Complexity in Landscape Ecology

by
David G. Green, Nicholas Klomp,
Glyn Rimmington and Suzanne Sadedin

Interactions matter. To understand the distributions of plants and animals in a landscape you need to understand how they interact with each other, and with their environment. The resulting networks of interactions make ecosystems highly complex. Recent research on complexity and artificial life provides many new insights about patterns and processes in landscapes and ecosystems. This book provides the first overview of that work for general readers. It covers such topics as connectivity, criticality, feedback, and networks, as well as their impact on the stability and predictability of ecosystem dynamics. With over 80 years of research experience of both ecology and complexity, the authors are uniquely qualified to provide a new perspective on traditional ecology. They argue that understanding ecological complexity is crucial in today's globalized and interconnected world. Successful management of the world's ecosystems needs to combine models of ecosystem complexity with biodiversity, environmental, geographic and socioeconomic information.

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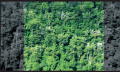

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Landscape Series

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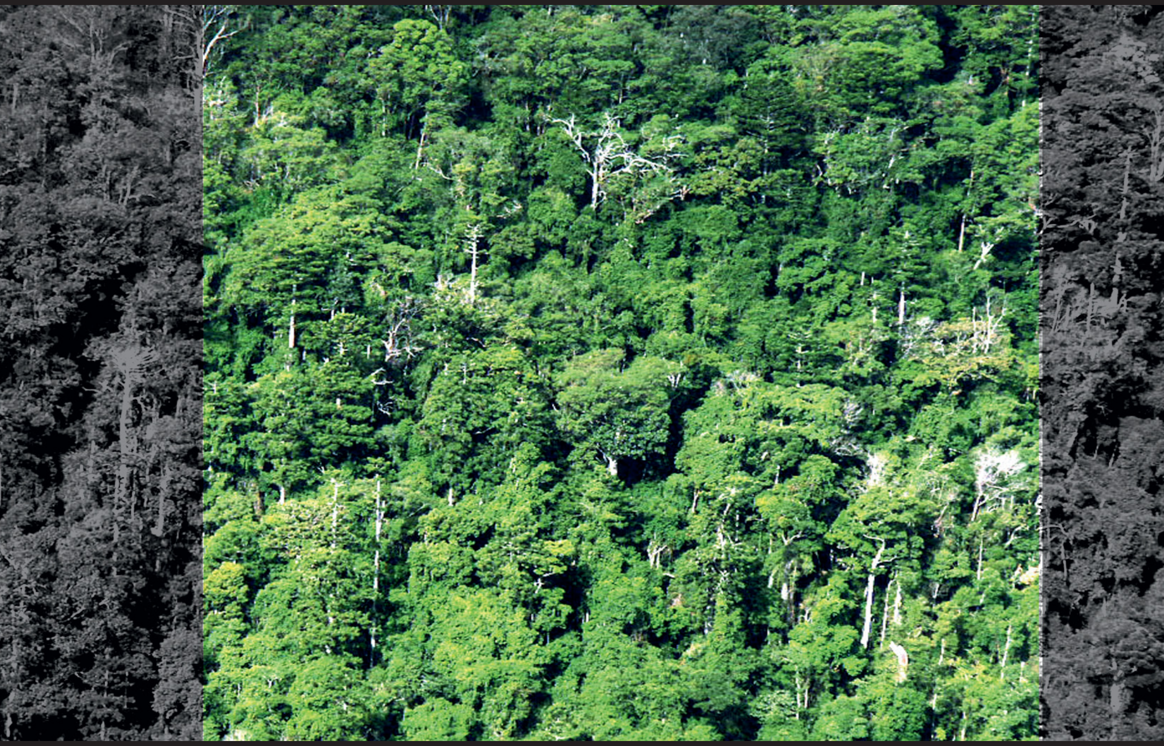

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Landscape Series

COMPLEXITY IN LANDSCAPE ECOLOGY

Landscape Series

VOLUME 4

Aims & Scope:

The Landscape Series publishes manuscripts approaching landscape from a broad perspective. Landscapes are home and livelihood for people, house historic artefacts, and comprise systems of physical, chemical and biological processes. Landscapes are shaped and governed by human societies, who base their existence on the use of the natural resources. People enjoy the aesthetic qualities of landscapes and their recreational facilities, and design new landscapes. The Landscape Series aims to add new and innovative insights into landscapes. It encourages contributions on theory development as well as applied studies, which may act as best practice. Problem-solving approaches and contributions to planning and management of landscape are most welcome. The Landscape Series wishes to attract outstanding studies from the natural sciences, social sciences, humanities as well as the arts and does especially provide a forum for publications resulting from interdisciplinary and transdisciplinary acting teams. Ideally, the contributions help the application of findings from landscape research to practice, and to feed back again from practice into research.

COMPLEXITY IN LANDSCAPE ECOLOGY

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Foreword by the series editors

One of the most important aims of Springer's innovative new *Landscape Ecology* series is to bring together the different fields of scientific research which relate to natural and cultural landscapes. Another is to provide an effective forum for dealing with the complexity and range of landscape types that occur, and are studied, globally. In *Complexity and Landscape Ecology*, the third volume of the series, David Green and his co-authors are outstanding in successfully fulfilling both of these aims.

Green and co-authors, Nicholas Klomp, Glyn Rimmington, and Suzanne Sadedin, draw on their wide experience, gained in universities and research institutes across Europe, the United States, Australia, and China, to bring together the fields of ecology, landscapes and complexity theory. With backgrounds spanning areas as diverse as mathematics, computer science, ecology, environmental management and population dynamics, these authors suggest new ways to integrate traditional field ecology within a larger theoretical and management framework. They also demonstrate effectively how the innovative findings of complexity theory can be applied to landscape ecology. Examples include: the network model of complexity; connectivity and connectivity patterns; emergent behaviour and properties; chaos, feedback, modularity and hierarchy; criticality and phase changes.

Given that plants, animals, landscapes and people interact in highly complex and unpredictable ways, it has become necessary, over time, to study the interactions between these different elements, rather than focus only the elements themselves. Green et al. have successfully provided a new framework for further developing these often multidisciplinary studies, and in doing so they make an important contribution to the theoretical advancement of landscape research.

However, the strength of the book is not limited to its theoretical implications, providing, in addition, an effective bridge both between different disciplines and between theory and practice. In view of the need to conserve the world's living resources, the book plays an important role in improving communication between field ecologists, artificial life modellers, biodiversity database developers and conservation managers. At the same time it provides a means for effective communication between academic research and practical landscape management. Written in a vivid and easy to understand language, the authors make a difficult subject easily accessible. As a result, the book will be not only a valuable resource for landscape professionals, but also an interesting introduction for students and the general reader.

Toulouse and Aberdeen, September 2005

Henri Décamps
Bärbel Tress
Gunther Tress

PREFACE

Pick up any typical adventure story, and you are likely to read how the intrepid explorers drop everything and race off into the unknown, where they have hair-raising encounters, see amazing things and eventually win through to their goal. What those stories don't tell you is the boring part - the even longer struggle that the explorers had to endure even to get started on their great adventure. Everyone knows that Columbus discovered the New World. What is often ignored is that he spent long years patiently lobbying at the Spanish court before he even started.

Science tends to be the same way. You read about a great discovery without hearing about the long and often intense struggle that led to it. When we were students, one of our professors used to say that each generation of scientists struggles long and hard to understand some phenomenon. But the next generation accepts that hard-won knowledge as simple and obvious. Newton said that he was able to make his discoveries because he stood on the shoulders of giants. One of these giants was Johannes Kepler, whose three laws of planetary motion were the fruit of an entire lifetime of studying astronomical observations.

It is the same with the science of complexity. As students, we studied science that tended to ignore complexity. It is very satisfying, therefore, to see mainstream ecology beginning to come to terms with complexity. In the course of writing this book, we were surprised to discover just how many ecological studies now adopt the ideas and methods that form an important part of this book. Studies using such techniques as multi-agent simulations and fractal pattern analysis are now commonplace.

The aim of this book is to introduce our readers to the exciting new field of complexity in ecology. Our goal is to provide an easy-to-read introduction. One group of readers we especially hope to serve are people who already have a basic knowledge of, or interest in, ecology, and wish to know what complexity is about. In keeping with these goals, we have tried to keep the book short, rather than have it blow out into a massive tome. Inevitably, we have had to leave out much. This account is in no way intended to be a comprehensive account of the entire field of complexity or landscape ecology. Rather we have chosen to present topics that we hope will provide you with a gentle introduction to this important and exciting area of research.

There is a deliberate trend throughout the book to move from small to large. So we start (Chapter 2) with individuals and even within individuals (in the case of growth and development). At the other extreme, the final chapters deal with large-scale and even global phenomena.

As we explain in the course of the book, simulation models play an important role in studying complexity. We recognise the importance for readers of being able to play these virtual experiments themselves. Therefore we have bundled up many of the models that we describe here as online demonstrations that can be accessed via our Virtual Laboratory web site:

http://www.complexity.org.au/vlab/.

We are indebted to many people who provided material assistance during the writing and production of the book. Tom Chandler and several of his students and colleagues provided images from their virtual reality models for Chapter 9. Our colleagues David Roshier, Gary Luck and David Watson contributed critical comments on several chapters. Joanne Lawrence carried out useful literature surveys during the early stages of writing. Tania Bransden contributed to the editing, indexing and references, and provided a much needed reality check, never letting us get away with lapses into jargon, irrelevance and incomprehensibility! Jeanette Niehus did much of the final formatting, copy editing and proofing of the manuscript. Justine Singh helped with the references and compiled the index. Dr Ann Sadedin and Ruth Cornforth provided useful comments on the manuscript as well as careful proof reading of final drafts.

We are also indebted to the publishers and the series editors for their faith in us and for their encouragement throughout the writing and production of the book. Finally, we are grateful to the Australian Research Council and to the Australian Centre for Complex Systems for funding assistance.

David G. Green
Nick Klomp
Glyn Rimmington
Suzanne Sadedin

Melbourne, August 2005

CHAPTER 1

COMPLEXITY AND ECOLOGY

Many severe environmental problems have complex causes. This photo shows a section of the Murray River near Albury in New South Wales, Australia, recently declared the country's most endangered heritage site in 2002.

Covering an area of more than 6 million square kilometres, the Amazon Basin dominates northern Brazil and forms a large part of the South American continent. The richness of its biodiversity, and the hostility of its natural environment, mean that even today we can form no clear picture of the Amazon rainforest ecology. Yet even fragmentary glimpses reveal that the Amazon forms an extravagance of nature beyond the wildest imaginings of taxonomists. When biologist T. L. Erwin examined a single species of Amazonian tree, he found 163 unique species of beetle living in its canopy alone (Erwin 1982). Comparing sites seventy kilometres apart, Erwin found only a 1% overlap in the beetle species present (Erwin 1988). Brazil has more species of flowering plants and amphibians than any other country, and ranks in the top four countries on earth for mammals, birds, butterflies and reptiles (Fearnside 1999).

Up until the mid-twentieth century, the Amazon rainforest remained shrouded in mystery, isolated by its sheer size and inaccessibility. But a rapidly growing technological society, with a huge appetite for raw materials, could not leave such a massive resource untouched forever. The forest seemed to promise fertile croplands, and the trees themselves became valuable exports under the chainsaw.

In 1960, the Brasilia-Bellem road opened, making the Amazon accessible for commercial exploitation. The road sliced the rainforest open, bringing swarms of loggers and farmers eager to claim a share of the wealth. During the next two decades, the human population of the region swelled to more than 17 million. Soybean farms and cattle ranches proliferated. In the 1980s, the rate of deforestation across Amazonia exceeded 22,000 square kilometres per year (or about 4 ha per minute). During the late 1990s, the Brazilian government began efforts to reduce the rate of land clearing. However, their attempts were frustrated by the sheer scale of the problem, with illegal operations being responsible for up to 80% of logging in Amazonia. By 1998, over half a million square kilometres of Brazilian rainforest had been cleared (Fearnside 1999), and destruction continues to accelerate. During 2004 alone, over 26,000 square kilometres were destroyed, an area roughly the size of Belgium[1].

The assumption that clearing lush rainforest would yield prime agricultural land proved to be a tragic mistake. Beneath a thin surface layer of rich soil, farmers mostly find infertile wasteland. After a season or two of good crops, the soil is used up, erosion is rife and rainfall declines. Farmers are forced to douse the land with chemical fertilizers, and leave fields fallow for many years, in order to maintain any yield at all. For poverty-stricken smallholders, often faced with an immediate need for cash crops to service World Bank loans, such management techniques are unfeasible. Consequently, millions of displaced farmers move ever deeper into the rainforest, clearing more and more forest to eke out a few extra years' worth of crops.

Ironically, the reason for the land's failure lies in the extraordinary efficiency of the rainforest itself. In the dense, lush ecosystem of the forest, almost nothing is wasted. Nutrients that reach the ground are quickly decomposed and recycled into fast-growing plants. Little is left in the soil: when the trees vanish, so do the raw

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[1] Brazilian government report, 2005.

materials of life. Even the rain itself depends on the trees: approximately 50% of the Amazon's rainfall is recycled through the forest (Fearnside 1999).

From an ecological viewpoint, the exploitation of the Amazon has been an unmitigated disaster. Logging creates networks of roads, encouraging further migration of farmers into untouched forest. Their slash-and-burn methods break up the forest, gradually turning it into isolated fragments. This fragmentation leads to sharp increases in fires, in hunting, and in soil erosion, as well as invasions of grasses, vines and exotic species. All of these changes spell trouble for native plants and animals.

The story of development in the Amazon Basin is a dramatic example of how simple assumptions about ecological systems can lead to disastrous mistakes in land management. Almost always, problems arise because the complexity of landscapes and ecosystems defeats our efforts to understand them as simple systems of cause and effect. In the case of the Amazon, building a road into the region initiated a cascade of mutually reinforcing processes. The underlying error in this ongoing catastrophe is "cause and effect" thinking: assuming that the forest ecosystem is a direct effect of suitable climate and soil conditions, rather than a complex, dynamic process in itself.

We can see this failure to grasp ecological complexity in early attempts to understand the role of landscapes. When people first began using computer models to study ecosystems, spatial interactions were largely ignored. Local interactions between individuals were assumed to be minor effects that would average out over time and space. Understanding the influence of landscape was therefore seen as easy. To account for a hillside, for instance, all you needed to know was what happened at the top of the hill, at the mid-slope and in the swale. The assumption was that the differences in environmental conditions from place to place were the only factors that influenced the outcome, so accounting for them would tell you all you needed to know about the role of landscapes in ecology.

Unfortunately, the assumption that local effects will average out over time and space is not only incorrect; it is in many cases drastically misleading. Interactions do matter, and local interactions can blow up to have large-scale effects. In ecological systems, many of these interactions are not simple, one-way cause and effect relationships, but complex feedback relationships. Only by explicitly studying these interactions can we explain many of the patterns and processes that occur in landscapes.

The landscape, the Earth's surface, is the stage on which ecology is played out. It comprises the landforms, the soils, the water and all the other physical features that influence the organisms that make up an ecosystem. And just as the landscape constrains and influences the ecology of a region, so too the ecosystems interact with and affect the landscape.

This book is about the profound but often subtle ways in which interactions affect both ecosystems and landscapes. Our aim is to help readers to understand the nature of complexity in the context of landscape ecology.

In the chapters that follow, we will explain what *complexity* is and what recent research has been learnt about it. We will also look at some of the many ways in which complexity turns up in ecosystems and in landscapes. As we shall see in Chapter 3, the landscape itself can be complex. In subsequent chapters we will look both at the many processes that make ecosystems complex, and at the ways in which the interplay between landscapes and ecosystems creates complexity of its own.

Finally, we will explore the relationship between landscape ecology, complexity and the information revolution. Besides describing some of the key ideas and the insights that flow from them, we will also introduce some of the techniques that are emerging to deal with ecological complexity in practice.

1.1 WHAT IS COMPLEXITY?

Like life itself, complexity is a phenomenon that is well known, but difficult to define. A general definition is difficult because the term complexity appears in different guises in different fields. In computer science, for instance, it usually refers to the time required to compute a solution to a problem. In mathematics it is usually associated with chaotic and other nonlinear dynamics.

Here we will take "complexity" to mean the richness and variety of form and behaviour that is often seen in large systems (Bossomaier and Green 1998, 2000). Complexity is not the same as size. For example, a herd of zebras feeding on a grassy plain do not behave in the same way as billiard balls on a table. If you strike one of the billiard balls it will roll around hitting the other balls. Eventually its motion and energy will dissipate through repeated collisions between the balls. This is simple behaviour. Although the balls interact, their energy soon averages out and they stop moving. On the other hand, if one zebra starts running, then the entire herd is likely to panic, creating a stampede. What is more, the stampede is not random. The running zebras avoid colliding with each other, but remain packed close together and head in the same direction. This is complex behaviour. The stampede emerges out of interactions between the zebras.

The property that is most closely associated with complexity is *emergence*. This idea is captured by the popular saying: the whole is greater than the sum of its parts. Emergence takes many forms. A forest emerges from the interactions of millions of individual plants, animals and microbes with each other and with the landscape. A forest fire emerges from the spread of ignitions from one plant to another. A flock of birds emerges from the individual behaviour of many individual birds interacting with one another. The organisation of an ant colony emerges from the joint behaviour of many individual ants interacting with each and with the colony environment. To understand complexity in ecosystems, we need to learn how large-scale properties like these emerge from interactions between individuals.

Which came first, the chicken or the egg? This famous conundrum exposes a gap in our intuition[2]. It is natural to assume that each cause has a simple effect, and vice versa. So an egg "causes" the chicken that hatches from it. Conversely, the chicken "causes" the egg that it lays. The chicken or egg question invites an answer in terms of simple causality. In reality, however, both the egg and the chicken are manifestations of a complex process[3]. Ilya Prigogine expressed this mental transition from static causal models to dynamic systems models concisely in the title of his book, *From Being to Becoming* (Prigogine 1980). Similarly, Barry Richmond talks about the need for structured thinking over simple causal thinking (Richmond 1993).

Many situations in landscape ecology are like the chicken and egg problem. Look again at the story that began this chapter. To understand what happened in the Amazon rainforests, it is necessary to realise that a rainforest is not a fixed object, but an on-going process. Traditional cause and effect classifications characterize a rainforest as a forest that grows in areas of high rainfall and soil that is rich in nutrients. Based on this model, it seems reasonable to conclude that if you cut down a rainforest for timber, then the high rainfall and rich soil will cause rainforest to grow back again in a few years. Not so! The truth is that the rainforest is a complex system. The species richness, the lush soils, and the high rainfall are all mutually dependent. They are each the product of a long feedback process. Higher-order or systems thinking is needed to understand the rainforest, which contains a vast network of feedback loops, flows and accumulations.

The tendency to think in terms of simple cause and effect leads to many problems in conservation. People see a local problem and seek a simple, local solution. They are often unaware of the spatial interactions that may be involved and do not realise what effects their local actions may have elsewhere.

The Murray River is Australia's largest river system. Its catchment, which and encompasses some of the country's most productive agricultural land, covers 14% of the continent receiving water from 41 tributaries across four states. The health of this river is of critical importance to the country's economy. However, in 2002, the National Trust of Australia was forced to declare the entire Murray River to be the country's most endangered heritage site: "Today no water flows into the sea from the Murray River. This once magnificent river now regularly fails to reach the sea." In 2002 the National Trust of Australia gave the following statement:

> *"The significant threats to the health of the Murray remain largely unaltered. However, the community engagement process, along with the work of community organisations have raised the profile of the Murray issue considerably. National action is required, and the National Trust*

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[2] Philosophers have long been aware of problems with simple causality. For example, they distinguished between "proximate" and "final" causes. What causes a wild fire? A lightning strike may be the proximate cause, but hot weather and lack of rain also contribute as more final causes. These climatic conditions may themselves be caused by global warming caused by carbon dioxide emissions caused by oil and coal burning caused by humans. And so on.

[3] Evolutionary biologists would say that the egg came first. Fishes, amphibians and reptiles all laid eggs many millions of years before birds, and chickens, evolved.