the breadth of ecosystem studies, and the relatively recent development of its major concepts may explain the lack of a book to date that summarizes the methods used in ecosystem science.

One of the strengths of ecosystem science is the focus on the interactions among levels and between biotic and abiotic factors. This same strength results in a challenge to organize a methods book because most techniques examine the patterns and dynamics of more than one factor. Similarly, experimental manipulation of ecosystems that alter one part of the ecosystem frequently affect many other compartments and processes. This book is organized in four parts: the first encompasses methods related to carbon and energy dynamics, the second discusses those related to water and nutrient dynamics, the third describes experimental manipulations of abiotic and biotic factors, and the fourth discusses tools to synthesize our understanding about ecosystems.

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