Introduction

Most of us came to ecology with memories of special personal places. A cliff top that Claude Monet might have painted. Allen as a youth spent his holidays on the Dorset Coast near Swanage; he can still smell the sea breeze of his childhood. Curtin grew up on a farm in southwestern Wisconsin; the dew of the grass and the bright green of a June morning remains vivid. The catching of reptiles and insects for him awakened a curiosity about the natural world that has remained to this day.

But once into the field there came the scholarship. With ever tighter grant monies, the pressure to publish takes so much of the fun out of it. A climate of unbridled careerism prevails and shows itself in the incremental state of the literature: little things to list on this year's activities report. There are now even predatory journals that cynically do not seriously review submissions, and only collect page charges. Journal editors have a desperate time getting reviews done by mature scholars, instead of a hand off to their overworked graduate students. So what is to be done – how can we bring the joy and importance of discovery back into it all? After all, ecology is done by human beings. Mostly it is a personal mission, for what great ecologists write is frequently personal and life changing. So an undercurrent of this book is to remind us of and reveal the original purpose of science. Not professional advancement, but the genuine search for novel ideas and the imperative to share hard won insights and personal passions.

As to the theme of complexity, it reflects a reality that society is faced with unparalleled challenges such as climate change that are not decomposable into smaller parts, but demand fundamentally integrative science. The topic of complexity is relatively new in some senses, having come to prominence in the waning years of the twentieth century. But many of the questions and points of tension have been around as long as science has been a formal discipline. Without the vocabulary to probe complexity, many of our early authors were vaguely aware something big and new was happening, even if it was not articulated in contemporary terms. But some of the later authors close to the millennium were explicit in naming complexity per se. Expansive ideas address complexity in one form or another. However, complexity is a challenging notion which is rejected by some; by placing our selected papers in a book overtly about complexity, we aim to ease those with reservations into taking this relatively new movement in ecology and conservation seriously and sympathetically.

Background and Conceptual Organization

Our personal journey to create this book stretches back over 20 years to the early 1990s when Curtin was a graduate student teaching assistant for Allen's Ecology 460 class at the University of Wisconsin. At the time, Curtin advocated having students read more of the foundational literature. We adopted Leslie Real and James H. Brown's (1991) edited volume *Foundations of Ecology*, a collection of papers selected by senior ecologists that has gone on to spawn a range of other books composed of foundational papers.

However, Real and Brown (R & B) had a heavy emphasis on mostly linear, equilibrium approaches to population biology and community ecology and a minimal emphasis on systems perspectives. For example, co-editor Jim Brown has said he had to lobby hard to get E. P. Odum's 1969 classic of systems ecology "The strategy of ecosystem development" included in the original collection. Ecology and conservation began to change in the 1970s, as more dynamic complexity-based, non-equilibrium approaches to science and policy making began to emerge. These trends were largely missed in R & B due to its 1975 veil line, as well as because of the focus and interests of the contributors. We envisioned a companion volume to R & B that would reflect a more dynamic and complex worldview, and that would include more of a balance between evolutionary and systems perspectives.

Our ideas simmered for a few years and at the 1997 Ecological Society of America meetings in Albuquerque, we decided to act. Over the next several years, Curtin interviewed numerous scientists who had an interest in systems and complexity-based approaches to ecology and conservation. Our queries to researchers were met with an overwhelmingly positive response. For example, C. S. Holling (also featured in R & B) replied to us, "What an excellent idea to balance the Real and Brown book. Their volume speaks to the past. We need another set of selections that speak to the future." However, the book was not completed, in part because of time constraints of the authors, but mostly because it became evident that not enough time had elapsed to gain a clear picture of how complexity-based approaches to ecology were evolving. We were in the middle of a paradigm shift and barely knew it (e.g. Kuhn 1962).

By 2011–2012, sufficient time had elapsed that recent trends in ecology and conservation were clearer than they had been a decade earlier. We sent around another formal request for nominations to all the original respondents as well as a few additional researchers who we missed in the original query, and tallied these additional responses. What has emerged is a document that is vastly more interesting and valuable than if we had published circa 2000 as originally intended. With the benefit of time, in what our contributor Chilean Pablo Marquet jokingly called "slow ecology," it became apparent we had captured a transitional era with the emergence of a discrete perspective as issues of scale and complexity moved from the fringes of the discipline to being a core part not just of ecology and conservation, but of science in general. As disciplinary boundaries in the sciences began to break down, a more holistic view of complex systems emerged that began to integrate ideas across systems with an increased interest in socio-ecological paradigms that span the natural and social sciences.

Beyond the topic area, this book is a fundamental departure from previously collected volumes in three significant ways. First, we specifically sought as wide a diversity as possible in our contributors in gender, race, and national origin. Of the over 100 people queried, we received approximately 60 responses from an international cadre of experts from 15 countries and spanning every continent (except Antarctica). Of those responses, we tabulated those papers or authors most widely selected. In subsequent reviews, we polled people as to what topic areas were missing and included a small number of papers that filled specific gaps in the literature or lesser known publications that made significant contributions. At the outset of the project, we asked people to recommend new classics in ecology related to complexity since Real and Brown's *Foundations of Ecology* 1975 end date as well as earlier classics missing in other contributed volumes. In the end, we only reprinted papers from 1975 to 2000, but include in our narrative reference to many of the pre-1975 papers suggested by our contributors as well as discussion of the historical context of many of the foundational ideas.

While we sought a balance of early, mid, and late career ecologists at the outset, those who responded were skewed toward the more senior scientists. We were surprised and delighted at the generosity of busy luminaries with their precious time. However, this demographic in the responses denied us our intended correction for the gender bias that was, until recently, considerable in ecology. In short, we biased our invitations toward diversity, but could not control the response bias toward more senior ecologists. Based on the responses, we chose for inclusion papers selected multiple times or a single author who was cited multiple times but for whom there was not a single clear distinguishing paper. We also included seminal papers that the respondents had missed, based on our perspective of being able to see the entire constellation of selections and insights from our contributors. The goal was to seek a balance between commonly cited classics and a few hidden gems known to a smaller number of researchers which are either groundbreaking or indicative of a significant area of thought.

Second, we did not complete the work in a short period, but extended our poll over more than a decade, initially querying people in the late 1990s and early 2000s, and then again ten years later. For the most part, the respondents' selections remained the same over the course of our project. However, the longer view has made it clearer which papers had staying power, as well as introducing us to a few new favorites that emerged in the intervening years. For example, one notable paper that was not cited at all circa 2000, but was widely suggested for inclusion a decade later was Simon Levin's 1992 paper on scale (Article 3). Conservation issues in general increased dramatically in importance and recognition, leading us to add a whole chapter on applied ecology and socio-ecological synthesis.

Finally, in the spirit of highlighting the perspective of the personal scientist, we asked those who suggested papers to explain the importance of the readings they selected. Pressing further in this direction, we also asked those authors whose papers were nominated, where possible, to provide personal insights into the genesis and significance of their papers. They were often eager to give the inside story, their source of ideas and sometimes the struggle in the review process. Thus, we have obtained an insider's look at the evolution of a paradigm and the scientific process in general. In doing so, we gained insights impossible from online search engines whose citation counts are at best a crude index of a paper's importance. After all, journal significance scores were originally intended only to assist librarians in making orders for their libraries. One of the founders of citation indexes, linguist and a founder of bibliometrics and scientometrics Eugene Garfield, explicitly forbade their use as importance criteria for scientific significance; how they are calculated was never meant to reflect intrinsic intellectual importance. By contrast, our use of extensive first-hand commentary, by many of the era's most influential ecologists and systems thinkers, has resulted in a unique and transformative book. We hope it will be of lasting value to ecologists, conservationists, and historians of science. But equally significant, it is a tribute to a generation of scientists who advocated and embraced change and sought new ways of thinking that transformed science and conservation action.

Introduction to *Complex Ecology*

Complex Ecology is an anthology of papers that reviews a number of the foundations of complexity-based approaches to ecology, conservation, and systems science. In taking a complexity-based approach it reflects a paradigm shift that has been occurring across many areas of science in recent decades (e.g. May 1973, Gleick 1987, Capra 1996, Levin 1998, Folke 2006, Drack and Apfalter 2006). The noted environmental historian Carolyn Merchant (2002) recognized complexity, or what she called "chaotic ecology," as the latest step in the evolution of ecology from human, to organismic (population), and economic (systems) perspectives. In recent decades it appears increasingly clear that balance or stasis in natural and human systems is only a temporary, fleeting state of apparent stability, poised between the inevitable flux that is the norm in all systems. Merchant writes, "The chaotic model of nature allows full expression of nature as an actor and shaper of history, rather than a passable backdrop to the inorganic machine. Unpredictable natural events and climatic conditions can trigger changes and transitions in local places, the impacts of which are felt at great distances." In essence, the recent emphasis on complexity-based approaches is on the flux between interacting forces and the order and dynamism that emerges from interactions, rather than on predicted end-states as had been the emphasis of ecology and conservation for much of their development. For the action is in the interaction, and not in the individual pieces in a perspective that is almost the diametric opposite of traditional scientific perspectives that typically focus on the pieces rather than the whole.

Thus, in recent decades, there has been a transition away from seeking an understanding of the machinery of nature and linear explanations of a clockwork world, as emerged 400 years ago in the Age of Enlightenment (e.g. Manchester 1992), toward non-equilibrium, non-linear depictions of reality. There has also been an increasing realization that non-linear dynamics and complex interactions are an ever present reality that drives ecological and social systems and leads to intrinsic unpredictability and complexity (May 1976, Levin 1998).

The issue of complexity takes us into some significant points of tension. It is commonly misunderstood that complexity is a material matter. We submit that complexity arises from the way of looking at the world and deciding on what questions to ask. In essence, people do not address reality directly and have no straightforward access to it. Scientists do not see systems; they only see the system they have under analysis, for the level and approach to analysis frames the outcome of research. This was first widely recognized through the rise of quantum mechanics over a century ago (around 1900), and has been foundational to Buddhist traditions and other Eastern philosophies for millennia (e.g. Dalai Lama 2005). This stated, much of ecology (and most science) still embraces a positivist approach that looks at the world in a narrow, realist and linear way.

From Parmenides to Plato, Augustine, Descartes, Newton through to the present, scientists and philosophers have long assumed a balance of nature and a linear world. (Worster 1977, Manchester 1992, Wu and Loucks 1995). It was after all a perspective that brought so much power and focus to science through the work of Descartes in the sixteenth century, and Newton and others in the seventeenth century and beyond. From steam locomotives to moon landings, a linear approach to inquiry has powered many intellectual and industrial leaps. It is no accident that much of complexity is still the domain of theorists because the empirical science that embraces complexity is hard to do and typically much slower to accomplish than conventional linear science (e.g. Curtin 2015). As a result, a disproportionate number of the papers in this volume are in the domain of theoretical ecology. However, there are innovative and effective empirical studies that embrace complexity too, and a few of these are reviewed in the pages to come.

Despite the professional and institutional pressures that tend to run counter to a complexity-based perspective, in a world of increasing uncertainty, a positivist approach is reaching its limits.

The complex systems approach grew and blossomed through work on chaos in the 1960s and 1970s, which provided a fundamental challenge to an orderly and predictable Cartesian–Newtonian worldview (Lorenz 1963, May 1973, 1974, 1977, Mandelbrot 1977, Gleick 1987). Meanwhile, the social sciences were coming up against similar constraints in that an orderly and predictable world of scholarship did not match the experience people had on the ground (e.g. Forrester 1971, Newell and Simon 1972, Rittel and Webber 1973), while increasing levels of computational power freed people from the need for extreme simplification of scientific analysis. By the 1990s, influential work at the Santa Fe Institute and elsewhere illustrated the profound importance which complex interactions and emergence had on humanity and nature (e.g. Gell-Mann 1994, Holland 1995, 1998, Capra 1996).

The challenge of separating complicated and complex challenges is significant. Complicated problems fit the Cartesian–Newtonian model in that one can understand and predict the outcome of interactions if one can measure and account for all the parts. Whereas in a complexity-based paradigm, even simple interactions can have understandable, but unpredictable outcomes (e.g. Lorenz 1963, May 1976). This tension between simplicity and reality is not new to science and has been a point of discussion since at least the 1920s (Weiss 1925, 1977, Koestler and Smythies 1969). Evolutionary ecology founder Robert MacArthur in the 1960s was fond of paraphrasing Pablo Picasso in stating, “Science was the lie that helps us realize the truth” (Wilson and Hutchinson 1989). Systems scientists such as Kenneth Watt and Crawford Holling countered that to be relevant, real-world problems needed to be grounded in reality, not “simple theory” (e.g. Watt 1962, 1966, Holling 1966). In physics, systems are assumed closed and close to equilibrium; those assumptions, while false even in physics, are essential for bookkeeping. Theoretical physics gets away with such simplifications of reality, but in leaky biological systems we cannot. Science becomes then less about truth and more about finding lies we can get away with, essentially depictions of reality that provide leverage for understanding complex challenges.

Two foundational papers that explicitly consider complexity in the context of ecology, thereby providing an overarching framework for ecological complexity, are a 1995 book chapter by James H. Brown and a 1998 paper by Simon Levin. Both these contributions are eminently deserving of inclusion in this volume in their entirety, and perhaps they should have been. They were not for the simple reason that the works of both these authors are already well represented here, and neither author nominated them as their most influential work. We encourage the reader to seek out both for they are a logical jumping off point for any consideration of ecological complexity that helps put other approaches in perspective.

Brown (1995) makes the case that species and ecosystems be considered Complex Adaptive Systems (See Arthur et al. 1997, Holland 2006 for more detailed discussion). He notes that a fundamental discontinuity exists in ecology between population/community perspectives and ecosystem ecology, the former grounded in evolution and biological properties, the latter based on physical laws and properties of mass balance. Of course, neither is by itself true, and material ecological systems include strong interactions between these postures. There is a fundamental need to find common currencies that allow a cross-walk between different discrete perspectives to find common ground in the properties that sustain life and ecosystems at all levels (e.g. Capra 1996). The complexity paradigm provides a means of doing this.

Within this body of theory, Complex Adaptive Systems can be described as having six core properties: (1) they are composed of many different interacting components; (2) they have the capacity to self-organize; (3) they are open systems that exchange energy and materials with their environment; (4) they maintain a state far from thermodynamic equilibrium; (5) they have the capacity for adaptive change; and (6) they have unique structure and dynamics that reflect their history (Holland 1995). Many of the foundational papers discussed in this book illustrate, from a range of perspectives, how properties of Complex Adaptive Systems exist in most natural and social settings.

Levin (1998) also considers ecology in the context of complexity. However, rather than focusing on the interaction of organisms with their environment, he focuses on ecosystem processes up to the biosphere. Whereas Brown emphasizes creating unity in ecological theory, Levin focuses on the societal imperative of addressing the loss of biodiversity and ecosystem function. Levin presses an understanding of the implications of species and habitat loss as the ultimate complex problem with profound implications for humanity and the planet. He eloquently states: “The study of Complex Adaptive

Systems is a study of how complicated structures and patterns of interaction can arise from disorder through simple but powerful rules that guide change.” The essential elements are: (1) sustained diversity and individuality of components; (2) localized interactions among the components; and (3) an autonomous process that selects from among the components, based on the results of local interactions, a subset for replication or enhancement. In essence, the core properties of complex systems are emergent with many included in the topics discussed in the coming pages.

Levin also explores four fundamental properties of Complex Adaptive Systems as set out by Holland (1995): aggregation (the way individuals, species, and functional groups are assembled, and different conceptual frameworks that comprise systems); diversity (which refers less to simple species counts, and more to the complex web of life that sustains systems); flows (which includes not just nutrients and energy, but also information and materials); and non-linearity (e.g. path dependency in outcomes between interactions of chance events and the role of thresholds in systems). In this volume, we use Holland’s properties of Complex Adaptive Systems as our organizing framework. The four initial chapters review the foundations of ecological complexity by dividing the papers into separate sections: (1) aggregation, (2) diversity, (3) flows, and (4) non-linear interactions. Following these chapters are ten papers that examine the applications of ecological complexity and related disciplines, beginning with a focus on global change ecology, followed by conservation biology, resilience science, and finishing with socio-ecological perspectives that frame how systems are studied or managed.

Thus in a fundamental departure in content from many of the foundation volumes in ecology, some of our foundational papers are not strictly from the natural sciences, but include elements of the social and physical sciences too. In recognition of the reality that in complexity studies, disciplines are intrinsically entwined, the outcomes of biological studies are frequently driven by social and physical processes, whether researchers chose to recognize this or not, because human perspectives, while impacting the natural sciences, are largely the domain of social science. We close our collection of papers with several that focus on the social processes underlying science and conservation, in recognition of the reality that governance and institutional design are essential in finding solutions to today’s complex and nuanced challenges.

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