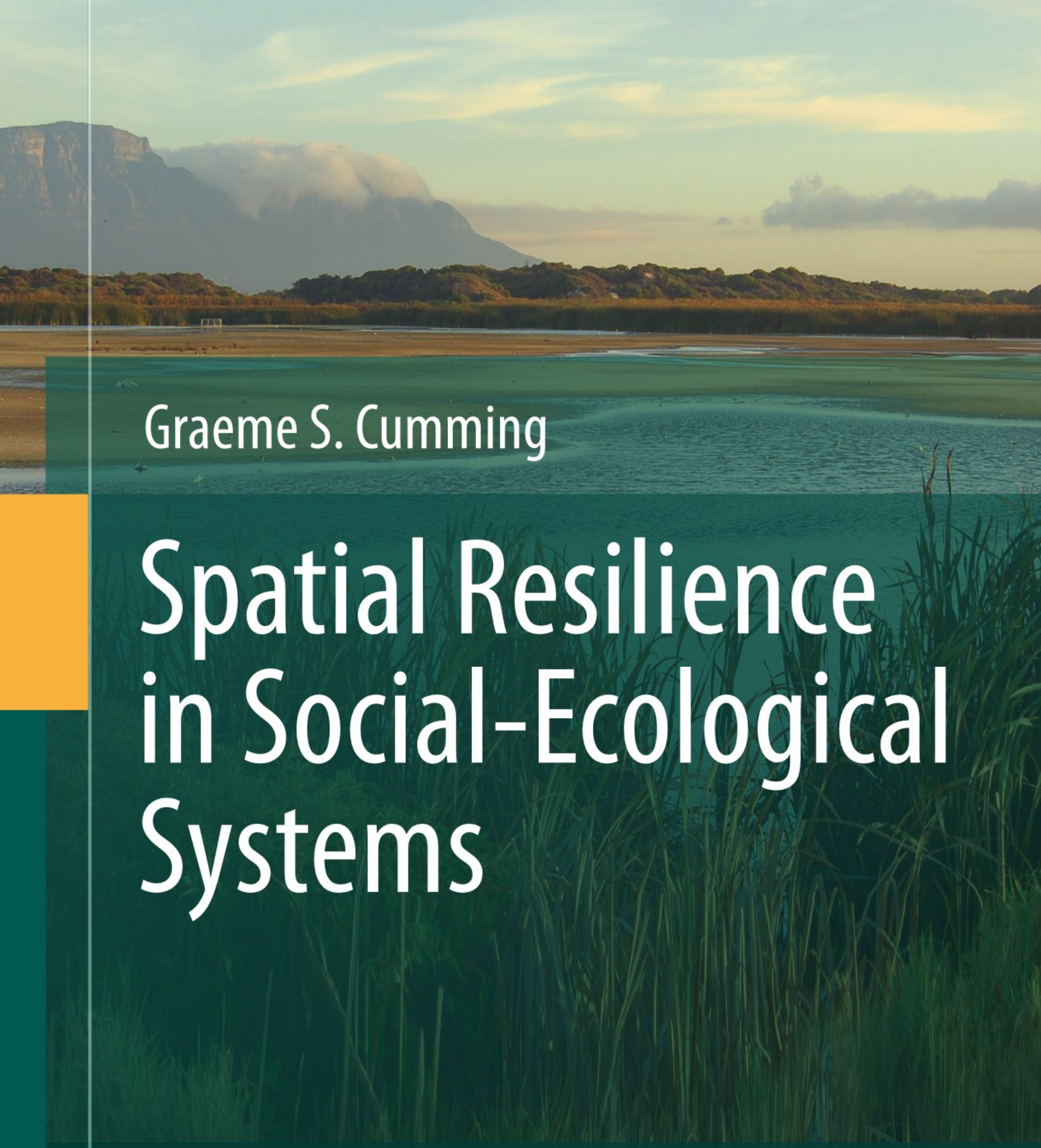

Graeme S. Cumming

Spatial Resilience in Social-Ecological Systems

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Graeme S. Cumming
Percy FitzPatrick Institute
DST/NRF Centre of Excellence
University of Cape Town
Rondebosch
7701 Cape Town
South Africa
graeme.cumming@uct.ac.za

The cover photograph shows a view from Strandfontein wastewater treatment works (near Muizenberg, on the edge of False Bay), looking towards Table Mountain. The idyllic appearance of this wetland disguises the high human use of this system and the ecological costs of the interaction: high *Escherichia coli* levels in the water in the settling ponds, invasive *Typha* reedbeds on the pond's edge, a landfill site just out of view to the left of the picture, and globally endangered lowland fynbos vegetation on the ridge behind the pond. Despite these problems, Strandfontein remains a nationally important site for waterbirds. Photograph by Graeme S. Cumming, 2008.

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To Nils and Clara, my delightful inspirations –

May you find as much pleasure as I have in exploring this green world!

Preface

This book represents a personal landmark along a path that I have been following for close to 15 years. Along the way I have spent considerable amounts of time debating and pondering with friends and colleagues over the relevance of space, and spatial variation, for the intricate workings of complex systems. These interactions have greatly enriched the journey, and I remain deeply grateful for them.

Thanks are due to many people. Although I can not list all of you here, I would particularly like to acknowledge the influence of three groups. The first consists of members of the Resilience Alliance, which has provided a wonderful arena for free thought and passionate debate. The Resilience Alliance has been the creation of many people who can not all be listed here, but my particular thanks go to Buzz Holling, Steve Carpenter, Carl Folke, Lance Gunderson, Phil Taylor, and Brian Walker for their role in consistently creating, redefining, and defending this small but highly influential think-space. Within the Resilience Alliance I am also deeply indebted to a group of younger scientists for crazy discussions and far-ranging debate: in this context, thanks are particularly due to Garry Peterson, Jon Norberg, Craig Allen, Marco Janssen, Marty Anderies, Örjan Bodin, Michael Schoon, and Henrik Ernstson.

The second important group of people is the roadies; an informal, interdisciplinary collection of academics and students at the University of Florida who met over the course of 4 years (and beyond) to discuss social-ecological resilience in the context of understanding the impacts of the transAmazon highway. From this group I would particularly like to thank Jane Southworth, Steve Perz, Grenville Barnes, Marianne Schmink, Mike Binford, Katie Sieving, and Bob Holt.

The third group consists of the many graduate students, now spread across different continents in various professional roles, who through their ideas, questions and uncertainties about spatial analysis have helped to highlight problem areas and clarify my thinking. Special thanks in this group are due to Lin Cassidy, Matt Child, Amy Daniels, Amy Duchelle, Simon Dures, Ann George, Grant Joseph, Matt Marsik, Mduduzi Ndlovu, Heidi Richter, Brian Spiesman, and Claudia Stickler.

This book owes its existence in part to Margaret Deignan of Springer SBM, who suggested the project and has proved a willing and supportive editor. Individual chapters have been greatly improved by the contributions of colleagues who took

on reviews of one or more chapters. Insightful and constructively critical comment was provided by Örjan Bodin, Matt Child, David Cumming, Henrik Ernstson, Eric Lambin, Harini Nagendra, Jon Norberg, Magnus Nystrom, Xanic Rondon, Jane Southworth, and Cathy Wilkinson. David Cumming deserves special mention for providing detailed input on six of the eleven chapters as well as providing several photographs; and Harini Nagendra, for offering invaluable big-picture comments on the entire book. Joshua Lewis kindly took a photograph of a floatable house for me, and I am further indebted to Steve Carpenter, Carl Folke and Bob Holt for their cover endorsements.

Writing this book has been a sabbatical project, and I am grateful to the University of Cape Town and the Oppenheimer Foundation for their financial support during the writing period. Additional assistance was provided by the Stockholm Resilience Centre and the Department of Systems Ecology at the University of Stockholm, with particular thanks to Thomas Elmqvist and Carl Folke for making our stay in Stockholm possible. I am also grateful to my parents, David and Meg, and to my wife's parents, Rolf and Elizabeth, for hosting us for periods in Zimbabwe and Germany respectively.

Finally, no set of acknowledgements would be complete without mention of my immediate family, who have supported me wholeheartedly in completing this book: my wife, Katharina; and my children, Nils and Clara, to whom this book is dedicated.

Cape Town, South Africa Graeme S. Cumming

Contents

Chapter 1
Introducing Spatial Resilience

Starting a book on the spatial resilience of social-ecological systems is a somewhat daunting task for both author and reader. Social-ecological systems are complex, and complex systems are, well, *complex*. The word itself suggests that perhaps this discipline is already well beyond the grasp of ordinary mortals like us. 'Resilience' is also one of those suspicious sorts of words; it is easy to see how it might suddenly slip away into the forest, just when you think you have grasped it, or turn around and give you a nip. Add to these conceptually difficult topics the non-trivial questions of how they influence and are influenced by spatial variation, and we have the subject matter of this book.

My starting premise may therefore surprise you: the claim that both complex systems theory and spatial analysis are grounded in ideas that we are all familiar with. Whether or not we have articulated it, we have all had to deal with daily uncertainties and to attempt to work with and understand the behaviour of complex systems. Once the jargon barrier presented by technical descriptions of complexity and resilience is overcome, many of the underlying ideas in the study of spatial resilience can be seen as expressing fundamental principles that will seem surprisingly familiar to most readers.

For example, one of my favourite complex systems is, at the time of writing, almost 3 years old. For such a little system he has some pretty complex behaviours, particularly when it comes to bed time. One of the many things that intrigues me about him is that while a year ago he couldn't talk, he can now express abstract concepts in two languages. This sudden increase in ability amounts to what complex systems theorists would call a *state shift*; he has entered a *new domain* that is already enabling him, through language, to achieve a new relationship with other complex systems and the world in general. His sister, too, will soon cross this *threshold*.

Richard Dawkins or David Hull might call my children *vehicles* who carry *genes* or *replicators* that dictate their *ontogeny*, or development (Dawkins, 1989; Hull, 2001); and Noam Chomsky or Stephen Pinker can rationally explain how each child is born with an aptitude for language and how a mastery of language interacts with thought processes (Chomsky, 1986; Pinker, 2007). But anyone who has tried to parent a small child or rear a puppy knows that there are many other facets to a complex system. A child grows, it learns, it develops character and consistency;

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it has whims, stubbornesses, develops likes and dislikes; learns the difference between pleasure and sadness; and slowly becomes better and better suited to surviving in its local environment. Even when it flushes my socks down the toilet, or places my cell phone in a bowl of water, it is acting according to a form of logical internal consistency and using experimentation and learning to gradually develop a set of consistent rules that guide its behaviour and help to link stimulus, information processing, and response.

My children have the advantage, relative to many other kinds of complex system, that they can move. Their mental map of the world is gradually expanding, from the home environment to the park next door to the kindergarten down the road. Their awareness of space and their ability to mentally represent spatial relationships allow them to make decisions about where they should go next. The push-car is just outside the back door, the sandpit is past the swimming pool, the indoor toys are in the bedroom, and lunch is on the kitchen table. The fact that they can choose where to be gives my children the potential to select a preferred environment from among the environments that are on offer, and to make choices that influence their ability to learn (Fig. 1.1).

Things are different for complex systems that cannot move. I live in Cape Town, and Cape Town will probably remain a city by the sea for as long as our civilisation persists. Cape Town is a system of people and nature in which I and my family are tiny pieces. Its location by the sea brings it certain benefits. They include, for example, a Mediterranean climate that has contributed to the formation of one of the most diverse floras in the world, the fynbos; a large and busy harbour, with full access to trade and shipping routes; and easy access to fresh fish for its inhabitants. However, its location also means that it is far from the gold mines and industrial expansion that have made Johannesburg the nation's business centre; it gets cold and wet at the same time, being in southern Africa's only winter rainfall region; and it is one of the few South African cities to have been invaded post colonisation and taken over by a foreign power (the British took the fledgeling Cape Colony from the Netherlands in the 1806 battle of Blaauwberg).

The aim of this book is to explore the question of how space, or more accurately spatial variation, influences and is influenced by complex systems. The focus on space is deliberate, but as we shall see, many of the same general principles also apply to variation in time. Just as a city occurs within a particular landscape, it also occurs within a period of history. Great old cities, like London or Prague, have grown and changed over the centuries in response to the societal changes that they have weathered.

As a way of focusing our thinking about the spatial aspects of change and sustainability in social-ecological systems (SESs), I have chosen to concentrate on the topic of resilience. Resilience is just one of many emergent properties of SESs that I could have selected as the focus for this book (vulnerability, stability, robustness and diversity might also have served), but I like resilience because of its integrative nature.

When we try to analyse the resilience of an SES, or any other complex system, we are asking a bigger question than one might think at first glance. You can think

Fig. 1.1 Two of my favourite complex systems learn basic physics by experimenting with gravity and friction. Photograph by Graeme S. Cumming

of your own resilience as your ability to keep your identity intact. Analysis of your personal resilience demands consideration not only of elements that are internal to you (e.g., your physical strength and mental agility), but also of elements that are external to you (e.g., where you live, what kinds of environmental challenges you face, and with whom you interact) and elements of surprise (e.g., floods and wars). Resilience may be deliberately enhanced in response to a specific concern (e.g., you start to wear a cycling helmet on your way to work), but that precaution may be irrelevant to coping with another kind of surprise (e.g., a dog attacks your legs as you walk from your bicycle to your office). You may be ideally suited to life in an urban environment but poorly suited to surviving alone in a rainforest or an African savanna. System resilience can not be considered without an awareness of the context in which a system exists and the kinds of change and disturbance that it is likely to have to deal with.

Broadly speaking, spatial resilience refers to the ways in which spatial variation – including such things as spatial location, context, connectivity, and dispersal – influences (and is influenced by) the resilience of an SES or other complex system. At a personal level, spatial variation matters immensely. For example, you may be dressed suitably for the weather in Harare but not for when you get off the aeroplane in Cape Town; you may be far more likely to be knocked off your bicycle on one of your possible routes home from work; moving through a public space, such as an airport, may increase your chances of contracting the latest influenza virus from someone else; taking a wrong turn on your way up Table Mountain can result in a broken leg; and the urge to travel may ultimately lead you to settle somewhere far away from your country of origin, creating a grandparent-shaped vacuum in your baby-sitting roster if you should be lucky enough to have children.

This book is the first attempt to provide a cohesive synthesis of ideas relating to spatial resilience in social-ecological systems. The novelty and scope of the subject matter have been provocative and exciting to grapple with (not quite as adrenaline-heavy as jumping out of an aeroplane, but as close as academia gets), but the experience has also made me aware of how little we really know about some everyday things. Given the many areas of spatial resilience in which our ignorance is obvious, I hope that you will excuse me for the weaknesses inherent in this synthesis, taking them as a challenge to do better rather than mistaking them for deficiencies in the concepts.

The book commences with two conceptual chapters and one background chapter. The technical details of what spatial resilience is and how it can be defined more rigorously are addressed in Chapter 2, which provides the conceptual background that is necessary for understanding the material that is presented through the rest of the book. Chapter 2 also provides an introduction to some of the jargon in what has become an unfortunately jargon-littered discipline. Chapter 3 places the idea of spatial resilience in a broader framework and deals in general terms with the question of how we can think about and analyse spatial resilience. Chapter 4 takes a step sideways to offer some important background on modelling and spatial models, offering not only an introduction to modelling in general but also, more subtly, an introduction to some different ways of thinking about space.

The layout of the rest of the book follows a trajectory of increasing realism that travels from spatial models (Chapter 5) through analytical approaches (Chapters 6 and 7), experiments and social-ecological fragmentation analyses (Chapters 8 and 9), and the analysis of specific aspects of spatial resilience in real-world systems (Chapter 10). Attention is divided more or less equally between conclusions that have been derived primarily through the formulation and testing of theory (such as the insights into spatial resilience that have been obtained from studies of fragmentation) and approaches that derive primarily from the application of spatially explicit methods (such as network analysis and remote sensing). Chapter 10 brings several of these different strands together in thinking about a real-world problem, the resilience of large river basins. Finally, Chapter 11 concludes the book with a summary of some of the spatial principles that the preceding chapters identify, discussion of some important philosophical questions, and consideration of research needs and future directions.

One of the most important ideas to keep in mind as you read this book is that social-ecological systems are seldom at equilibrium and almost never static. The nature of change is multifaceted. Some kinds of change matter a lot to us as individuals or societies, while other kinds of change are desirable or largely irrelevant. The sun rises and sets as predictably as the earth rotates, and we experience the earth's orbit around the sun as seasonality. These kinds of change have happened throughout the evolution of life, and we (and many other organisms) are well adapted to cope with them. This book is less about consistent and predictable change and more about the kinds of unexpected change that matter to people, to ecosystems, and to social-ecological systems. The vast majority of works of science deal with constancies; things or relationships that can be described unambiguously, exist reliably, and behave predictably. This book deviates from the norm by its interest in inconstancy and dynamism, as well as through its focus on the role of spatial variation in temporal change.

One of the central arguments underlying this synthesis is that many of the themes that are most important to understanding SESs can be unified (and discrepancies between case studies explained) through consideration of the role of spatial and temporal variation and scale. I will argue throughout the book that conceptual and empirical unification of seemingly conflicting theories should be a central goal in resilience research, which has many theories and many case studies but relatively few analyses that bring theory and case study together in a rigorous and predictive manner. Despite the fact that we are all intimately familiar with the working of complex systems, considerable work is still required to articulate that familiarity, to bridge the gap between theory and practice, and to embed the study of social-ecological systems within a rigorous scientific framework.

Now that I have voiced these introductory thoughts and qualifications, it is time to take the plunge and dive headlong into the topic of spatial resilience.

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Chapter 2
Conceptual Background on Social-Ecological Systems and Resilience

Introduction

The study of social-ecological systems (SESs) from a complex systems perspective is a fast-growing interdisciplinary field. It is a vibrant, exciting endeavour that promises to link different disciplines into a new body of knowledge with high relevance for solving some of the most pressing problems of our time. The contributions made by spatial variation to resilience are poorly understood and extremely important – and hence, the need for books like this one. Before we can delve into the most interesting aspects of spatial resilience, however, I need to lay a conceptual foundation on which to build. This chapter is intended to provide that foundation.

In what follows, I first discuss the origins and conceptual basis of complexity-oriented approaches to the study of SESs. I then offer definitions of complex systems, resilience, and some related concepts. This discussion sets the stage for understanding spatial resilience as a subset of ideas about resilience. The final section of the chapter presents and explains a formal definition of spatial resilience.

Conceptual Foundations and Origins of SES Theory

In my opinion we do not yet have a full-blown theory of social-ecological systems (according to the criteria of Pickett, Jones, & Kolasa, 2007), although a number of elements of SES-related theory can be identified from the recent literature and some promising theory-oriented frameworks are emerging (e.g., Holling, 2001; Norberg & Cumming, 2008; Ostrom, 2007; Waltner-Toews, Kay, & Lister, 2008). I have elected in this book to refer to the growing body of theory relating to SESs by the term ‘Social-Ecological Systems theory’, or ‘SES theory’ for short, because it focuses attention on the core subject matter and distinguishes it from other existing bodies of overlapping but not identical theory. For example, SES theory draws heavily on systems ecology and complexity theory, but it is not the same; the study of SESs includes some central societal concerns (for example, equity and human wellbeing) that have traditionally received little attention in complex adaptive systems theory, and there are areas of complexity theory (e.g., quantum physics) that

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have little direct relevance for understanding SESs. SES theory incorporates ideas from theories relating to the study of resilience, robustness, sustainability, and vulnerability, but it is concerned with a wider range of SES dynamics and attributes than any one of these terms implies; and while SES theory draws on a range of discipline-specific theories, such as island biogeography, optimal foraging theory, and microeconomic theory, it is broader than any one of these individual theories alone. Some authors (e.g., Waltner-Toews et al., 2008) have used 'linked social-ecological system' as a mid-point between distinct social and ecological systems and 'fully integrated socioecological or ecosocial systems'. I use social-ecological system here in the sense of a fully integrated system of people and nature that could in theory be parsed in several different ways.

Being a relatively new discipline, and one that is currently in expansion mode, SES theory is in a healthy state of flux. Complex systems theory can be considered one of its more important intellectual parents (Norberg & Cumming, 2008). The work that constitutes modern complex systems theory can currently be classified into at least three primary domains. The first and oldest of these consists of a core of ideas arising initially from the interface of physics, computer science, and biology. Classical themes in this domain include information theory, simulations of life, and research on genetic algorithms and artifical intelligence. Complexity theory in this domain is rooted in the writings of such prodigious researchers as John von Neumann (e.g., von Neumann & Morgenstern, 1944), Alan Turing (1950), Ludwig von Bertalanffy (1968), Herbert Simon (1962), John Holland (1992, 1994), and Murray Gell-Mann (1992). A good recent introduction to the central themes of classical complex systems research is provided by Melanie Mitchell (Mitchell, 2009).

The second domain, which has incorporated many ideas from the first but has also expanded and built on them in an environmental context, is that of the study of social-ecological systems, or SESs. This is the primary domain in which this book is situated. The study of SESs is dominated by groups that have organized around particular higher-level concepts, including (but not limited to) resilience, vulnerability, adaptation, and robustness. Examples of publications in this field include the books by Levin (1999), Berkes, Colding, and Folke (2003), Gunderson and Holling (2002), Norberg and Cumming (2008), and Waltner-Toews, Kay, and Lister (2008). As these and the many other books on SESs make clear, SES theory is more than just complexity theory with a conscience; because of the social context in which SES research questions sit, and the likelihood that SES research will translate into recommendations that will genuinely affect real people, SES research has to be considerably more self-conscious and more pluralistic in its perspectives than complexity theory has ever acknowledged.

The third domain of research on complexity is less unified in its intellectual content and consists of a set of ideas and analyses that have some relevance to the study of complexity but do not fall into a standard corpus of knowledge. These studies are often ignored by researchers in the two previous domains because they do not seem to 'fit' within disciplinary norms; many scientists simply do not know what to do with them. In many cases it remains unclear whether this domain is characterized more by genius or by eccentricity. It is exemplified by attempts to create broader unifying theories by researchers like H. T. Odum (1995), Robert Rosen (2005), and Bob Ulanowicz (1999).

As the body of SES research has grown, its scope has expanded and its relevance to real-world problems has become increasingly more apparent. It now '. . . offers some simple guidelines and rules of thumb that could, if widely accepted, provide the basis for a quiet revolution in the theory and practice of the management of natural resources' (Norberg & Cumming, 2008, p. 278). Although this revolution is already well under way, there is still much ground to be covered before we can consider SES theory to be mature.

Defining Complex Systems and Spatial Resilience

First, a Word About Clarity

This book focuses on a new development, the analysis of spatial resilience, in a new field, SES theory. SES theory is emerging from a combination of disciplinary platforms and complexity theory. A frequent concern among systems theorists is that usage of the term 'complexity' (and of other terms in the social-ecological systems lexicon that have specific meanings, like resilience and adaptive management) becomes so generalised and so misunderstood that the term becomes a source of confusion (Grimm, Schmidt, & Wissel, 1992). Lindenmayer and Fischer (2006) lament the conversion of 'fragmentation' into a *panchreston*, which they define after Bunnel (1999) as 'a proposed explanation intended to address a complex problem by trying to account for all possible contingencies but typically proving to be too broadly conceived and therefore oversimplified as to be of any practical use'. Complexity runs a very real risk of becoming a panchreston because real-world systems exhibit complexity in a great variety of different ways; the term easily becomes a catch-all phrase for things that we do not understand, whether complex or not.

At the same time, however, as T. S. Eliot's Sweeney states in the *Sweeney Agonistes*: 'I gotta use words when I talk to you'. One of the challenges in discussing ideas about (or with) complex systems is that many words or phrases carry not only a definite meaning but also a set of connotations and implications that will be obvious to some readers but not to others, or (more dangerously) may differ between different groups of readers. For example, most biologists will associate 'evolution' with Darwin's ideas about the processes of descent, variation, and natural selection (Mayr, 1991). They will be aware (for example) of the dangers of linking evolution with progress, the debate over the validity of group selection arguments, and the falsity of the idea that evolution is in some way working towards a particular end point. These aspects of evolution are 'givens' in any in-house conversation; they need not be repeated during every debate, and biologists are generally happy to leave them in the background when discussing 'evolution'. While biologists do not have a monopoly on the meaning or use of 'evolution', the term has its origins in the biological sciences, and consequently biologists tend to feel that non-standard applications of the concept (e.g., as used in Beinhocker, 2007) need additional explanation.

Sometimes we run into difficulties in debating topics if the additional elements that are attached to a particular term become too prolific. This problem is particularly pronounced in interdisciplinary discourse because many disciplines have pursued related ideas in slightly different ways. For instance, functional perspectives in ecology are respectable, while in sociology they may arouse considerable controversy; ‘adaptation’ in the climate change debate is used in both an active sense (i.e., societal responses to climate change) and a passive sense (i.e., via the action of selection acting on diversity, as in evolutionary biology); and phrases like ‘non-linear’ or ‘threshold’ have become shorthand in some circles for describing a process or a combination of variables that can lead to alternate stable states in a complex system.

There are times when it serves a useful purpose to leave a concept a little vague. This is particularly true in the early stages of the development of a scientific discipline because it gives the scientific community the space to figure out what they really mean. ‘Ecosystem’, for example, took a while to pin down satisfactorily (Pickett & Cadenasso, 2002) and some scientists still advocate discarding it entirely (O’Neill, 2001). The same problems with definitions have arisen over concepts like ‘niche’ (Chase & Leibold, 2003) and ‘metacommunity’ (Leibold et al., 2004). Conversely, the danger with leaving concepts too fuzzy is that it is easy for confusion and misunderstandings to arise. Clarity is one of my central goals in writing this book, and I thus consider it important that I define and explain the foundational concepts and some of the terminology that will occur later in the book. In subsequent chapters I will undoubtedly slip, at times, into the jargon of the field; I ask your indulgence on this point, and hope that you do not get too bogged down in semantics.

Getting Down to Definitions

Many of the terms that are used in studies of SESs are vague, confusing, or novel. Given that systems change continually through time, even the problem of rigorously defining the study system can be thorny. As discussed in detail by Cumming and Collier (2005), the concept of identity is useful here: a system retains its identity if key components and relationships are maintained continuously in space and through time. When I write about a complex system I am thus referring to a set of elements (e.g., farmers, water, forests, pollinator species, or organs) that interact with one another in a shared environment. The philosopher John Collier has highlighted the importance of cohesion in complex systems (Collier & Hooker, 1999; Collier, 1986). Within the system, cohesion would be lost and the system would lose its identity if the forces that hold system elements together (centrifugal forces) were weaker than those that pull or push system elements apart (centripetal forces). Centrifugal forces include such things as trophic interactions, social capital, and trade. Centripetal forces include such things as habitat destruction, fragmentation, and conflict. Complete removal or elimination of a system, even if it is replaced by a very similar system, constitutes a loss of identity.

Complex systems have traditionally been differentiated from other kinds of system by their behaviour, rather than in terms of the number or arrangement of their components, although there are obviously strong connections between system architecture and system behaviour. Understanding the connections between structure and function is one of the central goals of complex systems research. Holling (2001) provides one perspective through his ‘rule of hand’, which suggests that the minimal structural criteria for complex behaviours include three to five interacting components, three qualitatively different speeds at which variables change or interact, and non-linear causation. Complex behaviours include such phenomena as non-linearities, feedbacks, the existence of thresholds, the potential for alternative stable states, and self-organization (Norberg & Cumming, 2008). Complex systems are also considered to contain and/or process information more, and more effectively, than simpler systems (Simon, 1976). Complex *Adaptive* Systems are distinguished from other complex systems by their capacity to respond to their environment through self-organization, learning, and reasoning (Norberg & Cumming, 2008). Social-ecological systems, which contain both human and ecological components, are both complex and adaptive. As a result the study of complex adaptive systems is directly relevant to understanding aspects of the environmental problems that are currently faced by human society. It is worth noting, in passing, that the number of experiments required to fully understand the behaviour of a complex system increases exponentially with the number of additional interacting elements. That is why most quantitative research on the mechanisms underlying complexity has focused on systems that are as simple as possible while still displaying complex behaviours.

There are several important caveats that relate to defining a complex system. The first is that most complex systems are hierarchical (Allen & Starr, 1982; Simon, 1962). In most studies of a particular system, a subjective decision therefore has to be made as to which level of the hierarchy constitutes the level of interest (i.e., the level at which analysis should take place). The choice of hierarchical level is closely allied to the choice of the scale of analysis. For example, an analysis of social-ecological interactions in South Africa could take place at the national level (South Africa), a provincial level (e.g., Western Cape, Gauteng), a city level (e.g., Cape Town, Johannesburg), or a municipal level (e.g., Rondebosch, Melville). Each of these different choices dictates a different spatial scale of analysis and will lead to differences in the trends that are observed and their predictability (Levin, 1992). Hierarchy theorists further recommend analysis of a level above and a level below the level of interest, following the adage that ‘upper levels constrain, lower levels explain’ (Allen & Starr, 1982). The option of exploring causality in detail across a range of scales is obviously appealing, and avoids the problem of subjective decisions about a level or levels of interest, but is seldom undertaken because of logistical constraints (Cumming & Norberg, 2008; Cumming, 2007). Scale and scaling are dominant themes throughout this volume.

A second important caveat is that definitions of what matters (i.e., the selection of what constitutes a key element or relationship) are subjective and depend heavily on the beliefs and values of the scientist and the paradigm within which he or she is working. In sociology, awareness of this problem dates back over a hundred years to the writings of Weber (1904). For example, if a social-ecological system is defined as consisting of ranchers and their livestock in a semi-arid area, would a shift from sheep ranching to cattle ranching constitute a loss of system identity? And if the rangeland system developed after a colonial takeover in which the land claims of the original land owners were systematically denied, as has been the case in many of the semi-arid areas of southern Africa, how should the ethical ambiguity over the 'correct' system definition be dealt with? Researchers and stakeholders often make poorly-informed or naïve judgements about what is 'right' or 'wrong' within a particular system, importing their own beliefs and value systems without adequate consideration of those of local communities, and leading in many cases to failures of conservation action (Batterbury & Bebbington, 1999). For example, the myth of wild nature has led to the exclusion of people from many African protected areas that must historically have constituted important resources for local communities (e.g., see discussion by O'Flaherty, 2003). Researchers who wish to find win-win solutions (such as conserving endangered species while improving local quality of life) in complex systems ignore these kinds of ethical issues, and the related political discourse around marginalisation and power, at their peril (Robbins, 2004).

Third, system boundaries are often fuzzy and changes in core aspects of a system may be more a question of degree than an absolute. While extremes are easily recognizable, even a relatively well-defined threshold can be subject to significant uncertainties when it is applied as an identity criterion. For example, elephant at densities in excess of 0.5 animals/km^2 are thought to gradually convert woodland to grassland (Cumming et al., 1997). However, elephant impacts may occur over 50–100 year time periods and are contingent on the covariance between elephant populations, fire frequency and distribution, and longer-term variations in rainfall. Is a failure to detect a significant biological response at densities over 0.5 animals/km^2 a consequence of the time delay between stimulus and response; a reflection on the inadequacy of the science underpinning the quantification of the threshold; or an indication that the environment is now, due to climate or food web change, more resilient to elephant impacts than it was? It is important to realise that there are no simple answers to most of these questions; uncertainty and ambiguity reflect the realities of working in, and on, complex systems (Ludwig, 2001).

Having established what constitutes a complex system, and having mentioned some of the baggage carried by the concept of a complex system, it is now possible to tackle definitions of resilience. This book is focused on understanding spatial aspects of resilience. Spatial resilience is a sub-set of the broader topic of resilience. Resilience has proved a slippery concept, particularly in regard to operationalisation and quantification, because of its multifaceted nature. It was originally defined as the time taken for a system to return to an equilibrium point following a shock or perturbation, with the less widely used term 'resistance' capturing the difficulty of pushing it away from equilibrium (Holling, 1973; see also Neubert & Caswell, 1997; Pimm, 1984). The older use of resilience has fallen out of fashion (although not entirely so) with the demise of equilibrium and climax concepts in ecology, and more recent usages emphasize resilience as an emergent property of a system rather than as a measure of return time.

I generally keep two definitions in mind when I think about resilience. The first is provided by Steve Carpenter and co-authors (2001). It is a three-pronged definition which suggests that resilience consists of (1) the amount of disturbance that a system can absorb while still remaining within the same state or domain of attraction; (2) the degree to which the system is capable of self-organization (versus lack of organization or organization forced by external factors); and (3) the degree to which the system can build and increase its capacity for learning and adaptation.

The second definition comes from my own work with the philosopher John Collier on system identity (Cumming & Collier, 2005). If we think of a complex system as an individual, it only remains the same system for as long as it has a consistent identity. Identity derives from the maintenance of key components and relationships, and the continuity of these through time. If resilience is low, identity may be lost; and correspondingly, if identity is lost, we can conclude that resilience was low. Resilience can thus be operationalized by quantifying identity and assessing the potential for changes in identity. This approach is discussed in considerably more detail, and fleshed out using an example from the Amazon basin, in Cumming et al. (2005).

It is important to understand that these two definitions of resilience are not in conflict. Both suggest similar approaches for the quantification and analysis of resilience. I have found that a focus on identity may make some aspects of resilience easier to define and quantify in real-world SESs, partly because it helps with the problem of selecting a small subset of variables to work with. A focus on identity also has the advantage that it makes the subjectivity of scientific analysis more obvious. For instance, in a workshop setting, people who are hesitant to describe alternate social-ecological states may be more willing to suggest thresholds that would constitute a loss of social-ecological identity. In other cases, focusing directly on regimes and state shifts may be a more productive approach to quantifying resilience (e.g., when developing dynamic simulation models). It thus makes sense to work with the definition of resilience that is most useful when applied to the problem under analysis.

At this stage I should make it clear, if it is not already, that many researchers use the term ‘resilience’ as shorthand for a number of closely related concepts. Resilience itself is a concept, not a hypothesis; it is not refutable. Its value depends on its utility and if it ultimately turns out to lack utility, it should be discarded in favour of a more useful term. For the moment, however, it is a convenient general concept that captures something important about the ability of a complex system to persist. There is a raft of other ‘competing’ terms that mean virtually the same thing at a similar level of generality. Examples include vulnerability, sustainability, fragility, and robustness (e.g., Adger, 2006; Adger & Jordan, 2009; Carlson & Doyle, 2002; Levin & Lubchenco, 2008; Montoya, Pimm, & Sole, 2006). Some scientists have tried to delineate minor differences between these different terms. In my opinion such differences are more reflective of differences in the ways that different research groupings have approached the same problem than of fundamental differences in the nature of the problem being addressed. In other words, they offer parallel streams rather than solutions to different problems. As a result I have lumped them, throughout this book, under the general banner of resilience (except for the few instances where finer distinctions matter). Some definitions of relevant terms are offered in Table 2.1.

Table 2.1 Definitions of some of the specialised terms most frequently used in studies of social-ecological systems. Modified from Cumming (2011). In addition to the references in the table, note that the discussion on stability by Grimm et al. (1992) offers a thought-provoking analysis of common usages of stability-related terms

Concept	Definition
System (Cumming & Collier, 2005)	A cohesive entity consisting of key elements, interactions, and a local environment; must show spatiotemporal continuity
Asymmetries (Cumming, Barnes, & Southworth, 2008)	Systematic variation in system components that can provide the impetus for a particular process to occur, and/or alter system dynamics in important ways. For example, asymmetries in land tenure as measured by the GINI index can lead to conflict; stream systems change predictably down environmental gradients; and selective intraguild predation can create asymmetries in food web dynamics
Network (Janssen et al., 2006; Newman, 2003)	A representation of an SES that uses graph theory to portray SES dynamics as a set of nodes and edges. Network analysis offers a powerful way of addressing relationships that are not easy to quantify using standard statistics (e.g., trust, social capital, and pathogen transmission pathways)
Regime, regime shift (Carpenter, 2003; Scheffer & Carpenter, 2003)	A locally stable or self-reinforcing set of conditions that cause a system to vary around a local attractor; the dominant set of drivers and feedbacks that lead to system behaviour; a 'basin of attraction'. For ecosystems, a regime shift has been defined as 'a rapid modification of ecosystem organization and dynamics, with prolonged consequences' (Carpenter, 2003, chap. 1).
Threshold (Scheffer & Carpenter, 2003; Scheffer, 2009)	In non-linear relationships, the point at which a function (or a rate) changes sign; in state space, the location at which a system tends towards an alternative local equilibrium or new attractor; the combination of variables under which a system enters a new regime
Resilience (Carpenter, Walker, Anderies, & Abel, 2001; Cumming et al., 2005; Holling, 1973, 1986)	There are at least two complementary current definitions of resilience (as used in the study of SESs). Carpenter et al. (2001) define resilience as consisting of (i) the amount of change that a system can undergo and still maintain the same controls on function and structure; (ii) the system's ability to self-organize; and (iii) the degree to which the system is capable of learning and adaptation. Second, based on Cumming et al. (2005) social-ecological system can be defined as consisting of essential actors, components, and interactions. System identity consists of maintaining these elements through space and time. Resilience can thus be redefined as the ability of the system to maintain its identity in the face of internal change and external perturbations. Various rephrasings of these definitions occur in the recent literature (e.g., Levin & Lubchenco, 2008, reiterate the definition offered by Carpenter et al., 2001)

Table 2.1 (continued)

Concept	Definition
Robustness (Levin & Lubchenco, 2008)	Gunderson (2000) unintentionally captures some of the problems with terminology in SES theory when he states that 'Adaptive capacity is described as system robustness to changes in resilience'. Anderies, Janssen, and Ostrom (2004) cite an engineering definition (Carlson & Doyle, 2002) focusing on 'maintenance of system performance either when subjected to external, unpredictable perturbations, or when there is uncertainty about the values of internal design parameters'. Levin and Lubchenco (2008) equate robustness and resilience, stating that both 'mean much the same thing: the capacity of systems to keep functioning even when disturbed'. Note that maintenance of *function* is a different criterion from maintenance of *identity* (unless identity is defined purely in terms of function, which is not usually the case) and this functional emphasis appears, as best I can tell, to be the primary distinguishing feature of 'robustness'
Vulnerability (Adger, 2006)	Vulnerability is a measure of the extent to which a community, structure, service or geographical area is likely to be damaged or disrupted, on account of its nature or location, by the impact of a particular disaster hazard (OECD Glossary). A more resilience-oriented definition is offered by Adger (2006): 'Vulnerability is the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt'
Sustainable development and sustainability (Norberg & Cumming, 2008)	First introduced to the policy arena by the Brundtland Report (WCED, 1987), which defined sustainable development as development that 'meets the needs of the present generation without compromising the ability of future generations to meet their needs'. It has also been defined as '. . .the goal of fostering adaptive capabilities and creating opportunities' (Holling, 2001). Sustainability has been defined as 'the equitable, ethical, and efficient use of natural resources' (Norberg & Cumming, 2008)
Differentiation, diversification (Levin, 1999)	The process by which system components (or entire systems) differentiate from one another, as occurs by mutation and recombination of genes or via the adaptation of technologies to a local environment. Differentiation is closely allied to what Holland (1995) termed 'tagging'; the creation of some indicator of unique or group identity that facilitates asymmetrical interactions (e.g., mate choice via quality indicators) and/or aggregation (e.g., school uniforms)
Selection (Levin, 1999)	The differential removal of elements from a system. Natural selection (Darwin, 1859) is one kind of selective process
Adaptation, Adaptive Capacity (Levin, 1999)	The improvement of fit between a system component or entire system and its environment. In evolutionary biology adaptation is considered to be a passive process, in the sense that adaptation occurs through the action of selection on diversity. In social systems a form of active adaptation, though decision making and proactive responses to environmental change, may be possible.

Table 2.1 (continued)

Concept	Definition
	The ability of systems to maintain their identity while responding to environmental change is often termed 'adaptive capacity'
Transformation and Transformability (Walker, Holling, Carpenter, & Kinzig, 2004)	A systemic change that alters not only the system's properties but also its state space. Old system models no longer apply. Can be equated to adopting a new identity (Cumming & Collier, 2005), as it usually involves losing or significantly modifying key components or relationships of the preceding system. For example, if the climate changes and a forest self-organizes such that its canopy species composition copes more effectively with drier summers, that would be adaptation; if it is gradually replaced by grassland, that would be transformation
Information processing (Anderies & Norberg, 2008)	The step that occurs between stimulus and response. It may be self-contained (as in the human brain), or dispersed (as in the formulation of international responses to terrorism). In SES theory, information processing relates closely to 'response capacity' (the ability of a system to respond to environmental change) and is seen as a component of resilience
Self-organization (Holland, 1994)	The process by which a system or community modifies its own internal structures and behaviours, often in response to internal growth and/or external change
Succession (Pickett, Collins, & Armesto, 1987)	A process of sequential replacement of one community by another. A classical example would be the gradual colonisation of an abandoned patch of farmland by grasses, then shrubs, and ultimately trees. Succession provides the basis of the adaptive cycle, which is discussed under a later section on models. Note that succession is also used in sociology to indicate sequential change (e.g., Lee & Wood, 1991, discuss white-to-black demographic shifts in 58 cities)
Aggregation (Holland, 1994)	The emergence of complex large-scale behaviours from the aggregate interactions of less complex or smaller-scale agents, as occurs in an ant colony or a political party. Aggregation also brings in the idea of building blocks, smaller pieces out of which larger or more complex systems can be built. Building blocks in complex systems include such things as genes, quarks, and the notes that make up music
Compartmentalization and Modularity (Levin & Lubchenco, 2008; Simon, 1962)	First explored and illustrated by Nobel prize-winning economist Herbert Simon (1962). Levin and Lubchenco (2008) offer a clear, concise definition: 'Modularity refers to the compartmentalization of the system in space, in time, or in organizational structure. . . [it] confers robustness by locking in gains and compartmentalizing disturbances'. Compartments in this context are subsystems in which interactions between elements are stronger than their interactions with system elements outside the compartment. For example, plants and their specialist pollinators may represent a compartment within a food web if predation pressure by birds on the pollinators and by herbivores on the plants is relatively low

I should also highlight the fact that ‘resilience’ is not always a good thing. Systems may become locked in to regimes that are undesirable from a human perspective; in these instances, achieving positive system change may be impossible without reducing the resilience of the current state. For example, poverty can create a resilient regime for a household. Without capital, it is hard to generate capital and attain a higher quality of life. Interventions to end the ‘poverty trap’ focus on reducing the resilience of the ‘poor’ state through such actions as providing credit facilities (Yunnus, 1998).

Before focusing explicitly on spatial resilience, there are a few other complex systems theory terms that merit discussion. These include higher-order or emergent properties, feedbacks, thresholds, and alternative stable states.

Higher-Order or Emergent System Properties

Complex systems can be described by the components from which they are constituted and the relationships between those components. Such descriptions are essentially reductionist. Alternative, more holistic ways of describing complex systems also exist. These approaches attempt to capture what might be termed higher-order or emergent properties of complex systems. Emergent properties arise from a combination of system components and relationships; they often can not be predicted solely from studying the behaviour of individual components. The human brain, in which thought emerges from interacting neurons, is a good example of a system with emergent properties. In ecology, Charles Elton’s trophic pyramid (Elton, 1927) can be considered an emergent property of an ecosystem. The loss of energy between each level of the trophic pyramid is the mechanism which explains why consumers are scarcer than producers. The second law of thermodynamics thus explains an emergent property of ecosystems, that of system self-organization by feeding guild.

Descriptions of emergent system properties include many terms that we find useful but that can be surprisingly hard to operationalise and quantify. Defining what it means to be alive, for instance, is non-trivial. Examples of emergent properties in SESs include sustainability, function, vulnerability, transformability, and resilience. All of these system properties arise from the number and nature of system components, their interactions with one another and their external environment, and their ability to process information and respond to internal or external change through action, adaptation, or learning. Note, however, that the fact that emergent properties arise from lower-level mechanisms does not mean that reductionist approaches will necessarily lead to understanding complex systems; as Gell-Mann (1992) has argued, ‘. . .it is necessary to look at the whole system, even if that means taking a crude look, and then allow possible simplifications to emerge from the work’.

Feedbacks, Thresholds, and Alternative Stable States

Feedbacks, or feedback loops, refer to situations in which an effect influences its cause. They can be divided into two categories: negative or dampening feedbacks, which push a system towards equilibirum; and positive or amplifying feedbacks, which push it away from equilibrium. The human body provides obvious examples of both. Sweating is a negative feedback that makes a warm body cooler, while hyperthermia is a positive (and dangerous) feedback that makes a warm body warmer. In addition, some complex systems appear to exist by remaining far from equilibrium; decreases in entropy run counter to the laws of thermodynamics and can be thought of as non-equilibrial events (Kay & Boyle, 2008).

A *spatial* feedback in its simplest form involves an interaction (whether dampening or amplifying) between A and B, where A and B are in two different locations. For example, A might represent a market and B a lake. If the market is far from the lake, people using the market may be unaware of declines in fish stocks, the dampening feeback from stock to buyer will be weaker, and over-fishing to meet unregulated demand may be more likely (Levin, 1999).

Thresholds are closely related to feedbacks because negative feedbacks tend to move systems away from a threshold, while positive feedbacks push them towards one (in the heating example, overheating the human body can result in a breakdown of other systemic functions and eventually in death). Thresholds indicate the point at which a system shifts, or flips, from one state to another (Walker & Meyers, 2004). They often arise as a consequence of non-linearities within a system (Scheffer, 2009). Alternative stable states are defined as locally stable because the system is kept in a particular state by a set of feedbacks that provide some form of local equilibrium; non-linearities in the responses of key system variables to changes in other variables can result in the crossing of a threshold, beyond which the dynamics of interactions between system components become fundamentally different (Box 2.1).

Box 2.1 Thresholds, Feedbacks, and Alternate Stable States

Social-ecological systems can be viewed as *walking* through *state space*. *State space* is a multi-dimensional continuum that is defined by the values of key parameters; it can be visualized as an area or a volume. *Walking* implies that each successive location of the system in state space is a function of the previous location plus subsequent movement. Some areas of state space are *attractors*, combinations of parameter values to which the system tends to move; other areas may be completely untenable by a given system. For example, imagine a simple case involving the two variables rainfall and temperature and a 'system' defined as a grasshopper population. If the grasshoppers have a typical response curve to environmental variation, they will favour places that experience mid-range temperatures and mid-range rainfall. They may also be able to survive in a far warmer area if the rainfall is high. However, areas of the climatic state space that are cold and dry, or that freeze in the winter, will be uninhabitable. If environmental conditions at any one time determine the reproductive rate of the population, *r*, then the magnitude of *r* for each possible rainfall-temperature combination provides a three-dimensional view of state space. Note that the attractor in Fig. 2.1 is depicted as being higher, rather than lower, in the landscape (unlike the ball-and-cup metaphor).

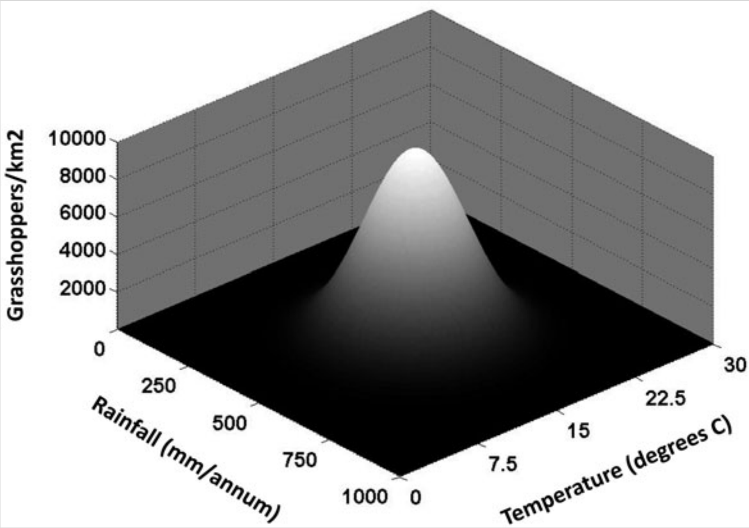

Fig. 2.1 Areas of state space for a hypothetical grasshopper population. The x and y axes are defined by rainfall and temperature; the vertical (z) axis shows potential population size per km^2 under each rainfall-temperature combination

In a system with alternate stable states, state space can still be thought of as being defined by the parameters that it would be necessary to include in a model of the system. A good example of a system with two alternative stable states is a shallow lake (Carpenter, 2003). Each state is reinforced by a set of stabilising feedbacks – one of the hallmarks of a complex, nonlinear system. Shallow lakes can exist in a clear water (oligotrophic) state or a turbid (eutrophic) state. Turbid lakes are great for some animals, such as dabbling ducks like the Cape Shoveller *Anas smithii*, but have lower human values for swimming, fishing, and drinking. The primary driver of shifts between these two states is phosphorus, which is a limiting nutrient in aquatic environments.

Even at relatively high phosphorus loads, lake ecosystems can keep the water clear. Clear water is maintained by the presence of macrophytes (big plants, such as water lilies and reeds) that remove nutrients from the water, inhibit the growth of plankton, and stabilise sediments. Macrophytes also provide refugia for zooplankton from fish predation, and zooplankton consume phytoplankton. By contrast, turbid water is maintained by high levels of plankton, which inhibit macrophyte growth by reducing light penetration through the water column; high levels of sediment in the water, which are enhanced by reductions in macrophytes together with the stirring action of bottom-feeding fish such as carp and by winds and storms; and predation by planktivorous fish on zooplankton (Fig. 2.2).

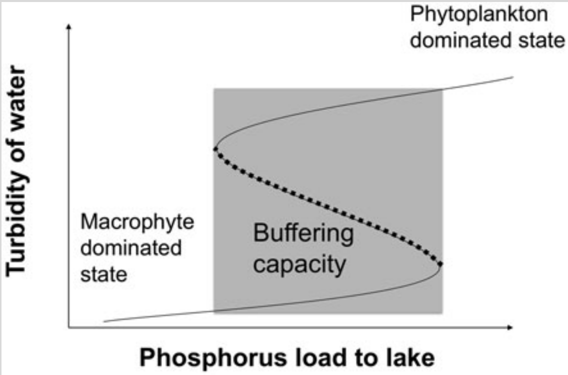

Fig. 2.2 Sketch of the relationship between phosphorus load and turbidity. In the *grey* zone, in which the ecosystem can buffer the water against changes in phosphorus levels, the lake could be either turbid or clear

One of the important consequences of ecological buffering for the management of lake water quality is that the phosphorus-defined threshold can be crossed without any obvious change in water quality. Lakes in this situation are like a boulder poised on the edge of a cliff; with only a small push, such as a storm that stirs up the sediments, they can shift quite rapidly from clear to turbid water, or vice-versa. Once in a turbid state, the phosphorus threshold *and the buffering capacity of the turbid state* must be exceeded before the system can return to a clear water state.

In a well-known science fiction novel, ‘The Restaurant at the End of the Universe’, Douglas Adams’s character Pizpot Gargravarr provides an informative summary of a positive economic feedback in action on the planet Frogstar B: ‘Many years ago this was a thriving, happy planet – people, cities, shops, a normal world. Except that on the high streets of these cities there were slightly more shoe shops than one might have thought necessary. And slowly, insidiously, the numbers of these shoe shops were increasing. It’s a well-known economic phenomenon but tragic to see it in operation, for the more shoe shops there were, the more shoes they had to make and the worse and more unwearable they became. And the worse they were to wear, the more people had to buy to keep themselves shod, and the more the shops proliferated, until the economy of the place passed what I believe is termed the Shoe Event Horizon, and it became no longer economically possible to build anything other than shoe shops. Result – collapse, ruin and famine. Most of the population died out. Those few who had the right kind of genetic instability mutated into birds – you've seen one of them – who cursed their feet, cursed the ground, and vowed that none of them should walk on it again.' (Adams, 1980, p. 61).

This concludes my somewhat selective summary of key terminology from complex systems theory. These ideas and terms provide the building blocks for understanding the next section: what is spatial resilience?

What Is Spatial Resilience?

To the best of my knowledge, the term 'spatial resilience' originated through a series of discussions during Resilience Alliance (http://www.resalliance.org) meetings; no single person can lay claim to it, and it has been used in several different ways in the previously published literature. Nystrom and Folke (2001) provide the first published definition of the term, using it as 'the dynamic capacity to cope with disturbance and avoid thresholds at scales larger than individual ecosystems.' Somewhat confusingly, they also discuss 'spatial sources of resilience'. Peterson (2002) used spatial resilience in a different way, to refer to the resilience of a landscape to change. Obura (2005), citing Nystrom and Folke (2001) and Bengtsson et al. (2003) as his sources, proposed that the concept of spatial resilience was differentiated from that of ecological resilience purely by scale; that is, that spatial resilience extends beyond local boundaries 'to include large-scale functions and processes beyond the boundaries of an ecological unit.'

I favour a somewhat broader definition, and one that I feel better captures the spirit of the discussions that I have had with colleagues on this and related topics over the last decade:

Spatial resilience refers to the ways in which spatial variation in relevant variables, both inside and outside the system of interest, influences (and is influenced by) system resilience across multiple spatial and temporal scales. It has elements that are both internal and external to the system.

The primary internal elements of spatial resilience include the spatial arrangement of system components and interactions; spatially relevant system properties, such as system size, shape, and the number and nature of system boundaries (e.g., hard or soft, and whether temporally variable or fixed over time scales of interest); spatial variation in internal phases, such as successional stage, that influence resilience; and unique system properties that are a function of location in space.

The primary external elements of spatial resilience include context (spatial surroundings, defined at the scale of analysis); connectivity (including spatial *compartmentalization or modularity); and resulting spatial dynamics, such as spatially driven feedbacks and spatial subsidies.*

Both internal and external elements must be considered in relation to other aspects of system resilience, including such things as the number and nature of components and interactions, the ability of the system to undergo change while maintaining its identity, system memory, and the potential inherent in the system for adaptation and learning.

A possible point of confusion in applying this definition is that patterns and pattern-process relationships may themselves be resilient. Note, however, that in thinking about the resilience of a pattern, the system definition is critical. If the system is the entire landscape, pattern resilience is captured by the internal elements of spatial resilience; if multiple systems constitute the pattern, then the resilience of the pattern is captured by external elements (i.e., spatial resilience at broader scales than the system). In either case, pattern resilience is embedded within this definition.

Note also that this definition is couched in terms of complex systems, rather than solely ecological systems; that it acknowledges the relevance of spatial variation in both pattern and process within, around and between complex systems as well as the two-way interaction between a complex system and its environment; and that it is critically dependent on the selection of adequate definitions of the system and of resilience.

The different components of spatial resilience are best elucidated by a series of examples, which I will mostly draw from a South African setting. The city of Cape Town sits within a unique floral kingdom, the fynbos (literally 'fine bush'). One of the reasons why the fynbos is special is because it occurs in sub-Saharan Africa's only winter rainfall region. Different aspects of the spatial resilience of Cape Town and the fynbos biome can be described as follows.

Internal Elements of Resilience

The spatial arrangement of system components and interactions; spatially relevant system properties, such as system size, shape, and the number and nature of system boundaries (e.g., hard or soft, and whether temporally variable or fixed over time scales of interest); spatial variation in internal phases, such as successional stage, that influence resilience; and unique system properties that are a function of location in space.

These variables summarize the fine-scale spatial arrangement of system units and boundaries within a complex system. They include such things as patch size and shape, geometry, alignment, and edge. For example, the difference between ocean and land provides a hard boundary that constrains the expansion of the city of Cape Town in southerly or westerly directions. The layout of roads within Cape Town and the Cape Peninsula is largely a consequence of the domination of city topology by Table Mountain and neighbouring peaks; one of its results is that traffic

Fig. 2.3 View of the Constantiaberg, part of the Table Mountain Range, from a settling pond at the wastewater treatment works at Strandfontein, which sits on the edge of False Bay. One of the city's landfill sites is immediately adjacent to the pond. Strandfontein must historically have been one of the few relatively flat estuaries entering False Bay; even today, the settling ponds remain an important moulting and breeding site for waterbirds. The suburb of Muizenberg is squeezed between the mountains, False Bay, and Strandfontein. Photo: Graeme S. Cumming

congestion is high, resulting in increased pollution and a potential loss of economic productivity as commuters spend long periods sitting in traffic each morning and evening. Similarly, the spatial layout of power supply grids, sewage treatment plants, water supplies, and other public services (e.g., Fig. 2.3) affects the likelihood of different suburbs experiencing failures in service delivery and has an overall influence on the resilience of the city to natural disasters. This aspect of spatial resilience also includes post-disturbance legacies, defined as the things that are left behind after a major perturbation and their location(s) within the system.

Spatial variation in temporal dynamics is important in the Cape in several different ways. The fynbos is a fire-maintained vegetation type that regenerates following fire (e.g., Bond, Midgley, & Woodward, 2003; Brown, Jamieson, & Botha, 1994; Keeley, Keeley, & Bond, 1999). However, over-frequent fire can be as damaging as fire suppression. Hot fires can cause substantial property loss and often become a problem during the middle of summer (Fig. 2.4). The relative successional phases and spatial arrangement of different patches of fynbos, which are

Fig. 2.4 The sun shines dimly through a cloud of smoke rising from a fire on the far side of Devil's Peak, Cape Town. Although fynbos is fire-maintained, too-frequent fires can lead to fynbos mortality. Photograph by Graeme S. Cumming

partly contingent on when they were last burned, have implications for recolonisation and regeneration rates of fynbos vegetation and hence of the ecosystem services, such as water purification and tourist appeal, that they provide. In the social realm, a parallel arises in the housing market. Cape Town has been expanding at its periphery for many years; expansion tends to be driven by a demand for high-density, low-cost housing, while the development of a larger middle class in South Africa is gradually increasing the demand for middle-income housing and a slow process of gentrification of formerly low-class neighbourhoods. The gradual shift from poor to middle-class that has occurred in many neighbourhoods has a clearly defined spatial pattern that in turn has relevance for a range of social issues, such as security, service provision, education, and poverty (e.g., see Lemanski & Saff, 2010; Lemon & Battersby-Lennard, 2009; Samara, 2010; Vanderschuren & Galaria, 2003).

'Unique system properties that are a function of space' captures the idea that locations differ from one another in important ways (Levin, 1976). Location-based spatial variation may be unique or relative to a gradient and forms an integral part of the complex system of interest. An example of the location-based properties of the fynbos biome is that the southern and western Cape of South Africa contain a series of mountain ranges in close proximity to the sea. The mountains dominate local weather patterns (for example, the east-facing suburb of Newlands, in Cape Town, receives more rain than average; and the wetter side of the mountain supports an endemic species of frog) as well as providing a huge range of elevation gradients and potential refugia for fynbos species.

The primary external elements of system resilience include context (spatial surroundings, defined at the scale of analysis); connectivity (including spatial compartmentalization or modularity); and resulting spatial dynamics, such as spatially driven feedbacks and spatial subsidies.

Context refers to what surrounds the system. The fynbos is located roughly 34–36° south of the equator, which determines the amount of energy that it receives at different times of year, and it is bordered on the west by the Atlantic ocean. The Atlantic off the South African coast is a cold ocean, with currents coming up from Antarctica. To the north of the fynbos lie biomes composed of semi-desert. Context has high relevance for fynbos resilience because it determines local climate and makes the fynbos the only winter rainfall area in mainland Africa south of the equator.

Connectivity refers to linkages to other actually or potentially interacting units. It also captures the potential for subdivisions of the system into semi-autonomous compartments. The fynbos, for example, is far enough from other similar mediterranean or maquis systems that it has no natural connectivity to them, and hence no long-term history of an exchange of plant species, despite ecological convergence (Cowling & Lamont, 1998; Cowling, Macdonald, & Simmons, 1996). It is, however, connected to a variety of other biomes around the world through human transport systems; and this has in turn created a significant problem with invasive species entering the fynbos (Cowling et al., 1996; Richardson & van Wilgen, 2004). Lowland fynbos relict patches in urban areas of Cape Town, for example, are currently being threatened by an introduced Australian woody plant, *Acacia saligna* (Dures & Cumming, 2010; Yelenik, Stock, & Richardson, 2004). Connectivity also includes the fact that exchanges of species of birds, mammals and reptiles (amongst others) with adjacent biomes have been possible throughout the history of the fynbos (Hockey, Dean, & Ryan, 2004). In a social context, the history of the colonisation of southern Africa, and hence the future trajectory of social-ecological systems in the Cape, was strongly influenced by the fact that the malaria- and sleeping sickness-free Cape was seen to provide both a provisioning station for ships on voyages to India and a gateway to the mineral resources of southern Africa. The concept of connectivity is an important one in the study of spatial resilience and is dealt with in more detail in Chapters 6, 8 and 9.

Spatial feedbacks are feedbacks that occur between spatial variation and systemic processes (e.g., migration, settlement, competition, herbivory). For example, lowland fynbos is highly diverse and highly endangered. One of the reasons for its endangerment has been the settlement of the Cape flats by high-density shanty towns. Many of the decisions made under apartheid governments, such as the zonation of suburbs for different race groups and the implementation of the group areas act, resulted in the marginalisation of these communities. As settlements became established, and as they became areas of resistance to apartheid and the rule of law that were left largely unpoliced, development occurred in an unplanned manner and further entry of people occurred without restriction. Discriminatory policies thus created a self-reinforcing feedback between settlement, law enforcement, and property prices that continues today (e.g., Samara, 2010).

Spatial subsidies are external inputs that are (a) important components of the study system and (b) in social-ecological systems, typically come at some cost to the system providing the subsidy (Polis, Anderson, & Holt, 1997; Polis, Power, & Huxel, 2004). Subsidies can involve spatial and/or temporal separation. The resilience of a social-ecological system can be dependent on subsidies in at least two ways; subsidies that it is expected to provide, and subsidies that it relies on. For example, communities living in the upper catchments of river systems subsidise downstream cities if they incur opportunity costs through the provision of clean water. More specifically, for instance, restrictions currently in place on forestry activities in stream catchments in South Africa prevent local communities and forestry companies from planting timber in upland riparian areas because water loss via evapotranspiration would reduce water flow to the river basin, affecting the subsidy that downstream communities depend on (e.g., see Le Maitre et al., 2002; Scott & Lesch, 1997). Similarly, industry in Cape Town is dependent on the immigration of labour from the surrounding countryside; and the city relies on food imports from the agricultural areas that surround it. In the biophysical system, mountain fynbos plant communities appear to depend on aerosol transport of dust (and more recently, combusted petrol particles) for nutrients (Soderberg & Compton, 2007). These interdependencies in space and time are important to long-term resilience and also offer an avenue for approaching questions of spatial separation and scale from within a resilience framework. Lastly, when subsidies are provided by organisms or other kinds of dispersing agent, the properties of the agents themselves may be important components of spatial resilience. For example, if fish are viewed as vectors of nitrogen (e.g., Schindler, Leavitt, Brock, Johnson, & Quay, 2005), the fact that adult salmon die (after laying their eggs) in sufficient numbers to significantly enrich the environment in which their offspring will grow means that juvenile survivorship is enhanced.

Scale is a central issue in quantifying all of these aspects of spatial resilience, and consideration of scale introduces additional considerations for theory, analysis, and the interpretation of research findings (Cumming & Norberg, 2008). Such considerations include the illusion of stability; the role of fine- and broad-scale drivers; and the interplay of pattern-process interactions between and within scales. Patterns and processes at different scales may reinforce or undermine one another if they reduce or enhance the potential for change at other scales, and the nature of the match between system function and system composition (i.e., the number and nature of system components) can be critically scale-dependent. For example, as cities grow larger, their 'footprint' (here meaning the extensive systems of food production and distribution, waste removal, and labour on which they depend) increases rapidly (Luck, Jenerette, Wu, & Grimm, 2001; Wackernagel et al., 2002); the larger the footprint, the greater the city's reliance on external production and absorption, and the less resilient it becomes to sudden changes in supply and demand systems. Cities may cease to function normally if the costs of transporting food suddenly become too high in relation to the costs of producing the food in the first place and the willingness or ability of consumers to pay for it. In Robert Mugabe's Zimbabwe, economic mismanagement, uncertainties over land tenure, and the aggressive removal of farmers from agricultural land set in train a series of knock-on effects that included reductions in food production, increases in transport costs, and a reduction in expendable income. The end result was food insecurity, outbreaks of communicable diseases such as Cholera, and a collapse of many basic services (water, electricity, waste removal) in Zimbabwe's capital city of Harare. At the time of writing, one of the most noticeable features of modern Harare (i.e., relative to the city that I lived in through the 1970s and 1980s) is the use of nearly every suburban commonage and vlei (seasonal marsh) for maize cultivation. It is also important to note that the resilience of an institution or organization may differ from the resilience of the function that it is expected to perform; for example, many government departments in Zimbabwe have remained staffed (with the majority of their now tiny budget being spent on salaries) while providing few or none of the services that they were originally created to provide.

Spatial resilience is a dynamic concept that applies not only to current system properties, but also to understanding social-ecological change. In most landscapes, resources are distributed patchily in both space and time. Local variations in variables that influence the frequencies and magnitudes of disturbance (such as fuel accumulation, slope, or elevation) can affect the local disturbance regime (e.g., Franklin & Forman, 1987; Hunter, 1993; Nepstad et al., 2001; Turner, Gardner, & O'Neill, 2001). At broader scales, location can be of extreme importance because disturbances seldom act homogeneously over large areas. The spatial properties of the environment can influence the trajectory of change within a landscape (Iverson, 1988; Mertens & Lambin, 2000), the kind and magnitude of social-ecological transformation (e.g., Gonzalez, 2001), the ability of the system to respond and adapt to transformative processes as they occur, and the regeneration of post-disturbance landscapes (Bengtsson et al., 2003; Lugo & Helmer, 2004). For example, self-organizing processes are often strongly dependent on feedbacks between system components (Levin, 1999). Tight feedbacks, such as those that arise when a predator continually monitors its prey source, lead more rapidly to local adaptation because dependencies are obvious and selective pressures are strong. By contrast, if a consumer purchases food in a store that in turn receives goods from many miles away, the feedback from resource to consumer is looser and overexploitation of resources becomes more likely. In general, feedbacks are tighter at smaller scales and between system components that occur near to one another in space (Levin, 1992); although this generality may not hold if the consumer base is large and transient, and a resource is perceived as plentiful (Fig. 2.5). The spatial arrangement of a social-ecological system will be central to its ability to cope with change. Relevant patterns in human-dominated systems include the spatial locations of centers of supply and demand, the spatial arrangement of different habitat types, and the number, magnitude and arrangement of infrastructure connections. Spatial variation in the magnitudes and fluxes of available resources is also central to system-wide transformation; communities in low-resource areas typically have fewer options, and regeneration of ecosystems will be slower in less productive locations.

Fig. 2.5 A colony of African Penguins shelters on a beach on Dassen Island, off the coast of the Western Cape. Swift terns, Cape and Hartlaub's gulls, and African oystercatchers are intermingled with the penguins. Dassen Island once hosted a breeding colony of thousands of penguins. Unsustainable exploitation of the island for guano (bird droppings, used for fertiliser), overharvesting of penguin eggs, and competition between penguins and offshore fisheries have since resulted in a severe population decline. Photograph by Graeme S. Cumming

One of the goals of attempting to analyse and understand spatial resilience is to be able to develop and apply general principles that will allow us to understand how and when spatial aspects of resilience at different scales influence system resilience. I will argue throughout this book that in many cases, aspects of spatial resilience that have been ignored in individual analyses may explain why so few generalities have emerged from resilience-oriented case studies.

In this chapter I have presented a set of fundamental concepts, introduced a comprehensive definition of spatial resilience, and illustrated the elements of spatial resilience using examples from the city of Cape Town. In the next chapter I turn to the question of how to operationalise the definition of spatial resilience in the context of the analysis of SESs.

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Chapter 3
A Theoretical Framework for the Analysis of Spatial Resilience

Introduction

The first two chapters have hopefully laid sufficient ground work for me to make an intelligible attack on the central themes of this book: the topic of spatial resilience and the ways in which it can be analysed in social-ecological systems (SESs). While clarity on terminology and concepts is important, as discussed in the preceding chapters, science advances through the interaction between new ways of thinking about the world and the testing of those ideas against reality (Hull, 1988). For genuine progress to be made, clarity must be achieved on the goals of scientific enquiry and the ways in which different ideas relate to one another. Any new set of ideas thus needs to be placed in the broader context of existing theory. Attention must also be paid to the questions of how the objects of study should be described and how theory can be tested empirically.

In this chapter I develop a theoretical framework for the analysis of spatial resilience in social-ecological systems. This involves building up an argument step by step. I start by discussing the questions of what theory is and how ideas about the resilience of social-ecological systems constitute theory. I then consider theoretical frameworks for the study of resilience before focusing more explicitly on *spatial* resilience. The chapter concludes with a discussion of some of the ways in which we can link theory to the empirical analysis of spatial resilience.

What Is Theory?

According to Pickett, Jones, and Kolasa (2007), a scientific theory is "a system of conceptual constructs that organizes and explains the observable phenomena in a stated domain of interest". The components of the theory depend on one another and exhibit a level of cohesion. The different components of a theory together define the set of methods (methodology) that will be brought to bear on the problem.

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Scientific theory represents an ever-changing dialogue between reality, observation, and concept; as theories grow and mature, different methods and constructs become necessary.

The primary components of any scientific theory include domain, assumptions, concepts, definitions, facts, confirmed generalizations, laws, models, translation modes, hypotheses, and frameworks (Pickett et al., 2007). These different elements of theory build on one another in a logical sequence. For example, the domain provides criteria for determining the relevance of an idea to a given field; and assumptions and definitions provide the building blocks that are subsequently used to explain ideas about cause and effect.

Social-ecological systems are complex systems that incorporate human societies (including economies), ecosystems, and their interactions. Studies of SESs, in contrast to studies of ecosystems or societies, are those in which the definition of the research question recognizes the fact that human communities both depend on natural resources and modify those resources through their actions. The feedback from human action to the environment, and from the environment back to human action, lies at the heart of SES theory and represents its primary domain. In addition, SES research views humans and human societies as elements of an ecosystem (Waltner-Toews, Kay, & Lister, 2008) rather than as external to ecosystems or independent of them.

The spatial and temporal scope of the phenomena addressed by SES theory ranges from local to global and over time scales that are relevant to human usage of natural resources. The scope of SES theory includes historical or archeological questions, such as why Mayan society collapsed (e.g., Haug et al., 2003) or how some irrigation systems persisted for hundreds of years (e.g., Falvo, 2000; Lansing & Kremer, 1993); questions that incorporate big extents, such as how excessive hunting of great whales impacts marine ecosystems (Springer et al., 2003) or how global influences drive land use and land cover change (Lambin, Geist, & Lepers, 2003); and a huge variety of more localised and shorter-term questions relating to the interactions of people and ecosystems.

Given its immense scope, and the huge number of different circumstances in which it is expected to be relevant, SES theory has a challenging task. Despite rapid recent progress, the integration of case studies under a single conceptual framework and the formulation of a solid core of relevant theory (i.e., that explains previous findings and drives further empirical work) remain major challenges (Cumming, in review). If the study of SESs is to achieve its full potential, we need to understand how, for example, a case study of forest harvesting in the Amazon can contribute usefully towards developing or testing theoretical principles that are also relevant to understanding fishery dynamics off the South African coast. Some of these kinds of integrative theoretical development are already present in some areas of research, such as Ostrom's (e.g., 2003, 2007) analyses of common property systems. The challenge in many cases is to establish the level of factual evidence that is needed to support or refute a particular generality, without losing the thread of the problem in a series of case-specific details.

Theoretical Frameworks for Analysing Social-Ecological Systems

A framework is an underlying set of ideas that serves to connect different concepts and make sense of them (Pickett et al., 2007). A number of general frameworks for the study of SESs have already been proposed (Table 3.1). Despite the existence of some very useful frameworks, none is fully sufficient as a theoretical basis for research on SESs. This is partly due to a profound philosophical problem. Most theoretical frameworks in science deal only with phenomenological questions and ignore research methods; they are goal-oriented in the sense that they do not offer specific recommendations about how research should be conducted. By contrast, when working with or on other people, *process matters*; the way in which research involving people is undertaken can have a huge impact on the results of that research (Adger & Jordan, 2009). A full theoretical framework for the study of SESs will need to address theoretical aspects of both the phenomena of interest *and* the process by which results are obtained.

In this view, the analysis of SESs can itself be considered as a social process that occurs at several different levels. At the broadest level are three different activities: (1) deciding what the problem or focal research question is and who 'owns' it; (2) undertaking research in accordance with accepted best practice; and (3) responding to, or acting on, the results obtained by research. Each of these steps leads to the creation of one or more frameworks or plans; respectively, an issues framework, a research programme that includes a system description and one or more system models, and some form of an action plan, including such things as deliverables and measures of success. Although events in the real world seldom follow a simple, linear progression, we can capture the most important aspects of this view of the study of SESs as involving the formulation and progression of a research question through three different arenas: the problem framing arena, the research arena, and the action arena (Fig. 3.1).

Since complex systems can be viewed in many different "correct" ways, the system description must be undertaken relative to an issues framework (a term borrowed from James Kay's diamond heuristic (Waltner-Toews & Kay, 2005)). The issues framework incorporates aspects of values and priorities, as well as suggestions of future intentionality within the system, as the visions and goals of the community are taken into account (see also Walker et al., 2002). The issues framework may revolve around theoretical or practical questions that science is intended to solve, but it is an important reference point in that it defines the questions, and hence the components and interactions within the system, that are of greatest interest.

The system description simplifies the complexity of the real world to capture key aspects of interest of the study system. It leads on to a second level of analysis in which the focus of scientific investigation narrows to the consideration of two different kinds of problem: the details of a particular case study or case studies as considered within a particular analytical framing of a problem, and the analysis of more general system properties such as resilience and sustainability. This level is

Table 3.1 Brief outline of six different frameworks that have been developed for the study of social-ecological resilience. S, Strengths; W, weaknesses. Note that most of these were not originally developed to act as overarching theoretical frameworks for social-ecological systems; highlighted weaknesses in all cases are directed at their potential to serve a broader role, rather than at the (different) question of whether or not they met their original goals

Framework (Author)	Key features	Strengths and weaknesses
1. Agent-based models (Holland, 1992, 1995)	Lays out seven key elements of complexity theory: four properties (aggregation, nonlinearity, flows, diversity) and three mechanisms (tags, internal models, and building blocks). Takes these elements and constructs an approach (“Echo”, a multi-agent model) to simulating complex adaptive systems. Towards the end, highlights the importance of hierarchies (“two tiers”)	S: Mechanistic and based on a clear set of first principles; highlights many areas for theoretical development; easy to apply to human interactions; strong on models and role of modelling W: Weaker on ecology, heterogeneity, and scale; focuses on understanding fundamentals of clear-cut complex adaptive systems (such as ant colonies and immune systems) but difficult to translate into understanding real-world SESs; connections to other, more recent ideas about SESs unclear
2. Panarchy (Holling, 2001; Holling et al., 2002)	Proposes that social-ecological systems are composed of a series of interconnected adaptive cycles at different scales	S: Creative, original; focused on dynamic aspects of social-ecological change; useful source of insights; offers some essential elements for further elaboration W: Relatively vague, difficult to operationalize; has little to say about some important aspects of social-ecological systems, such as spatial processes; more of a metaphor or an aid to thought than a source of testable hypotheses
3. Resilience Alliance Workbook	Incorporates and expands on ideas about Panarchy, with a focus on opertaionalising ideas about thresholds, regime shifts, and feedbacks. Developed to help find common patterns across different case studies of SESs, through posing a series of questions that have relevance to most SESs	S: Useful synthesis of relevant ideas; offers a way of working through a particular case-study; includes many important concepts; completion of workbook for multiple cases provides a way of developing further generalities and hypotheses W: Lacks a unified theoretical basis; does not immediately suggest general hypotheses; concepts can be difficult to operationalise

Table 3.1 (continued)

Framework (Author)	Key features	Strengths and weaknesses
4. Complexity Theory Framework: Asymmetries, Networks, Infomation Processing (Norberg & Cumming, 2008)	Builds on Panarchy and the RA workbook, with many of the same contributors. Considers complex adaptive systems (with a focus on SESs) in terms of three complementary properties: asymmetries, networks, and information processing. Added to these are considerations of history, scale and scaling, and adaptive management. Book chapters deal with different aspects at differing levels of detail	S: Provides a useful way to organize SES-related concepts without rigid compartmentalization along disciplinary lines. General terminology helps create linkages between different disciplinary approaches (e.g., connecting landscape ecology and sociology via asymmetries). Has both theoretical and empirical relevance; links theory and practice; consideration of the same system through each different "lens" can usefully highlight different aspects of the same system W: Probably too broad and not sufficiently mechanistic to act as a general framework for SES theory, although the alternative perspectives on 'what is important' are useful
5. SOHO Framework: Self-Organizing, Holarchic, Open Systems Approach (Kay & Boyle, 2008)	Suggests a basis for self-organization as a consequence of the dissipation of energy. Exergy refers to the quality of energy, particularly its ability to do useful work. Proposes that as systems move further from equilibrium, exergy increases, more dissipative opportunities become available, and more organization emerges. Flows from ecosystems provide exergy that both supports and constrains human society. Assumes hierarchies of structures and processes; focuses on flows, feedbacks, and thresholds. Note that the SOHO framework is considered here as distinct from the problem-oriented AMESH and Diamond frameworks developed by the same group (Waltner-Toews & Kay, 2005)	S: Offers a basis for SESs in thermodynamics and suggests some ways of obtaining a "common currency" of measurement that could be applied across different kinds of system. Meshes nicely with ecosystem ecology, systems ecology, and the work of HT Odum (e.g., Odum, 1983, 1995) W: Probably too abstract and too hard to operationalise to be useful; some key aspects remain vague; focus on exergy fails to translate into the kinds of units – actors, interactions, abiotic conditions – that most natural resource managers and most professional scientists spend their time thinking about

Table 3.1 (continued)

Framework (Author)	Key features	Strengths and weaknesses
6. Sustainability Framework (Ostrom, 2007, 2009)	Divides SESs into four basic interacting entitites (termed 'first-level core subsytems'): resource units, a resource system, a governance system, and users. Decomposes these further into sub-units. Aims to identify relevant variables and provide a common set of variables for organizing comparisons of similar SESs	S: Expresses a well thought-out summary of important variables in SES dynamics; incorporates institutional, governance and policy issues better than other frameworks; provides clear recommendations and predictions; has been developed in combination with empirical studies and hence many examples and well-grounded in fact. In many ways the most obviously 'useful' of the frameworks summarized in this section W: Weaker in relation to ecological aspects of SESs (ecosystem components anthropocentric and simplified); descriptive (correlative) rather than mechanistic, outside of institutional domain; aspects of framework still fragmented in the absence of unifying concepts

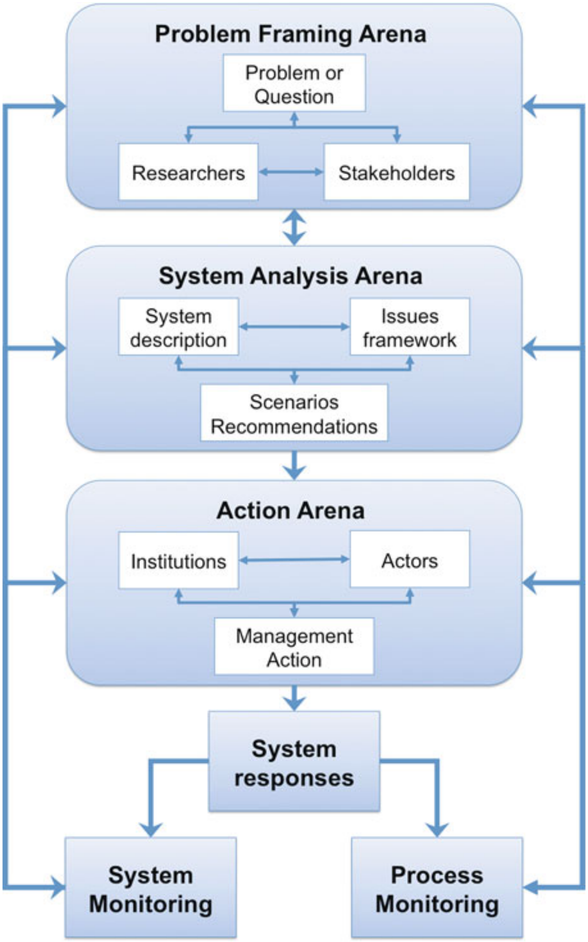

Fig. 3.1 Different arenas through which a typical social-ecological problem must travel before it is resolved. Further details in text

the point at which generalities about SESs are expected to emerge, and conclusions from this stage should in turn influence both the system description and the research process.

Participants in each of the three arenas of Fig. 3.1 may be the same or different. Problem (or question) framing may occur proactively, or in response to a presenting problem situation. Identifying and establishing the nature of a social-ecological problem is typically a dynamic interaction between researchers and the community that is confronted by the problem. Once the problem has been framed, its underlying causes and consequences are analysed in the system analysis arena.

A system description married with a suitable issues framework will lead to the creation of a set of guidelines, recommendations, and/or scenarios. Sometimes the tangible elements of the process end at this point, with its only direct implications occurring through the changes in perspective and mental models that have occurred in workshop participants. Recommendations will remain in a conceptual realm unless they find a champion, an actor of some sort who is willing to push them into an action situation and attempt to implement them. At this point actors will usually have to interact with and possibly create, modify or enforce institutions, such as hunting restrictions or forestry policies, to achieve tangible outcomes. The process by which such engagement with other actors is undertaken has been the subject of a number of existing frameworks, such as the Institutional Analysis and Development (IAD) framework (Gibson, McKean, & Ostrom, 2000; Imperial, 1999) and Soft Systems Analysis (Checkland, 1981, 2009).

If the questions are phrased appropriately and if a genuine attempt is made to integrate political processes and research activities, the eventual outcome of the process of SES research is likely to be a change in system dynamics. Such changes will go undetected unless a monitoring programme is in place. I have labelled the act of monitoring for system changes as "system monitoring". Note that system monitoring should probably occur before, during and after the management process and in ecological, social and economic domains. At a minimum, good baseline data on the pre-intervention state of the system are needed.

The other aspect of monitoring, which should occur as a feedback process at all stages, is that of process monitoring; monitoring how different steps in the process are implemented, how and why particular decisions are made, and how the management process is impacted by system behaviour. The first kind of monitoring is relatively straightforward, but the second is less common; it involves posing and answering such questions as whether a sufficient diversity of perspectives has been represented in workshop situations, whether participatory processes are working, whether workshop participants feel that workshop outcomes reflect their concerns, and so on. These 'touchy-feely' data (as quantitative scientists outside the social sciences might label them) are seldom collected and seldom published, but if collected rigorously, should provide a context for self-assessment, a way of exploring the relationships between the nature of the research process and the success or failure of a given initiative, and ultimately the means to learn. A good example of the power of this kind of analysis comes from an in-depth analysis of the political economy of development aid (Gibson, Andersson, Ostrom, & Shivakumar, 2005). The authors explore the successes and failures of the Swedish development agency, Sida, and reach a deep understanding of problems and solutions in the context of development aid. Data of this sort are time-consuming and painful to collect, but ultimately offer the only way of reconstructing and understanding some of the sociological aspects of the process.

Figure 3.1 implies, deliberately, that the ways in which individual researchers choose to analyse and study SESs, and the impacts of their choices on the eventual conclusions of the study, are just as legitimate an area of study as the (more generally accepted) study of the details of how the system, once formally conceptualised and defined, operates. This point is not intended to endorse constructionist approaches (Burr, 1995), but rather to argue that because of their nature, analyses of SESs must consider the role of the researcher and the local community, and the impact of their respective backgrounds, beliefs and perspectives on the environment in ways that are largely irrelevant in many other disciplines (e.g., Baruah, 2003). Since the same complex system can be viewed in different ways, each of which is technically 'correct', the choice of both problem and analytical approach is to a large degree dictated by the background and comfort zones of the scientist. For example, when confronted with the problem of manging deforestation in Amazonian rainforests, an ecologist might focus on understanding the impacts of edge effects on biodiversity and seek solutions in fire management; while a sociologist might focus on the role of immigration and resettlement schemes as drivers of demand for cattle pasture, and hence for cleared land (e.g., see Armenteras, Rudas, Rodriguez, Sua, & Romero, 2006; Brondizio, Ostrom, & Young, 2009; Fearnside, 1993; Laurance et al., 2002; Nepstad et al., 2001). Amazonian research is fairly well integrated, but if researchers in different disciplines work independently they can easily reach different conclusions about causality and management interventions; although each might be technically correct, each study addresses only a part of the larger problem.

Developing and Working with a System Description

Having acknowledged the biases inherent in the research process, and the need to consider multiple perspectives in formulating a system description, the next step towards a framework for SES analysis is the characterization (description) of the objects of study: social-ecological systems and their dynamics. As spelled out above, this characterization must occur interactively with the issues framework, which defines the questions of interest and helps to focus the analysis on those aspects of the system that are particularly relevant to the problem at hand.

One way to approach the development of a systems description for SESs is to consider what would constitute the minimal elements of such an outline. A minimal framework for SES theory starts with the definition of an SES as a cohesive complex adaptive system with at least three different hierarchical levels (Allen & Starr, 1982; Collier & Hooker, 1999; Collier, 1986; Holling, 2001). These levels exist at different scales and exhibit dynamics at differing speeds that range from fast to slow. The SES is further defined by the presence of components that include elements of social and ecological systems; interactions between components; some form of continuity in space and time; and a degree of overall system coherence that connects the elements of the system into an identifiable entity (Cumming & Collier, 2005). In most cases a set of rules or institutions, both formal (*de jure*) and informal (*de facto*), governs the number and nature of interactions that involve human actors. Ostrom (2007, 2009) provides a good summary of many of these rules and their relevance for SES dynamics. With the possible exception of the global system, SESs will also have an external environment in which they exist; this environment provides perturbations and surprises, as well as inputs from other SESs and locations or actors to which system outputs are sent.

SES theory assumes that all SESs can be described using these basic concepts; and that any SES will have certain properties and exhibit certain kinds of behaviour. Among the expected properties of an SES are the potential for alternate states (Walker & Meyers, 2004); diversity, environmental asymmetries, and the ability to process information; and a degree of connectivity to other SESs and the surrounding environment (Norberg & Cumming, 2008). Examples of expected behaviours include the potential for replication or the addition of new system elements, non-linear relationships between cause and effect, and some form of adaptation or self-organization in response to environmental change (Holland, 1992; Levin, 1999). All SESs can thus be considered to exist along at least three main dimensions (Fig. 3.2).

The first axis (front side of the box in Fig. 3.2) can be described as a structural or inventory axis. It is comprised of elements, namely the SES and its environment (together with input and output functions that connect SES and environment) as perceived and measured at the current time and location by the observer. This axis suggests a range of quantifiable variables (for example, the total amount of phosphorus in the sediments of a lake, the total number of species present, or the different tenure categories and land uses present in the system). Depending partly on the question, aspects of other analytical frameworks will offer useful ways of thinking about the system description. For example, the number and nature of interactions within the SES are influenced by institutions (rules, norms, laws, etc.) and organizations, creating a clear connection here to the Sustainability Framework (Ostrom, 2007, 2009) which suggests a well-defined set of variables for consideration as components and interactions. Similarly, agent-based models (Holland (1994); a good example of a recent implementation is given in Bousquet et al. (2007)) offer ways of simulating and exploring how networks of interactions develop over time and what their relevance is for spatial pattern; and the Panarchy Framework

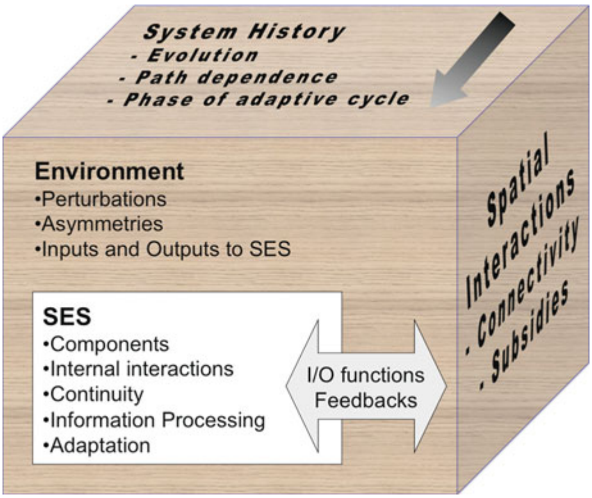

Fig. 3.2 Description of a complex system along three main axes: spatial, temporal, and structural. Further details in text

(Holling, 2001) highlights the relevance of important aspects of cross-scale dynamics. Note that some temporal and spatial elements (such as adaptation and perturbations) have been included in this axis for the sake of clarity.

The second axis of Fig. 3.2 concerns spatial variation, hierarchical system arrangements in space, and spatial interactions and connections at multiple scales. Spatial variation is relevant over at least three scales; internally within the system ("local"), and externally at the scale of the immediate context ("regional"), and the larger ("global") set of social-ecological systems that impact the SES. Outside the boundaries of the focal SES, the primary spatial elements of interest include context (spatial surroundings, defined at the scale of analysis); connectivity; and spatial dynamics that are driven via connections or system inputs, such as spatially driven feedbacks and spatial subsidies (Polis, Anderson, & Holt, 1997; Polis, Power, & Huxel, 2004). It is important to note that both internal and external spatial elements of an SES must be considered in relation to the structural aspects of the system, including (as outlined above) the number and nature of components and interactions, the ability of the system to undergo change while maintaining its identity, system memory, and the potential inherent in the system for adaptation and learning. I will return to the spatial aspects of the problem in the next section of this chapter.

The third axis of Fig. 3.2 concerns temporal variation, rates and temporal hierarchies, and the temporal location of a system within a set of processes or along a trajectory. Many of these aspects of temporal variation can be broken down in the same way as spatial elements, by considering local, regional and global dynamics and the relevance of sets of fast and slow variables. In addition, key aspects of this component of the framework include the diagnosis or assessment of the location of the system within a broader state-space, particularly in regard to its proximity to a potential threshold or regime shift; its location within an adaptive cycle (if the adaptive cycle is deemed to fit the system of interest), including whether key elements of the SES are growing, collapsing, or reorganizing; and assessment of the degree to which the system's history has created path dependence in its current and future dynamics (e.g., see Martin & Sunley, 2006).

Slow variables are considered to be particularly important in SES theory because of their role in creating regime shifts and alternative stable states. For example, soil fertility may be a slowly-changing variable in an agricultural system (e.g., Campbell, Frost, Kirchmann, & Swift, 1998; Van den Bosch, Gitari, Ogaro, Maobe, & Vlaming, 1998). If crop rotation times are insufficient to allow the restoration of soil nutrients, changes in soil nutrients can become a slow variable that ultimately limits the faster dynamics of crop planting and harvesting, with significant consequences for human wellbeing and social dynamics (Drechsel, Gyiele, Kunze, & Cofie, 2001). In the social realm, a similar problem exists in regard to climate change; the supposedly "fast" political and social processes that should be reducing "slow" increases in carbon dioxide emissions to the atmosphere are currently operating at too slow a rate to prevent global climate change.

While any one study will typically choose to focus on one axis of Fig. 3.2 more explicitly than another axis, all three axes (spatial, temporal, and structural) are inevitably present in any one SES. Many published system models are either not self-modifying or ignore important aspects of spatial variation, and so cover two of the three axes; but approaches that explicitly incorporate learning and adaptation, such as multi-agent models (e.g., Bousquet et al., 2007), allow the development of models that incorporate structural, spatial and temporal dimensions of the SES. Additional examples of system components and relationships that might be considered on each axis are provided as part of the case study discussion in Chapter 9.

Theory-based generalities start to emerge at higher levels of analysis (i.e., beyond specific case studies), and particularly those that consider systemic properties that can be quantified for seemingly disparate systems. For example, consideration of asymmetries in a farming system will lead towards analysis of properties such as rainfall and nutrient gradients and equity in property sizes; consideration of networks will suggest elements of connectivity to markets, social support systems, and activities like agistment (shared grazing rights; see Janssen et al., 2006); and consideration of information processing highlights the importance of adaptation and flexible decision-making processes, such as which crops to grow next year or how to respond to a drought event, that occur in response to changes in external inputs to the system.

System descriptions should interface in useful ways with a theoretical framework for SESs. Existing theory (see, e.g., Gunderson & Holling, 2002; Holling, 2001; Norberg & Cumming, 2008) suggests more generally, for example, that the resilience of an SES will (on average – exceptions will always arise) be enhanced by increased diversity (component differentiation), greater natural and economic capital, a greater ability to learn or adapt, and an intermediate degree of connectivity to other similar systems (the implications of connectivity are, of course, contingent on the nature of perturbations; consider the different implications of sharing technological innovations vs. the spread of pathogens). In addition, the history of an SES, its exposure to past perturbations, and its embedded memory of past responses (successful or not) will influence its ability to cope with a perturbation; SESs go through sequential developmental phases that alternate periods of growth with periods of collapse or reorganisation; different elements of an SES may enter these cycles at different times, in or out of synchrony; and consequently, the timing of perturbations relative to the state of SES components will be critical in determining and understanding the resilience of the system to a given perturbation. SES theory also predicts the existence of relationships between system architecture and system function, for example between the degree to which elements are spatially distributed and the ability of the system to respond timeously.

Analysing Spatially Explicit Aspects of Resilience

Building on the ideas that I have just outlined, we can now start developing a framework for the analysis of spatial resilience. Remember that in the last chapter, I defined spatial resilience as follows:

Spatial resilience refers to the ways in which spatial variation in relevant variables, both inside and outside the system of interest, influences (and is influenced by) system resilience across multiple spatial and temporal scales. It has elements that are both internal and external to the system.

The primary internal elements of spatial resilience include the spatial arrangement of system components and interactions; spatially relevant system properties, such as system size, shape, and the number and nature of system boundaries (e.g., hard or soft, and whether temporally variable or fixed over time scales of interest); spatial variation in internal phases, such as successional stage, that influence resilience; and unique system properties that are a function of location in space.

The primary external elements of spatial resilience include context (spatial surroundings, defined at the scale of analysis); connectivity (including spatial compartmentalization or modularity); and resulting spatial dynamics, such as spatially driven feedbacks and spatial subsidies.

Both internal and external elements must be considered in relation to other aspects of system resilience, including such things as the number and nature of components and interactions, the ability of the system to undergo change while maintaining its identity, system memory, and the potential inherent in the system for adaptation and learning.

Consideration of common themes between these different ideas and definitions suggests that the interface between resilience, scale, and system identity offers a synthetic way of viewing spatial resilience (Fig. 3.3). It is important to remember that system dynamics are difficult to capture in static diagrams like Figs. 3.1, 3.2 and 3.3; complex systems at each hierarchical level are changing through time, and these changes can impact not only their own resilience but also that of the systems with which they interact (e.g., Adger, Brown, & Tompkins, 2005). Dynamic feedbacks occur between and within different hierarchical levels, and the stability of the entire system may be enhanced or disrupted by the timing of changes (Holling, Gunderson, & Peterson, 2002).

People often struggle to visualise cross-scale interactions and feedbacks. An illustrative example is that of the booking system for accommodation in the National Parks of Kwazulu-Natal (one of South Africa's provinces). Bookings are made centrally at a single booking office, offering the ease and efficiency of having a single contact and making a single payment for accommodation at a number of different Parks. For instance, an overseas visitor can book a week's housing in the Drakensburg followed by a week in Hluhluwe-Imfolozi Park by making a single payment with no additional transaction costs. However, problems may arise at the local level if the visitor wants to modify their itinerary. Cell phone contact from the Drakensburg mountains with head office is difficult, and the local office is not empowered to modify or make bookings at a time scale longer than 1 or 2 days. Negotiating a change of cottage or an additional night's stay is considerably harder than it would be if bookings were managed locally. In this example, efficiency at the top of the hierarchy creates problems lower down in the hierarchy. If the system were modified to give individual parks greater control over their own accommodation, the converse would be true. Inefficiencies at the individual park level could

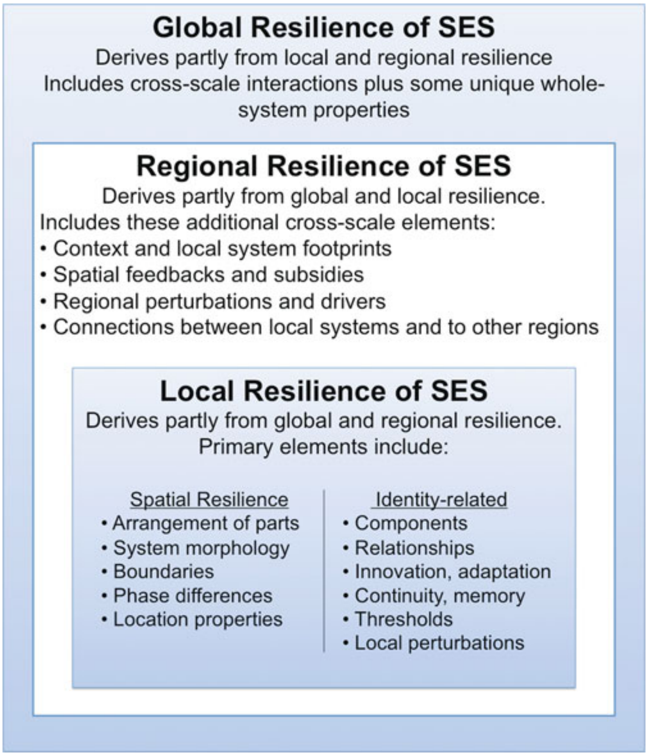

Fig. 3.3 General framework for the analysis of spatial resilience. For the sake of interpretability, the diagram illustrates only three scales of interest. System definitions are scale-dependent (i.e., constitutes "local" or "regional" is subjective) and should ideally follow actual system boundaries. Such boundaries may be natural, such as catchments, coastlines, or biomes; administrative, such as national or municipal; or based on other social-ecological landscape elements, such as land tenure, fences, roads, or land use types. However the system boundary is defined, hierarchy theory suggests that resilience will be influenced by events at the hierarchical levels immediately below and above the level of interest. Spatial variables such as physical connectivity and membership in a network of interacting nodes become increasingly relevant at broader scales. At the global scale, some system properties are unique. For example, the earth's proximity to the sun has a huge influence on life; the mixing of gases in the earth's atmosphere occurs in such a way that the resilience of weather systems to greenhouse gas emissions is a global problem; and the absence of other similar locations near to the earth makes the global system uniquely isolated by comparison to finer-scale systems

in theory create a gap between bookings and reality and might eventually gridlock the entire system. The solution is of course to ensure that cross-scale interactions between the upper and lower levels of the hierarchy are fast and frequent, a goal that Ezemvelo-KZN Wildlife generally achieves. Note also that in this example, interactions between head office and park offices are considered cross-scale because they occur between units with different spatial jurisdictions and at different hierarchical levels, whereas interactions between different park offices would be considered within-scale.

Scale may itself influence the predictability of complex systems behaviours. Levin (1992) has proposed that larger-scale processes should ultimately be more predictable than fine-scale processes, because they average over fine-scale variance (which is often a form of "noise") and provide a more reliable indicator of mass trends. Scientific perspectives on complexity oscillate between the reductionist and the holist, with reductionists seeking to explain system behaviour by looking at ever-finer details of mechanisms and holists emphasizing emergent system properties (i.e., those that are not predictable from the sum of the parts). For those who would tread the middle ground, the balance between these contrasting perspectives must be maintained in the study of spatial resilience. Assumptions about scale must generally be treated as working hypotheses rather than as givens; in many cases the key question is less one of "At which scale should I study this system?" than one of "How does this relationship change as I quantify it across scales?" (Cumming, 2007).

Hierarchy theory provides another valuable tool for dealing with aspects of spatial resilience. There have again been many good treatments of hierarchy theory in the recent literature (e.g., Allen & Starr, 1982; Wu, 1999), to which the reader needing additional information is referred. Hierarchy theory offers an important conceptual basis for distinguishing between different kinds of complex system and for dealing with the aspects of nestedness and scale that are inevitably part of a social-ecological system. Spatially nested systems, such as increasingly finer administrative units (e.g., country-province-city- municipality) have been the primary focus for hierarchical analyses of spatial relationships (e.g., Cushman & McGarigal, 2004; Wu, 1999); increasing interest in networks has more recently led researchers to start looking at the role of spatial variation and location in the resilience of non-nested hierarchies such as food webs and chains of command (e.g., Brose et al., 2005; Ter Wal & Boschma, 2009).

Consideration of Fig. 3.3 in the context of scale and hierarchies raises some intriguing questions about the nature of spatial resilience and the interactions between social-ecological systems at different scales. For instance:

- If local resilience is high in a high proportion of localities, does it add up to enhanced regional and global resilience? What is the relative importance of top-down, bottom-up, and lateral interactions? How does synchrony (or the lack of it) between interacting systems affect overall system resilience?
- If regional resilience decreases, does local resilience automatically decrease too? Is it possible for a local system to buffer itself against major regional changes?
- How do Holling's ideas of panarchical cycles relate to spatial resilience? Do particular spatial arrangements, and/or changes in spatial variables, influence the frequency and nature of panarchical cycles in predictable ways?
- Do particular kinds of system component or interaction cluster into particular locations along a scale-defined continuum, as proposed by Holling (1992), Peterson, Allen, and Holling (1998), and Allen (Allen & Holling, 2008; Allen, 2006); and how do these aggregations affect system resilience?

Figure 3.3 provides a general outline that summarizes the central issues in thinking about spatial resilience. The elements of the definition of spatial resilience can be readily applied in a case study setting (Table 3.2). A theoretical framework for spatial resilience should also address the ways in which the different aspects of spatial resilience expressed in Table 3.2 relate to other theories. At this stage I do not think that anyone really knows whether a single unifying theory for spatial resilience exists, or whether the elements in Table 3.2 are doomed to remain a kind of laundry list of things to think about. It seems unlikely to me that a Newtonian set of three laws, or an explanation based on entropy and dissipative structures, could somehow make it obvious how this list derives from first principles. Any unifying theory is likely to be multifaceted, in the sense that it will have to present several different perspectives on complex systems and to consider cross-scale interactions; and since we do not yet have a compelling theory of scale, a full theory of spatial resilience seems some way off.

Despite the difficulties of reaching a general theory that explains spatial resilience from a mechanistic perspective, there are other ways of viewing spatial resilience that can be highly informative (e.g., van Nes & Scheffer, 2005). At the time of writing, one of the most recent attempts at presenting a conceptual framework for thinking about social-ecological complex systems is that of Norberg and Cumming (2008). The framework arose from a series of discussions within what was then a group of younger members of the Resilience Alliance. It is based on consideration of three different facets of complexity: asymmetries, networks, and information processing. Spatial variation is relevant to each of these facets of complexity in different ways, and as a result they offer an interesting contrast with the ideas that I have so far outlined in this chapter.

Asymmetries refer to systematic heterogeneity within a complex system. Asymmetries may themselves be spatial, although this is not necessarily the case. For example, asymmetries in elevation can create a spatial gradient, while asymmetries in biological diversity can structure local food webs in a way that is largely independent of spatial variation. Cumming, Barnes, and Southworth (2008) argued that asymmetries in complex systems are important because they create a form of potential difference that can drive processes. In the context of spatial resilience, spatial asymmetries can drive pattern-process feedbacks and other socially and ecologically important processes, such as the movements of animals and rural to urban migration. Diversity (i.e., component differentiation) is another aspect of asymmetry in complex systems; analysis of diversity offers not only a series of insights into complex system processes (Norberg, Wilson, Walker, & Ostrom, 2008), but also a way of thinking through important resilience-related aspects of selection and adaptation in social-ecological systems. From a functional perspective, diversity offers a form of insurance against the loss of system components (and hence of functional collapse) in times of change (Loreau et al., 2001; Yachi & Loreau, 1999). Diversity is a tractable variable that is readily mapped, and one that is currently one of the central foci of the analysis of spatial resilience.

Table 3.2 A summary of the elements of spatial resilience, some of the things that theory suggests should be important as components of spatial resilience, and an example of a management-related problem from a particular social-ecological system (the Greater Limpopo Transfrontier Conservation Area, including its surrounding communities). A good reference for the GLTFCA is Du Toit, Rogers, and Biggs (2003). See also relevant papers by D. Cumming (1998), Du Toit and Cumming (1999), Guyer et al. (2007), Sankaran, Ratnam, and Hanan (2007), Smit and Grant (2009), Stalmans, Balkwill, Witkowski, and Rogers (2001), and Westoby, Walker, and Noy-Meir (1989)

Element of spatial resilience	What to think about in a resilience context	Greater Limpopo transfrontier conservation area example
Internal		
Internal arrangement of components	Distances between interacting units; strength and direction of interactions; arrangement along gradients; flexibility of spatial properties; path dependence in arrangement	Proximity of human settlements to one another and to park boundary; aridity gradient within GLTFCA; location of water sources and artificial well points
System morphology (size, shape, P/A ratio, etc.)	Is system size constant or changing; is it big enough to cope with potential perturbations; does shape (e.g., branching pattern) influence key processes or interactions; how does system size relate to movements of system elements; is size limiting growth; what is link between size and available resources	Carrying capacity for elephant population; extent of savanna woodland relative to extent of hot fire; capacity to offer unique "wilderness experience" to tourists
Number and nature of boundaries	Is boundary proportionally long or short; fuzzy or clear; are boundaries vulnerabilities; what is relative importance of edge effects	Length of fenceline; frequency of poaching incursions into protected area; relevance of fencing for spread of bovine tuberculosis
Spatial variation in phase	What are key elements of system that undergo successional-type change; relevance of heterogeneity; influence of spatial variation on temporal variation	Influences of different successional stages on key processes, such as spread of fire or movements of large herbivores
Properties of location	What are locally unique or unusual properties that play a key role in system resilience; does the area's history constrain its future	Poor quality soils for farming, low rainfall, hot weather; in South Africa, impact of apartheid on racial interractions

Table 3.2 (continued)

Element of spatial resilience	What to think about in a resilience context	Greater Limpopo transfrontier conservation area example
External		
Context (area influencing system) and system footprint (area influenced by system)	What lies around the study system (or what does it move within, for a mobile system); what are interdependencies between system and its surroundings; how is external environment changing; what are key cross-scale effects; how does regional context influence resilience	Relevance of national economies of South Africa, Mozambique, and Zimbabwe; influence of national policies; impacts of surrounding land uses and cropping systems on system resilience; clearing rates of native vegetation outside protected area
Connectivity	Is the system connected to other similar systems; can regional perturbations and innovations reach the system; where does it sit in various networks; what are properties of the broader network and how do they have local influence	Potential for dispersal of birds to/from other nearby protected areas; testing and adoption of new management approaches within SANParks network; income generated relative to other protected areas
Spatial feedbacks	Are there positive or negative feedbacks between spatial patterns and/or processes; to what extent does system alter its external environment	Does crop raiding by elephants or cattle predation by lions result in additional poaching activities in protected areas?
Spatial subsidies	Is the system strongly dependent on external, one-directional inputs; does it provide inputs to another system; how resilient are subsidies of different sorts and do they constrain or enhance system change	Relevance of upstream catchment areas (e.g., Bushbuck Ridge) for water quality; importance of service provision (e.g., clean water, fishing, game watching) to local and national stakeholders
Spatial resilience as a variable	Can tractable variables and/or relevant interactions or system states be quantified and mapped across a region of interest?	Contrasting spatial patterns in biodiversity and functional group composition offers insights into spatial resilience of ecosystem function to species loss (Cumming & Child, 2009)

Table 3.2 (continued)

Element of spatial resilience	What to think about in a resilience context	Greater Limpopo transfrontier conservation area example
Spatially relevant aspects of resilience		
Adaptation and learning	Is learning occurring; if so, it is active or passive and what mechanisms reinforce it; does adaptation occur proactively or passively (i.e., as a result of the action of selective processes on diversity)	Presence/absence of formal mechanisms for documenting and reviewing mistakes; experimentation; presence/absence of adaptive management
Memory	Does the system have some form of memory and where is memory located; is memory internal or external to the system	Location and accessibility of seed banks, archives, older people; impact of HIV/AIDS on longevity and memory
Thresholds	Does the system have the potential for alternate stable states and if so, what drives state change and where are the thresholds for change located	Rangeland dynamics (herbivory, fire, rainfall) can shift areas between woodland and grassland

Networks offer another useful way of thinking about spatial resilience. The resilience of a complex system is influenced by other complex systems that it interacts with. If systems are considered as nodes and interactions as links within a network, resilience is influenced by the location of a node within a network, the other nodes with which it interacts, and the overall properties (such as transmissivity or stability) of the network. Graph theory and associated network-derived metrics offer ways of quantifying important aspects of social networks, ecological networks, and social-ecological networks. For example, the resilience of a protected area network to the loss of either connections (links) between reserves or reserves themselves (nodes) can be explored by examining the effect of removing individual nodes or links on the overall functioning of the network. This approach can identify nodes that are particularly important for overall network connectivity; they may not be the largest or most resource-rich nodes, and hence might be easy to overlook without a more formal analysis. Good examples of network applications in a conservation setting are provided by Urban and Keitt (2001) and Janssen et al. (2006). I will return to these and related examples in Chapter 6.

Information processing refers to the step that occurs in a complex adaptive system between stimulus and response (Norberg & Cumming, 2008). While examples where information is processed consciously by individuals are the most obvious (e.g., individual fishermen share information to identify areas with more fish), information processing may also occur without conscious control (as in plants) or across different levels of hierarchical organization (e.g., the cumulative societal responses of organizations and individuals to concerns about chlorofluorocarbon (CFC) emissions led to the Montreal protocol and an improvement in the condition of the ozone layer (Beron, Murdoch, & Vijverberg, 2003; Powell, 2002)).

Although information processing does not on first inspection appear to be a subset of complex systems theory that has strong spatial relevance, this is not necessarily the case. Information exchange depends heavily on the transmission and receipt of signals and is usually accompanied by a filtering process that sorts genuine signals from noise. For example, political decisions about whether to act on climate change have been delayed because of uncertainties about whether the perceived warming trend in temperature data is genuine ('signal') or a random coincidence that could occur given the natural range of variation ('noise'). The potential for information to arrive in the first instance is strongly influenced by location, context, connectivity, and other aspects of spatial resilience. Filtering processes, and decisions about whether or how to act on information, may also have a spatial component. For example, the degree to which a new technology or a new management approach is adopted by a society may depend on something as small as where it is first tested. The spatial arrangement of units within a social-ecological system can have a strong influence on information processing rates and the nature of responses. Within the human body, for example, left-handed tennis players may have slightly faster reflexes than right-handers because the distance between the striking arm and the part of the brain that controls movement is very slightly shorter, resulting in a faster transfer of signals (Barthélémy & Boulinguez, 2002). At a broader scale, the vulnerability of a community to natural disasters may be influenced by the locations of response units; for example, having hospitals, fire stations, and police stations near to one another may be an advantage in cases requiring a rapid, well coordinated response; or may be problematic if that particular area is heavily affected, or becomes disconnected by something like the destruction of a bridge. Spatial arrangement is also relevant to information collection; in a system in which information itself is more spatially distributed, monitoring of widely dispersed natural resources (such as breeding populations of ducks) may take longer and be considerably more expensive than more standard monitoring efforts (e.g., see Haig, Mehlman, & Oring, 1998). Differences in the time that it takes to obtain and respond to information will influence the response capacity of the system during a time of crisis, potentially affecting its overall resilience.

Asymmetries, networks, and information processing together offer one potentially useful way of embedding ideas about spatial resilience – with its foci on internal system properties, location, context, connectivity, and spatial feedbacks and subsidies – within the broader context of existing publications on SESs. Contrasting my definition of spatial resilience with each of these three themes suggests some bigger-picture questions as guiding themes for the study of spatial resilience (Table 3.3).

There are several different ways in which the conceptual framework that I have been discussing can be used to develop concrete hypotheses about the relevance of spatial variation for resilience. I have so far focused on operationalising and coming to grips with the concept of *space*. What remains is to consider some different ways in which this framework can be better operationalised in regard to working with the concept of *resilience*.

Operationalising the Framework

The history of scientific research demonstrates the value of entertaining multiple working hypotheses and approaches (Chamberlain, 1890; Platt, 1964). I will not, therefore, attempt to outline a single approach or to push for a single empirical methodology as best practise. There are many different roads to Rome, and the best route may vary according to the nature of the problem (although it must be remembered not all roads lead to Rome; at the time of writing I have just seen a news article about a pair of Swedish tourists who entered into a handheld GPS unit (and blindly followed) the coordinates for Carpi, rather than their intended destination of Capri, and wondered why they found themselves in an industrial inland town rather than the famed holiday destination). In any case, several possible approaches suggest themselves in response to the question, "Where does spatial resilience reside?" These approaches represent alternative ways of doing science as much as they represent different ways of connecting the different elements of spatial resilience.

The steps in an empirical analysis of resilience, prior to analysing spatial resilience, will inevitably involve the determination of the scope of the study, its boundaries (physical, political, and conceptual), and the focal question(s) and/or

Table 3.3 Some examples of general questions in the study of spatial resilience in social-ecological systems. These questions are intended to conceptually integrate the analysis of spatial resilience with a previous framework for the analysis of complex systems, as outlined in Norberg and Cumming (2008). Although many of these questions could probably be answered for an individual complex system, generalities in the field will ultimately need to be established through a combination of modelling and case study comparisons. Some useful progress has already been made with some of them (e.g., Granovetter's hypothesis – see boxes marked with an asterisk*)

Spatial resilience	Asymmetries	Networks	Information processing
Internal			
Internal arrangement of components	Does local self-organization or stratification increase resilience? How does system diversity influence spatial resilience?	*Are weakly connected networks more or less resilient?	How does system structure influence responses to perturbations?
System morphology (size, shape, P/A ratio, etc.)	Which system properties scale predictably with system size, and what is the form of the scaling relationship?	How does network size influence the resilience of individual nodes?	Is there a threshold size beyond which information transfer costs outweight benefits?
Number and nature of boundaries	Are systems with more or longer boundaries more strongly influenced by environmental asymmetries?	How do physical boundaries influence network function?	If boundary permeability leads to a tradeoff of vulnerability against system response time, how does permeability influence resilience?
Spatial variation in phase	Do phase variations (i.e., in space) create the possibility for alternative stable states?	How does network synchrony (or lack of it) arise, and what are its implications for resilience?	How does resilience change with fluctuations in the capacity of different information processing units?
Properties of location	Can the specific properties of location ever determine system resilience independently of broader-scale asymmetries?	Are entire networks of a particular kind (e.g., social, trade, forest patches) more resilient when they link mainly similar or mainly different locations?	Do particular locations lend themselves to more efficient information processing, and what are the impacts of such differences on resilience?

Table 3.3 (continued)

Spatial resilience	Asymmetries	Networks	Information processing
External			
Context (area influencing system) and system footprint (area influenced by system)	To what extent does location along a resource gradient constrain possible adaptations?	Under what circumstances can nodes buffer one another against perturbations?	How do the spatial and temporal scales at which complex systems obtain information relate to their ability to respond to external change?
Connectivity	Does increasing broad-scale connectivity amplify or reduce the influence of environmental asymmetries?	*Is system resilience highest at intermediate connectivities?	How does the degree of system connectivity influence its response time?
Spatial feedbacks	Do feedbacks between spatial and temporal variation lead to self-organization?	Are more weakly connected nodes more likely to experience spatial feedbacks?	Are there general principles that predict when system responses will constrain the range of options for future responses?
Spatial subsidies	Under what circumstances do spatial subsidies create “traps” that keep social-ecological systems in undesired states?	What is the relative impact on resilience of subsidies that travel through networks, as compared to subsidies obtained from the immediate surroundings?	To what extent/how does the efficacy of filtering processes (e.g., those that distinguish signal from noise, or high quality information from low quality information) influence resilience?
Spatial resilience as a variable	Under what circumstances does environmental asymmetry influence system resilience?	If membership in a network enhances resilience, can we predict how the amount of gained resilience will vary between nodes?	Which are the most important characteristics of information processing for resilience mapping? (e.g., does response speed matter more than efficiency?)

Table 3.3 (continued)

Spatial resilience	Asymmetries	Networks	Information processing
Spatially relevant aspects of resilience			
Adaptation and learning	How do spatial asymmetries in adaptive capacity arise, and how can they be resolved?	Do particular kinds of network arrangement facilitate learning more effectively than others?	In an SES, can the ability to adapt be deliberately designed, or must it be learned?
Memory	Is distributed memory more resilient than purely local memory?	How does network structure affect the amount of information retained in the network at any one time?	What are the tradeoffs for resilience between centralised and distributed information processing?
Thresholds	Do the locations of thresholds in similar systems differ predictably along environmental gradients?	Are social networks dominated by emergent properties beyond a particular size threshold?	How does awareness or ignorance of thresholds influence decision-making processes?

hypotheses that are to be addressed. In research on social-ecological systems the focal questions are likely to revolve around the maintenance of natural resources, the role of management in the system, and the requirements of different groupings within the human population. System characterization can be done from the start with high awareness of the relevance of spatial aspects of resilience; or the influence of spatial variation on important system elements and interactions can be considered after a non-spatial view of the system has already been developed. There are costs and benefits to both approaches. In any case, elements that may be relevant to the analysis of spatial resilience in the given system must be selected and considered in relation to the specific properties of the system.

Some possible approaches to incorporating spatial resilience within a more standard resilience or vulnerability analysis include the following (note that these are by no means exclusive of one another):

Approach 1: Winnow Down

Winnowing down involves determining which of the wide range of potentially important spatially relevant variables can be quantified, either directly or indirectly. These variables must be "tractable" in the sense that they need to be measurable and to be mappable (either directly or through surrogates, such as looking at functional richness in place of resilience of function; see Cumming & Child (2009) for an example) and amenable to analysis. The initial steps of describing the system and listing tractable variables will be followed by sifting carefully through the list of variables and establishing which are likely to have the largest influence on the study system. Having quantified as many of this subset of important variables as possible, and tested quantitatively for spatial correlations (i.e., effect sizes in terms of an influence on patterns or processes of interest), analysing spatial resilience then becomes a case of using the small number of variables that seem truly important as the basis for empirical data collection and/or a mechanistic modelling exercise.

The chief danger with this approach is the 'drunk searching for her car keys under the streetlight' syndrome: in the same way that it is easier to look for something where you can see than where it is dark, there is a high likelihood that analysis of a complex system will be biased towards available data sets. These may or may not reflect the true nature of the problem. Data biases happen more easily than expected and can be extremely difficult to avoid. For example, in the Millennium Assessment report from the working group on biodiversity scenarios (MA, 2005), most of the conclusions about global biodiversity loss under different scenarios are based on data that were available, rather than for the taxa that might have been picked a priori to represent ecosystem function if unlimited data had been available. Fortunately, good data were available for some of the most relevant taxa, such as the flowering plants.

Approach 2: Identity and Threshold Focus

An identity and threshold focus starts with developing a set of identity criteria, as laid out in Cumming et al. (2005). These criteria are used to determine critical thresholds in the system. Spatial influences on identity criteria must then be assessed for their potential to push the system over a threshold. For example, the forest government in Acre (Brazil) has vowed to limit forest clearing to less than 18% (Cumming et al., 2005). Patterns of forest loss can be quantified through the use of satellite remote sensing data, and explored and projected using land use and land cover change models (e.g., see review by Agarwal, Green, Grove, Evans, & Schweik, 2002)). Identification of forest loss as a key threshold in a study system thus takes the analysis down a path of land cover change and deforestation analysis.

Identity and threshold criteria can be determined through a participatory approach or based on existing governance and management concerns, as in the Kruger National Park in South Africa. For the Kruger Park, various 'Thresholds of Potential Concern' (TPC) have been identified, and monitoring focuses on collecting data that are relevant to TPCs (Biggs & Rogers, 2003); when any monitored variable approaches a TPC, an alarm bell is sounded and a management response (in the form of direct action or more research) is triggered. For example, if elephant densities in the park approach a level that the vegetation in the park cannot sustain, actions to reduce the population size (such as culling, translocation, or sterilization) must be undertaken (Biggs & Rogers, 2003).

Approach 3: Add Space to a Simple Systems Model

This approach interfaces with a typical 'resilience analysis' approach (RA, 2007a, b; Walker et al., 2002) which includes the development of one or more system models. Spatial influences are included in the analysis more explicitly by attempting to factor them in to an existing systems model description, adding spatial complexity from a relatively simple non-spatial starting point. An outline for a gradual increase in model complexity is discussed in Bennett, Cumming, and Peterson (2005). Such an approach would work well in a situation where a single model can capture local dynamics that are relevant across a broader extent; inputs and outputs can be modified according to location, and the addition of lateral transfers of resources or actors between locations will allow the consideration of a range of basic spatial dynamics. In this context, some of the simple two-cell models developed by Bob Holt (e.g., Holt, 1985) for ecological problems are particularly relevant, in the sense that they demonstrate how spatial dynamics can be considered in useful ways even in models that have only two or three spatial compartments. An example of how a two-compartment model can add value in SES analysis is that of a river basin in which a simple spatial separation between upstream and downstream water users introduces the potential for conflict.

Approach 4: Use Scale and Scaling as Unifying Themes

Scale, and particularly scaling analyses, can provide a way of thinking through and understanding system dynamics. Holling's rule of hand (Holling, 2001) suggests that complexity can emerge from a set of three to five variables acting at different speeds and different extents. Applying scaling analysis to understand spatial resilience has elements of the previous approaches, in that it will require the selection of a minimal set of spatially relevant variables that will produce complex systems behaviour. However, it brings the additional challenge of tracking how key system interactions (and resulting dynamics) change with scale. For example, drawing on the ideas of Lin Ostrom (2007, 2009), a model of collective action can demonstrate how rules for natural resource management arise within a local context. An important question for spatial resilience is whether the same principles can be extended to cover larger groups of people – for example, whether agreements about water use within a single catchment, such as the Goulburn-Broken catchment of the Murray-Darling basin (Anderies, 2004), can be extended to cover an entire basin or whether some other scale-dependent factor, such as transaction costs or information availability, becomes limiting at broader scales.

Approach 5: Use of Narratives

Narrative-based approaches, such as scenario planning (reviewed by Peterson, Cumming, & Carpenter, 2003), offer an intriguing alternative to more standard analyses of resilience. The basic approach in working with scenarios in this context would be to develop four or five scenarios that pay particular attention to spatial aspects of resilience, as highlighted in Table 3.1. The narratives would highlight key uncertainties in the role of spatial resilience in the system, possibly in combination with one or more of the approaches outlined above. Quantifying and testing the storylines would provide the guidelines for determining which variables to quantify and which to incorporate in one or more formal modelling exercises. From this kind of analysis I would expect a more general understanding of the role of spatial variation in the SES to emerge, as well as some useful insights into the nature of key uncertainties.

Concluding Comments

This chapter has laid out the basic elements of a framework for the analysis of spatial resilience, starting from a systems perspective on the research process and moving through system description to focus explicitly on space and the relevance of spatial variation for resilience. The framework that I have presented here is intended to provide a way of integrating different approaches to the analysis of spatial resilience under a common umbrella. I will refer back to it periodically through the book in an attempt to make the connections between this framework and the subjects of subsequent chapters as clear as possible.

Considerable progress has already been made on understanding the relevance of spatial variation for pattern-process relationships across a range of inter-related disciplines. The next five chapters of this book explore different aspects of spatial resilience, following a roughly defined continuum of increasing empirical realism that runs from simple spatial models in ecology to attempts at full-on empirical analyses of detailed case studies of SESs. In successive chapters I explore what we have learned about spatial resilience in a particular research domain, explain its relevance for the study of SESs, and try to build bridges between areas of inquiry that may at first sight seem disparate. In Chapter 10 I return once again to the framework outlined in this chapter, discussing a set of case studies of large river basins in some detail. The final chapter of the book attempts to achieve two synthetic goals: first, to summarize the most important conclusions about spatial resilience that emerge across the different chapters; and second, to highlight those areas of research that seem particularly promising for further research on spatial resilience in SESs.

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Chapter 4
Introduction to Mechanistic Spatial Models for Social-Ecological Systems

Introduction

Modelling has played an important role in the development of systems thinking. It remains a central and important tool in theoretical and empirical investigations of social-ecological systems. This chapter provides the context and some of the conceptual and methodological background that will be necessary to understand the examples and models that are discussed in the next chapter, which focuses more explicitly on spatial resilience and presents some more detailed examples. Catering for an interdisciplinary audience is challenging and my intent in this chapter is to provide some background for the interested reader who has a limited background in modelling. Readers who are already highly familiar with the process of modelling and the development of spatial models should feel at liberty to skim or skip this chapter.

I should also add that because of my own disciplinary background my use of examples is biased towards. ecological models, which offer a good microcosm of modelling approaches as applied to complex systems. Ecology has benefitted enormously from applying relatively simple spatial models that have useful things to say about the mechanisms that underlie resilience. In many cases such models express and explore a set of fundamental principles that go well beyond the ecological problems that they were originally developed to address. My subjective impression is also that ecology has developed a much greater variety of theory-oriented spatial models than most other disciplines, with the possible exception of some branches of geography.

Mechanistic (i.e., process-based, as opposed to statistical or correlation-based) models have played an important role in the development of thinking about spatial pattern-process relationships across a range of different disciplines. In many cases the largest advances have been made through relatively simple, comprehensible models that have acted as interpretable tools with which to explore important kinds of relationship, while also producing occasional surprises. For example, John Conway's 'game of life' model (discussed in Gardner, 1970) successfully showed how a few simple rules and the addition of spatial pattern to a model could lead to complex, unpredictable behaviours. The game of life assumes that each cell on a

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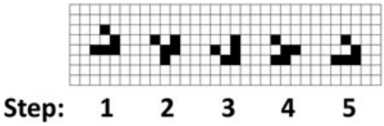


Fig. 4.1 A 'glider', as generated by the rules specified by Conway's game of life. This figure shows how a group of adjacent cells (indicated in *black*) changes over five different time steps. Note that although the glider returns to its original configuration at the end of the sequence, it is not in the same place. In an infinite space, this motif would continue to travel indefinitely. A related motif, the 'glider gun', itself remains stationary but produces gliders. The glider and the glider gun illustrate how simple rules that incorporate spatial relationships can generate seemingly complex behaviours, conditional on small differences in starting conditions

two-dimensional grid can be either 'on' (usually represented with a black colour) or 'off' (usually represented in white). Each cell in a square lattice has eight neighbours. The state of each cell is updated in each iteration of the game. Cells switch from on to off, between iterations, according to a set of simple rules: (1) if two neighbours are on, the cell stays in its current state; (2) if three neighbouring cells are on, the cell turns on; and under all other conditions, the cell turns off in the next round. Depending primarily on the starting configuration of cells, these simple rules will not only fail to produce a single, static equilibrium point; they will produce a bewildering array of different patterns, some of which (such as the so-called 'gliders' and 'spaceships') have the appearance of animated individuals (Fig. 4.1).

While the relevance of such a model to the real world may not be immediately obvious, it requires only a few modified or additional assumptions – for example, that neighbouring cells turn on or off according to the probability that seeds enter them from a tree in a neighbouring cell, or the probability that they cooperate with their neighbours through trade – to produce simple representations of some of the kinds of spatial dynamic that might be found in an ecosystem, a society, or an economy (e.g., Nowak, Bonhoeffer, & May, 1994). The ease of simulating complex behaviours in turn raises the exciting possibility that we may be able to identify (and ultimately, predict) ways in which local relationships and simple heuristics can generate particular kinds of spatial pattern, such as those generated by expanding cities or seasonal fires.

I will delve more deeply into the details of some spatially explicit ecological models and their relevance for spatial resilience in the following chapters. Before that, however, there are a few points about models in general and their role in the study of complex systems that need clarification.

Challenges in Modelling Complex Systems

Scientists who attempt to develop models of complex systems will inevitably encounter a number of challenges (Table 4.1). One of the first of these is that it is possible to view just about any complex system in a number of different ways,

Table 4.1 Some challenges in modelling and working on complex systems, and suggestions for coping with them during project planning and model development. Some additional discussion is provided in the text

Challenge	Suggestions for modelling SESs
Plurality: multiple 'correct' views of system	Develop alternative models and compare conclusions; recognize and explain limitations of a given perspective
Ambiguity: value-laden decisions about model structure, parameters and interpretation	Consider and reach consensus on value system before model development; be transparent about value-laden decisions; avoid judgements about 'good' or 'bad' outcomes; in participatory research, allow stakeholder community to influence evaluation and interpretation
Uncertainty: scientific assessment of probabilities and confidence levels	Where uncertainty is important, attempt where possible to quantify it; consider full range of sources of uncertainty; acknowledge likely underestimation of uncertainty by classical methods
Risk: possible negative consequences of decisions and of engagement with problem	Incorporate concerns about risk when focusing the modelling process; use scenarios to explore relevance of risk; apply precautionary principle and acknowledge uncertainties in developing recommendations
Ignorance: things we don't know we don't know	Consider important areas of ignorance explicitly at start of major projects, possibly using a formal scenario planning approach
Overwhelmingly large numbers of variables	Accept that models will always leave some variables out; focus on identifying smallest set that captures dynamics of interest rather than building a 'complete' model
Non-linearities and alternate stable states	Try to identify important non-linearities but limit models to manageable numbers of variables and parameters; explore consequences of thresholds individually before worrying about synergies; consider using state-and-transition models or frame-based models in complex situations
Hierarchical structure	Evaluate relevance of structure; decide between selecting a single level of analysis (acknowledging relevance of higher and lower levels as constraints and mechanisms) and incorporating different levels in the same model; consider exploring simple hierarchical models before assuming that hierarchical structure is irrelevant
Pattern-process feedbacks	Keep models simple. Consider starting with simple two or three-cell and/or category representation of space (e.g., dark vs. light vegetation; fuel loads high, medium or low)

Table 4.1 (continued)

Challenge	Suggestions for modelling SESs
Sample size requirements are high	Think carefully about statistical power, possibly applying formal power analysis. Collect plenty of empirical data and locate sampling locations across full extent of dominant gradients to maximize value of each sample. Large sample size ($n>54$) required for semivariograms; in multivariate analysis, aim for at least 6 independent measurements per variable; ensure comparability in all measurements. Don't embark on projects where sample size demands exceed funding
Tendency to focus on one's own area of special expertise	Develop strong collaborations with colleagues who bring other perspectives and skills; submit work to independent peer review on a regular basis
Tendency to focus on problems for which existing data permit quick analysis	Consider data needs objectively and independently of data availability; try to fill key information gaps; highlight low-data areas in publications
Over-reliance on existing models	Evaluate existing models carefully, for suitability as much as for fit to data; check relevance of model assumptions and underlying dynamics (e.g., assumptions about linear vs. non-linear relationships) to your study problem; don't be afraid to develop new models, even if far simpler, to capture essence of problem
Incompatibility of different data sets	Where possible, agree with collaborators on a standard extent and resolution; try to ensure that data collection protocols are rigorously observed; do provisional analyses early during project to identify any necessary revisions to data collection protocols
Failure to quantify ancillary variables that influence interpretation and comparability of results	Use standard preprinted recording forms and ensure that observer skills/biases and sampling effort are recorded as data are captured (e.g., keep detailed records of time spent searching or counting)
Tendency to fall in love with one's model	Treat models as hypotheses; work with several alternative/competing models whenever possible; don't be afraid to reject existing models if assumptions (e.g., rational choice) are untenable in a given situation
Tendency to be too ambitious in planning spatially explicit interdisciplinary projects	During planning, acknowledge real-world difficulties in planning and data collection processes; try to write proposals with some inherent flexibility; keep end goals (e.g., particular publications) in mind; identify core samples (e.g., locations and data sets) versus expendable samples, and ensure that quality at core sites/of core data remains high

each of which is equally valid (that is, complex systems have the property of *plurality*). For example, duality is fundamental to quantum physics; according to Bohr's Principle of Complementarity (Bohr, 1928), light can be modelled as a wave or as a stream of particles, with both wave and particle models receiving empirical support, but not from both perspectives simultaneously. It is axiomatic in modelling circles that all models are wrong (i.e., incomplete), but in complex systems, many different kinds of model can be 'right' (Simon, 1962, 1976). In studies of social-ecological systems, different, equally valid models can lead to different conclusions and conflicting mangement recommendations. Working effectively with models in a social-ecological systems context requires not only rigorous science but also a set of clearly defined objectives and the transparent resolution of issues of subjectivity, values, and questions of power and politics. For example, depending on the goals of the exercise and the values of the people involved, a model that is built to help with assessment of the resilience of timber production in the Amazon might either incorporate or ignore issues such as biodiversity loss, changes in ecosystem services, conflict over land tenure, the role of immigrant labour, forestry policy, and the dominance of local markets by ranching cartels.

Studies of complex systems are distinguished by different kinds of incertitude, classified by Andy Stirling (2003, 2007) as ambiguity, ignorance, risk, and uncertainty (Fig. 4.2). Ambiguity arises in situations where there is no clear compass for making decisions; risk involves making decisions about the long-term impacts and tradeoffs involved in particular decisions; and ignorance is a black box that contains a potentially vast number of unknowns. For instance, deciding whether to adopt a

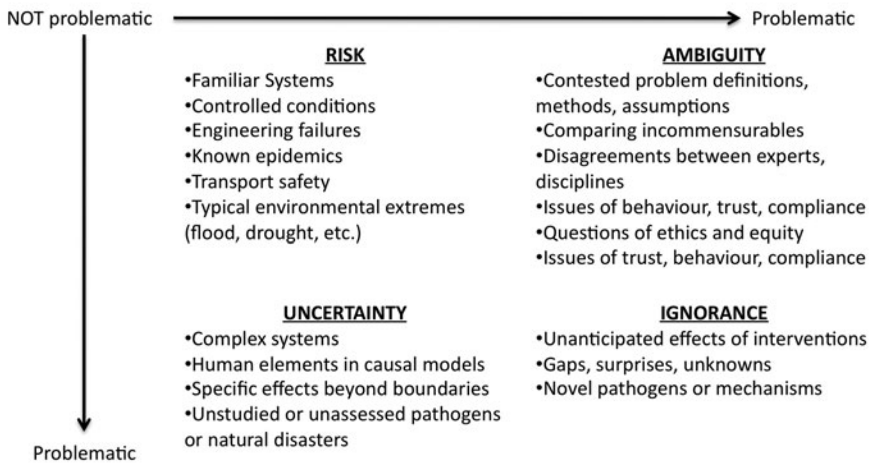


Fig. 4.2 Dimensions of incertitude, as conceptualized by Andy Stirling. This figure was redrawn (and slightly modified) after Stirling (2007). The axes refer to the challenge posed by each category of incertitude for classical scientific approaches. Although classical statistics offers some useful tools for assigning probabilities, and hence for quantifying uncertainty, it may have little relevance in situations that are characterized by ambiguity and ignorance

'science-based' western value of an ecosystem service or a valuation provided by an indigenous rural community may involve confronting and resolving ambiguity (for example, local people may place what seems to an outsider to be a disproportionately high value on forage production for cattle in relation to services like pollination or seed dispersal); and making decisions about how stringently to regulate carbon dioxide emissions involves the assessment of costs, benefits, and risks from multiple competing perspectives. Classical scientific analysis generally focuses on uncertainty and has little to say about ambiguity, ignorance, or risk; these issues must often be explored before a justifiable quantitative model of social-ecological interactions can be produced.

Complex systems are also characterized by a number of attributes that make modelling them conceptually and technically difficult, including large numbers of variables, a hierarchical structure, non-linear interactions and the potential for thresholds and alternate stable states, and feedbacks between pattern and process (Simon, 1962). Most models of complex systems incorporate changes through time but the vast majority assume that spatial variation is irrelevant, constant, or can be safely ignored. The inclusion of space in a model inevitably increases its level of computational difficulty because every pattern and every process must then be considered not only in its own right, but also in relation to what is happening around it. In some cases the exclusion of space is justified; for example, if a lake is well-mixed and its sediments are homogeneous, phosphorus dynamics can justifiably be considered at the analytical level of an entire lake (Carpenter et al., 2001). However, there are many other instances in which spatial dynamics are critical to understanding pattern-process interactions. For example, accidental species introductions in aquatic systems typically occur from a single location or point source of invaders – often a harbour in which ballast water is exchanged, or a docking point or boat slip where boats are placed in the water and bait buckets are emptied (e.g., Darbyson, Locke, Hanson, & Willison, 2009). If an introduced species such as a rusty crayfish (*Orconectes rusticus*) can persist in its new habitat, it will often colonise the area from its central location, creating a spatial pattern that consists of an area of high central density and a wave-like, expanding edge (e.g., Collingham, Hill, & Huntley, 1996; Fisher, 1937; Roughgarden, 1998). This pattern looks very different from classical models that assume equal mixing of individuals and homogeneous resource use, and the dynamics of a population in these early stages of colonisation are different from those of a well-established population that has already accessed most areas of suitable habitat. Understanding the ways in which the spread of a colonising population differs from more settled populations has practical relevance for the control of invasive species and pathogens, such as rabies, that must be controlled by containment.

The analysis of spatial resilience demands that models incorporate space and scale explicitly. One of the most important steps in the quantitative analysis of spatial resilience is therefore to think carefully about which spatial processes are particularly relevant to understanding a given situation or problem and how best to measure them. There will be many ways in which each process can be modelled or analysed, and many of these approaches will be data-heavy if the goal of the analysis is to quantify and make realistic predictions about changes in real-world quantities. One of the fundamental problems in assessing spatial resilience is therefore to determine which of the huge range of possible kinds of analysis will be the most productive as a way of coming to grips with the issues that are of greatest concern. Not all approaches will yield useful or interesting answers; as Peter Medawar put it, ‘If politics is the art of the possible, research is surely the art of the soluble’ (Medawar, 1967). One of the secrets of producing a good model lies in the art of selecting the smallest, most parsimonious set of variables and processes that will suffice to explain the dynamic of interest (Morris, 1967; Starfield, 1997).

Finding the right question is often as difficult as finding the right answer, and in many cases initial decisions about where the focus of a project will fall are primarily a matter of experience and luck. There are many traps in project design that are easy to fall into, including focusing on one’s own area of special expertise while ignoring other equally or more important processes; tackling only problems that can be addressed with existing data sets; relying too heavily on existing models and ultimately being constrained by their basic assumptions; collecting data on different parts of the system at different and incompatible spatial and temporal resolutions; and failing to quantify important ancillary variables like sampling effort and observer bias (see discussion in Table 4.1). In my experience, leaders of interdisciplinary teams are also quite likely to underestimate the time and effort that data collection in other disciplines demands. This is particularly true when spatial variation is one of the variables under study. For example, spatial interpolation using geostatistical methods usually requires sampling at well over 50 locations (Isaaks & Srivastava, 1989), and dynamic spatial models ideally require time series with numerous observations at each point. Developing a simple dynamic assessment of spatiotemporal variation in a single variable at a monthly frequency (e.g., temperature, water quality, human impacts, or bird community composition) could demand the collection of over 600 (50×12) samples in a single year. Investment in this level of sampling is not made lightly, and it is best to assess its relevance and eventual utility before large amounts of money are wasted on the collection of irrelevant or inadequate data sets.

Modelling offers a way of testing out ideas about mechanisms and assumptions in a low-cost environment. If used appropriately, and especially if paired with a small amount of preliminary data collection, it provides a relatively low-risk way of determining not only whether a project is feasible but also whether the right kind of question is being asked and whether the planned application of statistical methods will be adequate. Sometimes models can reveal very basic flaws in a methodology, such as mismatches in measurement scale between two key input variables.

Modelling is also an excellent tool for the development of theory through exercises that guide and shape thinking about a problem but do not translate directly into data collection. It allows the scientist to explore the connections between variables and the possible consequences of rules or assumptions that might have a large impact on system dynamics. Models that are poorly specified or conceived, however, can be misleading. For example, and at the risk of offending neoclassicist readers, assumptions of rational, informed choice by consumers have directed economic models down a dead-end road for decades (Beinhocker, 2007).

Given the abstract nature of modelling, there is a strong need for a constant interaction between models and reality, and particularly for the confrontation of models with data. Ecology suffers from a surplus of untested models as well as a related syndrome in which models are used to explore what is possible without necessarily considering what happens in reality. For example, a large number of ecological models of community dynamics include the notion of competition, often in the absence of any direct evidence that competition occurs in the system of interest or that if it does, its magnitude is sufficient to have a significant effect on community dynamics. Another interesting example comes from applications of the theory of island biogeography in patch-matrix studies; after many years of largely ignoring the matrix, landscape ecologists are coming to the reluctant realisation that matrix properties may be just as important as the effects of patch size and shape (Prugh, Hodges, Sinclair, & Brashares, 2008).

One of my early mentors was an expert on the biology of honeybees, and he used to caution me about simplifying assumptions in models. His favourite example was from a study that he had done on honey production. Models suggested that the honey to wax ratio of honey could be improved drastically if the edge to volume ratio of honeycomb could be reduced. Some experimentation showed that bees can be convinced to make bigger cells if they are provided with a starter mould in the desired dimensions. With a little more effort, a method was developed for mass production and my professor started to dream of the commercial potential of his invention. However, when the outputs from the first hive were assessed, there was a setback: the honey to wax ratio was the same as before. What had happened was that the bees, apparently possessing a superior grasp of physics, had made the cell walls thicker.

There have been many good books and review articles written about the theory and practice of modelling (e.g., Grimm, 1999; Starfield & Bleloch, 1991; Starfield, 1997) and so I will not dwell further on modelling itself except to say that in complex systems research, the greatest advances in understanding have emerged from models that incorporate relatively low numbers of variables and parameters. Huge multi-parameter models have their place in disciplines like hydrology and climate science, but even in these disciplines they can rapidly lose generality and become unintelligible and over-specified. In addition, each parameter introduces additional measurement error (in technical terms, additional parameters reduce the degrees of freedom available to extract useful information), and after the addition of 10 or 20 parameters it can be difficult to know whether you are exploring the system or the errors. If you do not understand your own model, its results are likely to be as uninterpretable as the process that you are trying to model, and the value of developing a model (rather than simply collecting empirical data) is questionable. Dynamic models in complex systems research should generally be seen as tools that help us to explore the way the world fits together, rather than as attempts to predict the future, although they may of course have a useful predictive role to play in certain contexts. Ecology as a discipline has made considerable and often highly successful use of a wide range of simple models; much of our current understanding of spatial processes in ecology has emerged from analysis of these models.

Spatial Models in Ecology

Relevant developments in the field of ecological modelling have proceeded along several different trajectories. These include (1) the exploration of mechanisms and the testing of hypotheses within ecology (theoretical advances, such as understanding donor control or the ways in which the scale of interactions can influence cooperative behaviour); (2) the development of new approaches and/or refinements to general methods (methodological advances, such as improving dispersal or optimization algorithms); and (3) the application of modelling methods to the solution of particular problems (pragmatic advances, such as determining likely rates of rabies spread in a particular landscape). Grimm (1999) considered that most Individual-Based Models had focused on the second and third categories, improving methods and solving pragmatic issues, rather than on the more general development of theory. This same observation is true of many other kinds of modelling studies. In defence of model-based approaches, however, I would also highlight the fact that there have been a large number of models that have explored and tested ecological generalities. Many of these generalities are also complex systems generalities (i.e., the findings are not only relevant to ecosystems).

For the remainder of this chapter I will concentrate on introducing spatial models in ecology. This introduction provides a general background to Chapter 5, which contains a more detailed discussion of dynamic modelling of spatial pattern-process interactions in ecology and its relevance for thinking about spatial resilience in social-ecological systems. Note that the focus here is specifically on spatially-explicit mechanistic or process-based models, as opposed to more pattern-oriented, normative, or correlative models (as typefied by predictions of species occurrences or analyses of patch size influences in landscape ecology). I should also state explicitly that a thorough review of spatial ecological models would easily fill several books, and so in what follows I have focused on the small subset of models and ecological problems that have been instrumental in shaping and advancing my own views on spatial resilience. As I shall hopefully make clear, existing ecological models and approaches for thinking about spatial processes have much to offer the study of social-ecological systems and considerable potential for expansion to include social as well as ecological dynamics.

Foundations of Spatial Models

The foundations of spatial models in ecology lie in several different lines of enquiry that ultimately have their own beginnings in the older disciplines of geography and evolution. Scientists like Charles Darwin and Alfred Wallace gained key insights into ecological processes by looking at spatial patterns. Recognition of the all-important influence of climate and landform on plant communities drove early efforts to classify plants into different floral kingdoms and biomes (dating back to von Humboldt & Bonpland, 1807 (reprint 2010)) which were assigned spatial locations. As it became more and more apparent that ecological communities change with changes in location, biogeographers and other scientists became increasingly interested in understanding the role of space in structuring ecological communities. While most early models of basic biological processes made simplifying assumptions of equal mixing and spatial homogeneity (as for gene flow; the Hardy-Weinberg equation is a good example (see Hardy, 1908; Weinberg published the same result in German the same year)), evolutionary biology and vicariance biogeography were reliant on the assumption that new species were formed in isolation (*allopatric speciation*). The mechanisms by which geographic isolation of populations occurred, and the role of spatial separation in evolution, therefore became questions of interest. Darwin's theory of natural selection (Darwin, 1859) placed a strong emphasis on the role of competition – 'survival of the fittest' – and community ecologists became increasingly interested in the spatial aspects of competition and coexistence. Scientific interest in spatial analysis gradually shifted from a descriptive, pattern-based approach towards trying to simulate and understand how variation in space influenced such fundamental processes as dispersal, colonisation, and competition; and the arrival of accessible personal computing technology in the 1980s triggered an explosion of modelling studies by providing the means to run simulation models for large numbers of iterations.

Computerised models naturally drew on intellectual foundations that were already in place, and particularly on a long analytical tradition of analytical (but generally non-spatial, or spatially implicit) population and community models, including such ecological standards as logistic growth equations and Lotka-Volterra predator-prey curves. Because models in ecology have generally been used as tools to test ideas and assumptions relating to a specific question of interest, they have tended to focus at a single hierarchical level. As a result there are distinct subdisciplinary differences between individual-based models, population models, community models, ecosystem models, and landscape models. All have something interesting to say about spatial resilience.

The term 'Individual-Based Model' (IBM) can be slightly confusing, because most ecological models make assumptions about things that individuals do. Basic ecological phenomena such as reproduction, mortality, or dispersal are undertaken by individuals but can be summarized at population or community levels. IBMs are defined by Grimm (1999) as those that explicitly incorporate differences between individuals. Population models look at the aggregate behaviours of individuals; individual reproductive success becomes a population growth rate, individual mortality becomes a population death rate, and individual dispersal frequency translates into a population expansion or contraction rate. Community models are developed through consideration of interactions between different populations that occur in the same location. For example, interacting populations may include predators and their prey or the different plant species that occur in the canopy of a forest. Landscape models have tended to take both population and community models and place them in a spatial arena, often using a patch-corridor-matrix approach (Forman, 1995) as a way of simplifying aspects of landscape structure to make spatial variation more tractable in simple models. Various attempts to integrate different aspects of these frameworks have been made, with varying degrees of success; the differences in predictions made using individual and population-level models respectively offer a potentially valuable source of insights into our understanding of ecology (e.g., Wilson, 1998).

By contrast to most of the other approaches to modelling in ecology, ecosystem models have largely focused on the search for 'common currencies' that can be measured in all system components and exchanged between them. The most widely used common currencies are energy and the pathways by which particular nutrients or compounds (such as carbon, nitrogen, or water) move through the system. The systems ecologist H.T. Odum made a concerted effort to define and work with system properties that also include aspects of human influence on the system, adopting the term 'emergy' (embodied energy) to capture the amount of available energy that went into making a product (Odum, 1995); but his approach has not been widely applied in ecology, partly because of the feeling that reducing ecosystems to circuits and emergy measures glossed over a wide range of important and interesting dynamics. James Kay and Michelle Boyle have recently published an attempt to derive models of social-ecological systems from first principles of thermodynamics (Kay & Boyle, 2008), but in the absence of suitable translation modes (i.e., from theory to practical application), the direct relevance of their approach to interpreting real-world SESs is not yet clear.

In each of these cases, scaling up individual interactions or behaviours to broader spatial and temporal scales results in the aggregation of some system properties and the separation of others (Levin, 1992). As Grimm (1999) states, finding the appropriate degree of resolution or aggregation for a given modelling problem is important; a model with a more appropriate resolution will solve the problem more effectively. Hierarchy theory (Allen & Starr, 1982) advocates the consideration of at least three hierarchical levels when problem-solving in ecology: the focal level, a level above, and a level below. This approach provides a general rule of thumb for what constitutes minimal complexity to include in a model or analysis of a complex social-ecological system. For example, if the focal level is selected as being the community of plants on an island, the level above contains external sources of propagules and herbivores and the level below includes such elements as individual populations and the finer-scale interactions (such as tolerance, facilitation, or inhibition (Connell & Slatyer, 1977)) that influence community composition.

Spatially Explicit Methods

Ecologists have used many different ways of viewing space, ranging from an information-rich depiction of space as a lattice (i.e., a grid composed of numerous cells, in which each cell has an explicit location in space and contains relevant spatially explicit information) through to a depiction of space as a network, a gradient, or a set of irregularly shaped areas such as continents or countries. Of these different approaches, the most intensive methodological development has probably been in creating population and community models in lattices and patch-matrix contexts. Tilman and Kareiva (1997) have provided an excellent introduction to many of these modelling methods. Taking the population as a fundamental entry point to the spatial dynamics of ecosystems, they present the development of mechanistic spatial models in ecology as resting primarily on three different kinds of model: the Levins model, cellular automata, and reaction-diffusion models. To their list I would add island biogeography (MacArthur & Wilson, 1967) as a dominant conceptual influence on spatial modelling, even though the models associated with early formulations of the theory were relatively simple and equilibrium-based. It is also important to note that spatial models have not proceeded as an independent initiative; over the years there has been a continuous two-way exchange of ideas between spatial models and classically non-spatial models, such as the Lotka-Volterra predator-prey equations (Berryman, 1992).

Consideration of evolutionary processes and the patterns of species occurrences on islands led Robert MacArthur and Edward O. Wilson (1967) to formulate the theory of island biogeography, which has been arguably the single most important influence on the analysis of spatial processes in ecology. Among the theory's key insights were the realisations that a wide range of ecological processes – including dispersal, colonisation, mortality, competition, and predation – are directly influenced by (1) the distance of a habitat from other similar habitats (an aspect of location); and (2) the size of the habitat under consideration.

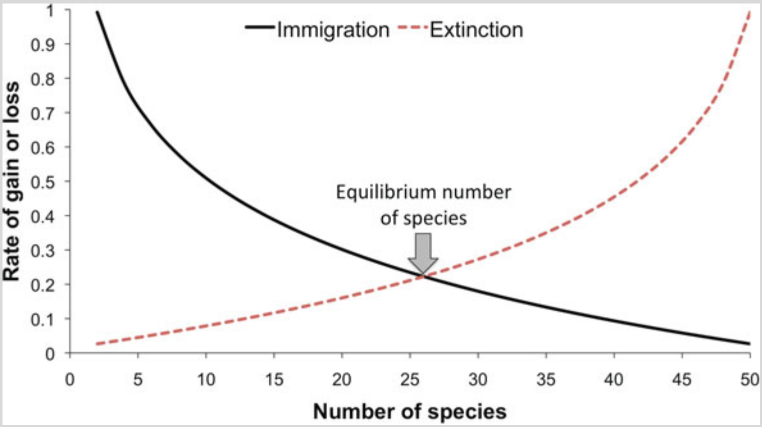
The theory of Island Biogeography drew attention to the importance of the order in which species colonised a habitat, leading to a long-lasting and often fruitless debate over whether general 'assembly rules' could be found for ecological communities (Weiher & Keddy, 1999). Initial formulations of Island Biogeography also made bold assumptions about the tendency of ecological systems towards some form of equilibrium (Box 4.1), setting up a series of debates in ecology that lasted for well over 30 years.

Box 4.1 Fundamentals of Island Biogeography

The theory of Island Biogeography (MacArthur & Wilson, 1967) was originally proposed to describe the relationships between mainland and island communities of plants and animals. The mainland community is assumed to be large, relatively stable (i.e., mainland populations are large and do not go extinct), and diverse. Island Biogeography states that the number of species on an island is determined primarily by immigration, emigration, and extinction. Immigration and emigration are a function of the distance between the island and the mainland, although larger islands should receive more colonisers if colonisation is random (as is often assumed for plant seeds). This is termed the *target effect*. Immigration of more individuals of the same species can also create a *rescue effect* for a small island population.

Extinction may occur through depletion of available resources, competitive exclusion (i.e., one species uses a limiting resource more effectively than another), predation, or perturbations (e.g., periodic eruptions on a volcanic island, or introductions of novel diseases). There has been considerable discussion about the degree to which island size determines extinction rates. For instance: are small islands more vulnerable to perturbations? Are small islands more readily depleted by predators? And does competitive exclusion occur more readily when space itself is limiting? The original theory also made the assumption that colonizing species were relatively interchangeable (i.e., it had elements of *neutrality*). In practise, of course, it could matter a lot for subsequent colonisations whether the first plant coloniser is an edible grass or a noxious weed.

Island Biogeography assumes that immigration rates of new species should decrease as species number on an island increases, simply because the likelihood of a new arrival belonging to a new species is lower. By contrast, the proportion of species going extinct should increase when more species are present because of the greater likelihood of competitive exclusion. These opposing trends lead to the classical Island Biogeography curves, as shown below, which predict a stable equilibrium number of species at the point where immigration and emigration curves intersect. The slopes of the curves are influenced by proximity to the mainland source pool and by island size, with islands that are nearer to the mainland and/or larger supporting more species.



Bob Holt (1992) provided an insightful analysis of the role of internal spatial dynamics in heterogeneous landscapes, linking the species-area concept and the theory of Island Biogeography. Holt was concerned with the influence of fine-scale effects on the predictions of Island Biogeography, particularly on larger islands. His models apply to a situation in which sampling for diversity is undertaken in a single habitat that occurs in several patches across an island (e.g., different wetlands, forest patches, or upland grasslands). Holt (1992) proposed three processes by which surrounding habitat can influence the probability that a species will occur within a sampling area: (1) the *stepping stone effect*, in which the remainder of the island augments the initial rate of colonisation of the island; (2) the *spatial storage effect*, which suggests that if a species goes locally extinct at a sampling site, rapid recolonization can occur from surrounding areas; and (3) the *internal rescue effect*, whereby spillover from nearby populations can buffer fluctuations in the local population and reduce the chance of extinction within the sampled area. Holt explored each of his models further using some relatively simple models, based on small numbers of spatially discrete, interacting compartments, and was able to demonstrate analytically that area effects should be apparent in some populations and not in others, depending on the relevance of each of the three effects. More generally, Holt's three models and his overall approach to exploring the relevance of spatial structure using a minimalistic framework have high potential for further applications in the analysis of the relevance of spatial variation in social-ecological resilience.

More recent developments in island biogeography have included, amongst others, Hubbell's unified neutral theory of island biogeography (Hubbell, 2001); extension of island biogeographic ideas to conservation planning through network analysis (Urban & Keitt, 2001; Urban, Minor, Tremi, & Schcik, 2009); and a wide array of empirical studies that have explored, and continue to explore, the ways in which real-world systems fit or fail to fit the island biogeographic paradigm (e.g., Prugh et al., 2008). A number of good reviews of Island Biogeography exist (e.g., Whittaker & Fernández-Palacios, 2007) and I will not dwell further on its basics tenets except to stress that although the original model falls short of reality in many ways, its value as a unifying framework for spatial analysis in ecology has been immense. As Lindenmayer and Fischer (2006) state, '. . .the island model [can] be seen as a good example of the progress of science and the extent to which it has evolved over the last 30 years'.

A second important influence on spatial models in ecology has been the Levins model, which dates back to 1969 (Levins, 1969). It is a spatially implicit population model, in the sense that it includes a spatial process without individually specifying exactly where within that space each step of the process occurs. The model in its original formulation assumes that a habitat can be broken down into different areas and that each area supports a population. Dispersal occurs within a specified distance away from a population. If dispersing individuals reach a vacant habitat, they survive and start a new population; if they reach an occupied cell, there is no net change to the overall site occupancy within the model. Dispersal occurs at each time step and is followed by a spatially random mortality event in which a certain proportion of occupied habitats are vacated. As Tilman and Kareiva (1997) explain, the model can also be viewed as a series of colonisation and mortality events by individuals. Even after many iterations, the Levins model suggests that no species will completely occupy its habitat at equilibrium unless it has extremely high dispersal ability and extremely low mortality. Interestingly, the model also demonstrates that spatial clustering can arise in the absence of environmental heterogeneity.

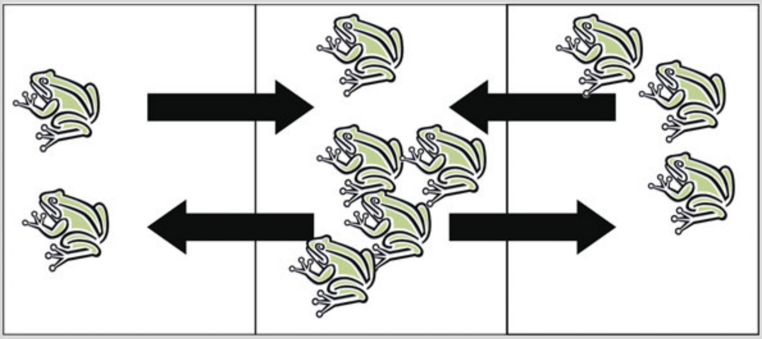
Hanski (1997) points out that the Levins model has served for many years as ‘a cornerstone of metapopulation studies, providing a conceptual foundation for much of the theory and inspiration for empirical studies’. The assumptions of the Levins model can easily be coded in a spatially explicit manner by assigning individuals or populations to a particular location in a landscape, and such translations of the Levins model give rise to a spatially explicit cellular automaton framework. Cellular automata have since become one of the dominant simulation approaches to thinking about spatial processes in ecology. Expansions on the basic model using individual-based approaches have shown that (1) local interactions and local dispersal lead to clumping (Durrett & Levin, 1994; Tilman, Lehman, & Kareiva, 1997); (2) equilibrial abundances in simulated populations tend to be lower than the analytical version of the Levins model, because local dispersal reduces the effective dispersal rate (Tilman et al., 1997); (3) habitat shape matters, because it influences dispersal, and hence can affect not only recolonisation rates but also equilibrial population size (Cumming, 2002); and (4) the relationship between habitat destruction or restoration and dispersal potential in a given landscape is non-linear (Tilman & Kareiva, 1997). All of these results, and other research building on these conclusions, have relevance for our understanding of spatial resilience.

A third major class of spatial approaches is that of reaction-diffusion models (Box 4.2). The great statistician R. A. Fisher was among the first to provide a formulation of spatially explicit gene flow through a population with his formulation of a genetic reaction-diffusion model in 1937 (Fisher, 1937). Reaction-diffusion models were applied more directly to entire organisms by a number of subsequent researchers and were brought to prominence by Skellam (1951) in his synthesis of data on invasions by muskrats and other species. Reaction-diffusion models are still important analytical tools in ecology (e.g., Okubo, 1980; Roughgarden, 1998).

Box 4.2 Reaction-Diffusion Models Explained

Reaction-diffusion models are spatially explicit models for continuous space and time. *Reaction* refers to a process of population change or species interaction in the absence of dispersal. *Diffusion* describes movement. In practice, reaction and diffusion are modelled separately, with reaction occurring between each set of movements (Okubo, 1980).

In a simple diffusion model, individuals are exchanged between locations in proportion to their local abundances. The diffusion coefficient, termed *D*, describes the dispersal rate. You can visualize diffusion in action by first imagining a small enclosure with high external walls, divided by two low partitions into three 20 × 20 cm compartments. Then visualize what happens if you put ten lively frogs into the central compartment.



If the partitions are only 1–2 cm high, the frogs can freely hop about at random, gradually resulting in a more even distribution of frogs between compartments. Raising the height of the partitions is equivalent to increasing the value of *D*; it gets harder and harder for the frogs to cross between compartments. Note also that in the central compartment, frogs can enter or leave via two different routes; while in the edge cells there is only one neighbour.

To express this process in mathematical terms, call *N*(centre) the number of individuals in the centre cell, and *N*(left) and *N*(right) the numbers in the adjacent cells. In a small unit of time, the change in *N*(centre) is given by the equation

$$\frac{\Delta N(centre)}{\Delta t} = DN(left) + DN(right) - 2DN(centre)$$

For cells with three or four neighbours, an additional term for each compartment is added and the number by which the central cell is multiplied changes from 2 to 3 or 4 respectively. This expression constitutes a discrete approximation to the equation

$$\frac{\partial N}{\partial t} = D\frac{\partial^2 N}{\partial x^2}$$

Where N is the number of individuals, x is space, t is time, and D is the diffusion coefficient. Adding logistic population increase (a very standard ecological equation) to this model gives us

$$\frac{\partial N}{\partial t} = D\frac{\partial^2 N}{\partial x^2} + rN\left(1 - \frac{N}{K}\right)$$

Where r is the rate of population growth and K is the carrying capacity of the habitat. This is the ‘Fisher equation’ that was first used by R. A. Fisher in 1937 to model the spatial spread of new genes in a population (Fisher, 1937). Although it looks imposing, it is quite straightforward to programme. Matlab code for a spatially explicit reaction-diffusion model (and an animated demonstration of the model in action) is available on line through the *Ecology and Society* web site, at the same URL as Cumming (2002).

Concluding Comments

Ecology, like many other disciplines, suffers from a surplus of untested models. In its defence, however, I would argue that spatial modelling in ecology has been relatively productive; and that this productivity has in part been due to the willingness of ecologists to confront their models (or more frequently, other people's models) with empirical data. In the past 50 years there have been many critical analyses and reanalyses of different assumptions in ecological models, and many of these criticisms have improved our understanding of both generalities and specifics in ecology. Field studies and the deliberate testing of model assumptions also have an important role to play in the development of social-ecological models and the advancement of SES theory.

In addition to the approaches that I have discussed here, there have been a number of other important influences on the development of spatially-explicit ecological models. Some of the more important of these have included work in epidemiology (understanding spatial patterns of pathogen occurrence); metapopulation and metacommunity models, which have largely proceeded from the Levins model and island biogeography, but with the addition of increasing levels of sophistication; spatial models of source-sink dynamics, predator-prey cycles, and synchronous population fluctuations; and neutral landscape models. Given the long history of models in ecology, and the potential for ecological models to be generalised to include other phenomena, many areas of ecological modelling have high relevance for our understanding of spatial resilience in social-ecological systems. Some of these areas of modelling are explored in more detail in the next chapter.

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Chapter 5
Spatial Models in Ecology and Spatial Resilience

Introduction

Chapter 4 provided an overview of the goals of modelling and some of the more important spatially explicit modelling approaches that have been developed in ecology. It also served to introduce some of the ways in which space is conceptualised in quantitative analyses; for example, as a series of islands sitting in a matrix, as a lattice of regularly shaped cells, or as a continuous space through which organisms can diffuse. Chapter 4 did not, however, address the question of what we have learned about spatial resilience in SESs from applications of these methods.

This chapter builds on the preceding chapters to address two important questions. First, if ecosystems are viewed as examples of complex systems, which areas of SES theory are particularly amenable to being explored in ecosystems? And second, what insights and general principles do existing ecological models offer about spatial resilience?

I start by explaining why I have focused this chapter on *ecological* models. I then present five areas of SES theory that have particular relevance for spatial resilience in SESs and explore how spatial models have been applied in each of these areas, focusing on ecology but drawing parallels outside ecology where possible. The chapter concludes with a summary of the general principles that emerge for understanding spatial resilience in SESs.

Why Focus on Ecological Models?

Some additional justification for devoting an entire chapter of an interdisciplinary book to the details of ecological models seems necessary. Approaches to modelling ecological systems are clearly an important tool in any analytical toolbox for the study of social-ecological systems. In my opinion, however, the value of many ecological models goes well beyond that of providing purely ecological insights. There are three important points to consider here.

First, the value of delving in some depth into ecological models in an interdisciplinary context is enhanced by the fact that ecology has borrowed freely from other disciplines. This borrowing extends well beyond the incorporation of models

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of the biophysical components of ecosystems from disciplines such as hydrology, geology, oceanography, climate science, and the science of land use and land cover change. Graph theory, for example, arose in pure mathematics and one of its offshoots has been a set of network metrics that were initially used in the social sciences for thinking about interactions between people. In recent times, ecologists have applied network analysis to such problems as understanding transmission pathways for pathogens (e.g., Kenah & Robins, 2007; Takeuchi & Yamamoto, 2006), defining key patches of habitat in protected area networks (e.g., Urban & Keitt, 2001; Urban, Minor, Tremi, & Schcik, 2009), and understanding food webs and mutualisms (Bascompte, Jordano, Melian, & Olesen, 2003; Pascual & Dunne, 2006). Ecology and evolutionary theory also have a long history of interaction with economics, particularly in regard to understanding resource limitation, competition, and adaptation to local conditions (e.g., Beinhocker, 2007; Nelson & Winter, 1982). Ecological models thus provide a representative cross-section of existing spatial models.

Second, because models and analytical techniques abstract so many aspects of reality and reduce them to a small subset of key components and interactions, disciplinary models often reflect a set of more general underlying principles. When jumping between disciplines, it is not uncommon to find essentially the same modelling approaches being applied (with subtle differences) in different circumstances and to different systems. Sometimes these approaches have arisen independently and in other cases a single major advance, such as the development of calculus, has become a key problem-solving tool that has then been applied to a wide range of problems. In either case, in-depth familiarity with any one discipline usually facilitates interdisciplinary applications.

Third, and perhaps most importantly, if complex systems that have traditionally been considered from separate disciplinary perspectives are organized according to a common set of principles, we would expect to find that both methods and concepts from any discipline that has truly grappled with complexity are readily transferable between contexts. This kind of transfer is of course not to be undertaken naively, through drawing loose but unsubstantiated parallels, but careful argument and empirical research have suggested that a number of common mechanisms underpin different kinds of complex system (Beinhocker, 2007; Norberg & Cumming, 2008).

A particularly interesting example of the potential for simultaneous conceptual and methodological exchange between superficially different areas of research is provided by genetic algorithms, which can be used to find optimal or close-to-optimal solutions to particularly difficult, non-linear problems (Holland, 1992a, 1992b; Mitchell, 1996). Genetic algorithms simulate natural selection by creating a large set of possible solutions at random; measuring the success (fitness) of each solution; and then allowing the more successful solutions to recombine, mutate, and replicate. Computer scientists initially advanced the development of genetic algorithms as problem-solving tools, focusing on problems in machine learning and artificial intelligence. Somewhat ironically, evolutionary biologists have since benefitted from the conceptual insights that their discipline offered computer scientists through the development of genetic algorithm-based approaches to determining parsimonious configurations of evolutionary trees. Genetic algorithms have been used in interesting ways in ecology, for example to model the group dynamics involved in anti-predator and foraging behaviours (e.g., Barta, Flynn, & Giraldeau, 1997; Ruxton & Beauchamp, 2008); to simulate adaptive dynamics in evolving populations (Dieckmann, 1997; Egas, Sabelis, & Dieckmann, 2005); and to predict species occurrences using an approach called GARP (Genetic Algorithm for Rule-Set Prediction; Elith et al., 2006; Roura-Pascual, Brotons, Peterson, & Thuiller, 2009; Stockwell & Noble, 1992).

Generalities and Models

Applications of spatially explicit models in ecology have explored at least five general areas of theory that have high relevance to understanding spatial resilience in SESs. They include (1) understanding the spatial behaviour and functional importance of individual system components, in terms of the number of different components, the abundance of each individual component, and the nature of the components (i.e., what their basic properties are, where they are located, and what they do); (2) understanding the spatial nature of interactions between components, including competition, predation, and various kinds of interdependence, cooperation and facilitation (such as mutualism, commensalism, and parasitism); (3) documenting spatial dependencies in scaling relationships, including how individual behaviours, such as reproduction or dispersal, influence population-wide trends, spatial persistence, and population and community resilience; (4) understanding the role of the external environment and the ways in which it influences and is influenced by system components and interactions; and (5) understanding the role of disturbance, the ways in which it affects system-wide properties, and how it is propagated across a landscape. I will structure my discussion of what spatial ecological models tell us about spatial influences on ecological and social-ecological resilience around these five themes. While exploring themes, there is some overlap in methods and a high potential for confusion; Table 5.1 is intended to help the reader to keep track of the different models discussed in this chapter and the preceding chapter.

The Importance of Individual System Components

Diversity (component differentiation) is a general property of all complex systems and has important implications for system resilience (Norberg, Wilson, Walker, & Ostrom, 2008). System components exist in space, and hence exhibit pattern; and in many cases, the spatial structuring of different components of biodiversity dominates system dynamics. For example, the distribution of different antelope species in an African savanna interacts with the distribution of lions in an ever-shifting mosaic that influences patterns of herbivory, nutrient cycling, and trampling impacts (e.g., Cumming & Cumming, 2003; Ogutu & Dublin, 2004; Valeix et al., 2009); and large termitaria can have a profound structuring effect on vegetation (Fig. 5.1).

Table 5.1 A brief guide to some of the kinds of model that are commonly used to study spatial processes in ecology, and their applications. Most of these models are discussed in more detail in the text of Chapters 4 and 5. This is not intended to be an exhaustive summary, but rather a quick reference for the reader who is unfamiliar with this particular area of research

Kind of model	Typical context	Use and spatial example
Analytical models – describe systems using one or more equations and draw inferences by solving and exploring the equations.	Used to develop theory and explore the world in many fields. The most comprehensive modern examples come from Physics (e.g., theory of relativity)	Amongst other things, analytical models have been used to describe ecological stability and regime shifts. Because of their generality they are the 'gold standard' of modelling, but they are limited to problems (equation systems) that can be solved, making them less relevant for spatial dynamics in which the explicit inclusion of space makes analysis difficult
Cellular automaton models – simulate processes in a spatial lattice by repetition of simple rules	Widely used in a variety of fields including ecology and economics	Useful for exploring influence of habitat structure and spatial variation on ecological processes. Easy for the unwary to over-parameterize
Disturbance models – model impacts of disturbances or perturbations on ecological communities	Community and population ecology Landscape ecology	Typically link a 'disturbance generator' function with a successional model that simulates system recovery. Spatial models of fire offer a good example, linking succession, habitat susceptibility to fire, and a cellular automaton approach to fire spread/contagion between patches
Individual-based models (IBMs) – simulate individual behaviours rather than average over a population	Population ecology Optimal foraging studies	Understanding costs and benefits of different individual dispersal strategies; analysing variation in avian or mammalian territory sizes. Relevant where individual differences matter for topic of study

Table 5.1 (continued)

Kind of model	Typical context	Use and spatial example
Levins model – spatially implicit model of plant propagation and dispersal in a homogeneous environment	Population ecology	Plant population dynamics in a spatial context. No longer widely used but made an important contribution to other approaches, including metapopulation models and cellular automata
Lotka-Volterra models – describe predator-prey population dynamics as a pair of waves, with predator numbers both regulating prey and being regulated by prey.	Population and food web ecology	Understanding impacts of increased or reduced predation on a prey population; explaining cyclical dynamics such as between owls and lemmings. Although not spatial, the original equations can be extended by making interactions spatially dependent, tracking numbers in different locations, and adding dispersal
Mass-balance models and related models of climate change – track flows of substances and quantify materials entering and leaving a system	Ecosystem ecology Climate change science	Global carbon budgets; exploring nutrient transfers between aquatic and terrestrial systems; global circulation models. Suitable for study systems in which nutrients or energy offer a good common currency to link different components
Classical population models – average properties over a population to describe 'typical' behaviours (e.g., recruitment, mortality, dispersal)	Population ecology	Quantification of maximum sustained yield from a harvested population; population viability analysis (PVA). Can offer useful guidelines when assumptions are met, may be invalidated by individual differences and environmental variability

Table 5.1 (continued)

Kind of model	Typical context	Use and spatial example
Metapopulation models – simulate dispersal, reproduction, colonization and extinction events in a patchy habitat	Population ecology Landscape ecology	Understanding dynamics of metapopulations of patch-dwelling organsisms, such as frogs, butterflies, or forest birds. Widely used to explore impacts of landscape change in conservation. Strong conceptual connection to Island Biogeography
Network models	Increasingly common use in ecology, sociology, and economics	Studies of food webs and plant-pollinator relationships. Network methods are discussed in detail in Chapter 6. Useful for exploring questions of system architecture in relation to system function
Random walk – null model of movement in the absence of choice	Movement ecology	Null model in which location at time t is independent of external environment but depends on location at time t+1. Simplest movement model
Reaction-diffusion models – model dispersal as Brownian motion in continuous space and time using differential equations	Population and Community ecology Movement ecology Landscape ecology	Simulating species invasions. Conceptually, the reaction-diffusion framework is widely used in model development (i.e., model movement and interactions or effects iteratively as two different steps)
Statistical models – often correlative, seek to explore and explain variation and/or to predict outcomes based on empirically derived (rather than a priori) relationships	Ecology, sociology, economics	Using multiple regressions to predict species occurrences; relating spatial heterogeneity to biodiversity or related ecosystem processes. Widely used across ecology Because statistical approaches often ignore mechanisms or lack a good underlying process model, there are many ways to go wrong in applying these methods. There is a recent trend towards entertaining and comparing multiple models rather than assuming a single model is ‘true’

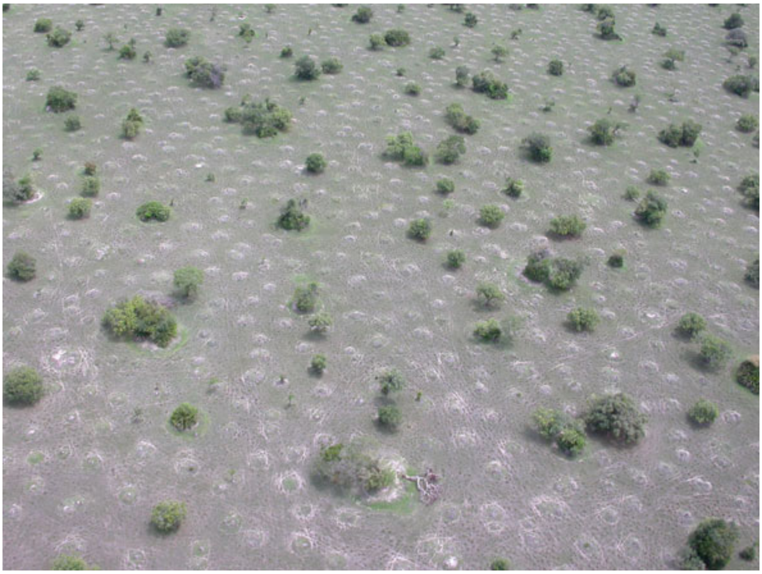

Fig. 5.1 Woody vegetation is found only on termite mounds in this seasonally flooded woodland near Lake Bangweulu, in northern Zambia. Photograph by Graeme S. Cumming

Ecological tradeoffs at the individual level are often explored using individual-based models. Individual-based models (IBMs) generally focus on explaining higher-level ecological patterns as a consequence of things that individuals do, such as feed, mate, raise offspring, defend territories, disperse, or die. They stand in contrast to many classical population models, including population viability analysis, which do not explore the significance of differences in individual traits. Ecology provides numerous examples of IBMs in action and interested readers are referred to the many good books on this topic (e.g., De Angelis & Gross, 1992; Grimm & Railsback, 2005) for greater detail.

Some kinds of IBM are more directly relevant than others to understanding spatial resilience. The most relevant IBMs include (1) models that take explicit account of dispersal, both as a driver of change and as a strategy for the persistence of populations; (2) models that focus on resource requirements and territory sizes, particularly where these interactions generate spatial structure in an ecosystem; and (3) models that consider the relevance of dispersion (as opposed to dispersal – dispersion refers to patterns of occurrences, such as aggregation, evenness or randomness) and other aspects of spatial pattern for important system dynamics.

Dispersal is a central process in nearly all spatial models and as technologies for tracking both plants and animals have improved, ecological understanding of dispersal processes and their importance for spatial pattern has greatly improved. Cain, Milligan, and Strand (2000) have argued that long-distance dispersal is particularly important for plants and plant communities, influencing a wide range of relevant aspects of their ecology and evolutionary biology. In many cases, attributes that make organisms good at dispersal are thought to make them weaker on other fronts, such as their competitive ability, their ability to avoid predation, or their ability to survive in harsh conditions. This tradeoff is particularly apparent in seeds, which disperse more readily when small and light but tend to be more effective competitors and more resistant to environmental hardships when large and nutrient-packed.

Individual-based dispersal models generally focus on the importance of variations in dispersal ability within a population and their relevance for population persistence. A number of models of plant dispersal have incorporated mixed dispersal capabilities, in which different probability distributions are used to model local and long-distance dispersal (Cain et al., 2000). A consensus appears to be emerging in this field that although long-distance dispersal events may be rare, they are fundamental to the long-term persistence of plants in variable environments (e.g., Nathan et al., 2008).

More generally, the tradeoffs between dispersal cost and competitive ability suggest some important principles for spatial resilience in social-ecological systems. Both resource acquisition and adaptation to local environmental fluctuations will depend heavily on the ways in which tradeoffs between size and manoeuvrability are determined. For example, in an economic context, one might expect a sunk cost effect to come into play. Sunk costs are past expenses that cannot be recovered – for example, investment in specialised machinery that can not later be resold. Although sunk costs should in theory be irrelevant to future decisions, they can be blamed for seemingly irrational decisions in a variety of contexts (Arkes & Ayton, 1999). Agrarian societies that have made high investments in infrastructure (houses, roads, irrigation systems, etc.) may be unwilling to abandon a degraded location during periods of climate or ecological change; sunk cost effects have been blamed, amongst other things (see Box 5.1), for consistent patterns of overexploitation of renewable resources by ancient societies (Janssen, Kohler, & Scheffer, 2003; Janssen & Scheffer, 2004). In a modern situation sunk cost effects might evidence themselves through trends such as chain stores that place a high investment in particular locations (e.g., large book stores or supermarkets with high amounts of standing stock) being less willing to move the locations of their outlets than smaller, more flexible chains that make lower investments in location. Consequently, the importance of competition with providers of similar products should differ substantially between these different business models. Although the analogy to organisms can only be stretched up to a point, this line of thinking does suggest that spatial resilience in firms, and their ability to adapt to spatially and temporally variable patterns of consumer demand, will also depend on a suitable tradeoff between dispersal ability, investment, and competitive ability.

Box 5.1 The Ghosts of Civilizations Past

People have been intrigued for centuries by the artifacts – such as buildings, pottery, and writing – of long-gone civilizations. The decline of the Roman empire has become one of the most famous events in history, but it was by no means unique; apparently similar fates overtook the Babylonians and the Maya, as well as a host of lesser-known empires such as the Rozvi in southern Africa and the Mauryan Empire in India.

The decline and collapse of empire states poses an interesting challenge for theories about complexity and resilience. Why have so few empires been able to remain resilient, and what can modern civilizations learn from the past? Although the collapse of a civilization is almost inevitably a consequence of a number of driving forces acting together (such as population growth and expansion, depletion of soil nutrients, disease and drought, weak leadership, and conquest), can ideas about resilience and complexity provide a way of identifying common threads?

An interesting perspective on the collapse of civilizations comes from the work of Joseph Tainter (Tainter, 1988, 2006). Tainter argues that many of the changes in civilizations can be explained by the relationship between society and what he terms social complexity. Social complexity can be thought of as consisting of the human structures – institutions, organizations, communications networks, and legal systems, for example – that we depend on as a society. Social complexity is essential for collective problem solving and hence for sustainability. While social complexity plays an important role in keeping society running smoothly, however, it also has costs. As Tainter argues, increasing amounts of energy, labour, money, information, and time are needed to create, maintain, and replace systems that grow to be increasingly demanding. In addition, increases in social complexity demand the creation of a whole set of roles for people who do not contribute directly to primary resource production.

Early in the growth of a civilization, the addition of social complexity tends to more than justify its own costs through the benefits that it produces. Over time, however, societies may reach a point where the cost of social complexity starts to return proportionally less and less. At this stage, the maintenance of social structures becomes an increasing burden on society. In the case of environmental problems, solutions that generate higher complexity and increased costs eventually become unsustainable. Collapse often follows the point at which problem solving through increasing complexity becomes unsupportable. In the case of the Roman Empire, for example, the cost of increasing social complexity was solved for many years by the acquisition of resource surpluses from neighbouring territories. Once the Empire became too large for this process to work effectively, problems such as regional crop failures could no longer be solved by conquest and the Empire gradually fell apart.

Tainter's theory is not usually considered a spatial theory, but it has strong overtones of scale and connectivity. Integrating his ideas with the analysis of spatial resilience presents an intriguing challenge.

A second entry point into thinking about the relevance of spatial variation in individual-based ecological models comes from the consideration of resource needs, and particularly of spatial and temporal variation in individual territory/home range sizes. Survival will usually be higher in areas with which an animal is familiar, because foraging becomes more efficient once resource-rich foraging areas have been identified, suitable shelter and roosting sites are found and re-visited, and local predators, as well as the definition and use of suitable predator escape routes, become familiar. Since most resources are not distributed evenly across landscapes, individuals of many species choose to find areas in which they can survive and to remain in them. At the population and community level, this tendency creates the potential for competition for particular favoured locations. Cody (1974) viewed spatial segregation (territoriality) as a consequence of attempts to reduce competition, both between conspecifics and between individuals of different species. Spatial segregation may also reflect differences in habitat requirements; it is not necessarily competition-driven, particularly in patchy environments (Wiens, 1992, p. 349). While spatial segregation may benefit organisms, it can also have costs in terms of mate-finding, predator avoidance, and reproduction. Many birds, for example, are communal throughout much of the year and defend territories only during the breeding season when rearing offspring creates higher energetic demands. Territory size, location, and heterogeneity, in both space and time, should therefore reflect the needs of the organism and its competitive ability as well as the nature of the surrounding community.

There have been many empirical analyses of territory size (e.g., see Kelt & Van Vuren, 2001). The basic ingredients involved in home range establishment have also been incorporated into numerous spatial models (e.g., Mitchell & Powell, 2004). Borger, Dalziel, and Fryxell (2008) have summarized research on home ranges under three primary domains: (1) movement models based on random walks; (2) individual-based models based on optimal foraging theory; and (3) statistical modelling approaches. They conclude that although development in each of these domains has occurred independently, the potential now exists for the development of an approach that will conceptually unify ideas about home range size, spatial and temporal scale, animal behaviour, and ecological and evolutionary processes. Such a development has the potential to contribute usefully towards the development of a broader mechanistic framework that will provide a set of expectations for the relationships between human societies, resources, and spatial variation in the environment.

Third, the dispersion and spatial pattern of individual components can have important implications for long-term ecosystem dynamics. Understanding the spatial impacts and spatial relationships between individual system components is important not only for our understanding of ecosystem processes but also for the management of social-ecological systems. For example, elephant can have profound impacts on woodland structure and at high densities can shift vegetation types between relatively stable states of woodland, shrub, and grassland, depending partly on the interactions between vegetation and fire. There is a tendency in southern African protected areas (such as the Kruger National Park in South Africa, or Hwange National Park in Zimbabwe) for managers to create artifical watering points to assist elephants and other herbivores through the dry season. Various attempts have been made to model the impacts of the addition or removal of artificial wells (Smit, Grant, & Whyte, 2007). Models and empirical analyses show that the addition of artificial watering points spreads elephant impacts far beyond what would have been historical norms, with potential negative consequences for other species in the ecosystem (Cumming et al., 1997).

Many spatially-explicit ecological analyses have strong parallels in human social systems. Humans are also animals and many people exhibit consistent spatial patterns in where they undertake different activities, such as work, recreation, sleeping, and shopping for food. As in other animals, the ways in which people use their environment can influence such things as information transfer, pathogen transmission, and mate choice. Some of the spatial effects of human societies, such as the extraction of resources, can be extended by human communities well beyond their immediate sphere of occupancy (Berkes et al., 2006); the ecological footprints of large cities, for instance, can extend many kilometres beyond their official boundaries (e.g., Luck, Jenerette, Wu, & Grimm, 2001). Where demands for resources overlap between different communities, conflict can arise. This is particularly apparent in regard to limiting resources, such as water; the existence of an entire branch of water law bears testimony to the continual conflicts that surround water extraction and the need to balance upstream and downstream demand.

As this discussion suggests, Individual-Based Models can play a useful role in exploring the relevance of spatial properties of system components, as well as the importance of spatial variation in their interactions with other components and with the broader social-ecological system.

Interactions Between Components

Interactions between components form the basis for community ecology. One of the big questions in ecology has been that of how biodiversity persists in the face of asymmetric interactions. In particular, the question has been posed as to why a single species (i.e., a superior competitor that could dominate access to available resources) did not become dominant in most real-world ecosystems. How do different species, particularly those that use the same resources, manage to coexist in the same environment? As the eminent ecologist George Evelyn Hutchinson (1959) put it, ‘Why are there so many kinds of animal?’ This theme is not unique to ecology; in the economic realm, laws are in place to restrict ‘unfair competition’ or market dominance by a single company. The same plot line can also be found many popular science fiction books and films: why should it be difficult for a single species of alien to take over the earth?

Explorations of different aspects of coexistence have dominated ecological models in community ecology. The answers that these analyses have found lie in both intrinsic system properties (such as the number and nature of species present, their interactions, and their abilities to exploit different niches) and the properties of the system's surroundings and context, including such things as the frequency and magnitude of perturbations (e.g., fires, floods, pathogen outbreaks) and the role of dispersal of propagules and organisms from other habitats into the system of interest. In recent years there has been an increasing recognition that spatial variation is an important component of ecosystems and can have profound effects on the resilience of ecolgical communities.

Holt and Dobson (2007) provide a useful summary of the ecological mechanisms that facilitate coexistence. Most of these mechanisms have formed the grist for various kinds of model, both spatial and non-spatial. Holt and Dobson (2007) summarize them under three main categories: (1) Coexistence in closed, equilibrial models (mechanisms include classical niche partitioning, localized interactions between individuals, food web effects such as density-dependent prey-switching by predators, and nontrophic mechanisms of population regulation); (2) Closed, nonequilibrial communities (mechanisms include temporal niche partitioning, also called storage effects, and nonlinear dynamics such as inherent instability in populations of one or both competitors); and (3) Open communities, for which external spatial mechanisms are invoked. The spatial mechanisms invoked under open communities include (a) migration and habitat selection (assuming first that if different species are regulated at different seasons and/or in different habitats, they can coexist; and second, that species with different dispersal capabilities can effectively partition resources by averaging over spatial variation in different ways); (b) metapopulation processes, for instance if inferior competitors can rapidly occupy vacant patches following a disturbance while superior competitors return more slowly; and (c) source-sink dynamics, under which a species that competes well in one habitat can remain present in a lower quality habitat if there is continued immigration from the higher quality habitat.

Ecologists have also been interested for some time in the role of spatial subsidies, typically in the form of inputs of nutrients or individuals from other locations (Polis, Power, & Huxel, 2004; Polis & Strong, 1996). Recent research has shown that many real-world ecosystems are heavily reliant on spatial subsidies (Box 5.2), ranging from long-distance transport of dust fertilising oceanic islands (Chadwick, Derry, Vitousek, Huebert, & Hedin, 1999; Vitousek, 2002) through to inputs of nutrient-rich salmon in low-nutrient Alaskan streams (e.g., Helfield & Naiman, 2001; Wipfli, Hudson, & Caouette, 1998). One-directional inputs of organisms from one habitat to another can also be considered a form of spatial subsidy. Spatial subsidies create the potential for a variety of intriguing dynamics, such as source-sink relationships, in which a habitat that is a net importer of individuals can nevertheless maintain a population of a given species if immigration rates from an adjacent source (net exporter of individuals) are sufficiently high (e.g., Breininger & Carter, 2003; Dunning et al., 1995; Gundersen, Johannesen, Andreassen, & Ims, 2001).

Box 5.2 Spatial Subsidies

Recognition of the importance of spatial subsidies is relatively recent in ecology. From a food web perspective, the basic components of food webs (nutrients, detritus, and organisms) are all capabale of crossing the boundaries between supposedly distinct systems (Polis, Anderson, & Holt, 1997, 2004). These border-crossings can have large impacts on the receiving food web. As Polis et al. (1997) point out, the degree to which a system receives subsidies is often a function of its perimeter to area ratio. Systems with proportionally more edge are likely to receive more external inputs. The relative importance of a subsidy is thus expected to change predictably with system size and shape as well as with location along a biophysical gradient.

A good illustrative example of spatial patterning in subsidies comes from the river continuum concept (Vannote, Minshall, Cummins, Sedell, & Cushing, 1980). The river continuum concept suggests that rivers change predictably along an elevation gradient from their headwaters to their estuaries, passing through several notably different stages. Near the source, typical rivers are small, rocky, fast-flowing sequences of riffles and pools. At this stage the amount of edge relative to the width of the river is high, sediment loads tend to be small, and the influence of external inputs (such as leaf litter and surface runoff) is large. Specialised invertebrate communities in healthy streams maintain water quality by breaking down leaf litter and recycling nutrients along the stream's length.

As a typical stream cuts through its escarpment and reaches a coastal plain, its width increases and the nature of the underlying substrate shifts from rocky to sandy or muddy. By the time a large river reaches the sea, it is often composed of a number of high-volume braided channels with relatively flat channel morphology and high sediment loads. For large rivers, the proportional impact of external subsidies is usually small; leaf litter and immediate runoff inputs are trivial by comparison to the volumes of substances already present in the water. However, since the quality of the water is strongly determined by upstream processes, water-borne nutrients can be considered a subsidy from upstream to downstream ecosystems (Polis et al., 1997).

In Alaskan streams that are used by salmon (*Oncorhynchus* species), salmon themselves provide a subsidy (Helfield & Naiman, 2001; Wipfli et al., 1998). The adults mature at sea, capturing marine nutrients. When they reach maturity they carry these nutrients upstream from the sea, mating and then laying their eggs in small, clear, cold water streams before dying. Research has shown that the amount of nitrogen released from the decaying bodies of the adults is sufficient to increase juvenile survival. Salmon-derived nutrients also have beneficial effects on riparian vegetation and may be further transported into terrestrial environments by animals like bears and eagles (Spencer, McClelland, & Stanford, 1991). The highlands of Alaska are thus intricately connected to the oceans through the web of life.

In many of these cases the basic principle is clear: spatial variation, both within and between communities and habitats, provides opportunities for population persistence that generally do not exist if a community is well-mixed and homogeneous. Spatial heterogeneity can therefore be seen as a stabilising influence in some cases, depending on the match of organisms to habitats. Spatial heterogeneity can also lead to instability; and this instability can in turn lead to either increased or decreased system resilience, depending on its scale, its interactions with the disturbance regime, and its influence on community composition. More than 20 years ago, Peter Kareiva (1986) pointed out that insect communities have been difficult for ecologists to understand because environmental heterogeneity has not been included in theories of species interactions and spatial aspects of variation have been ignored in field studies. Although it is no longer true that environmental heterogeneity has been ignored in entomology, Kareiva's comment is highly relevant for many studies of social-ecological systems, in which spatial influences are likely to have much greater effects than the typical case study assumes.

Studies of spatial aspects of classical ecological interactions often offer useful insights into spatial resilience. I will illustrate this point using examples from two different kinds of ecological interaction, predator-prey relationships and plant-pollinator mutualisms.

Predator-prey dynamics in ecology are commonly modelled using the Lotka-Volterra equations (formulated independently by Alfred J. Lotka in 1925 and Vito Volterra in 1926; see review, and comments on subsequent developments, by Berryman, 1992). In their simplest form, the equations assume a simple two-step interaction in which first, predators deplete their prey until prey numbers become low enough to regulate predator numbers; and second, with predation reduced, prey numbers increase to the point where predator populations can start to rise again. If changes in predator and prey populations are plotted over time, this dynamic produces a pair of curves that are slightly out of phase because of the time lag involved in demographic responses (response time is usually longer for predators, which are often larger-bodied than their prey and typically produce fewer offspring).

If spatial variation in the environment is introduced into analyses of predator-prey interactions, a number of different variables must be considered when framing the problem. Predators tend to use particular landscapes in particular ways, taking advantage of natural variation in such things as den sites, drinking water, cover, movement corridors (Fig. 5.2) and locations of prey (e.g., Valeix et al., 2009). Prey are capable of responding their predators and tend to avoid areas where predation risk is high, giving rise to 'landscapes of fear' (e.g., Laundré, Hernández, & Altendorf, 2001; Willems & Hill, 2009). Predators must locate their prey in space and in some circumstances searching and handling times become critical, depending on the benefits received from each prey item. The three basic types of predator-prey relationship, and the mechanisms underlying them, have been nicely captured by Buzz Holling (1959a, 1959b, 1966).

Fig. 5.2 A spotted hyaena follows a road to Mpila Camp in Hluhluwe-Imfolozi Park, South Africa. Hyaenas are commonly seen near to camp in the evening, travelling along the roads to scavenge on discarded rubbish and unattended cooking fires under the cover of night. Photograph by Graeme S. Cumming

Simple models suggest that predator-prey models that incorporate the aspects of space, dispersal, and localized interactions are more stable than models that assume homogeneous mixing of predators and prey (Holt, 1984; Holt & Barfield, 2009; Hosseini, 2006). Some detailed insights into the nature of the problem are offered by Pascual, Mazzega, and Levin (2001), who investigated the role of space in predator-prey dynamics in some detail using simple simulation models. They concluded that spatial variation at broad scales reduces the total number of predator-prey interactions on a per capita basis, but leaves the basic form of the relationship intact. The result is that some of the oscillations that might be found in a more homogeneous system are ironed out. In other words, spatial variation at broad scales can reduce temporal variation within the system. Fine-scale interactions are ‘flashier’ and at intermediate scales, irregular predator-prey cycles can arise as a consequence of interactions between demographic stochasticity and the ‘decaying’ fluctuations in population sizes that result from spatial patterns.

There are a number of real-world examples that support these conclusions. A particularly interesting case study of the importance of spatial variation in considering predator-prey dynamics comes from the reintroduction of wolves into Yellowstone National Park in the USA (Laundré et al., 2001; Ripple & Beschta, 2003, 2007; Ripple, Larsen, Renkin, & Smith, 2001). During the period when wolves were absent the elk literally became a bunch of lazy socialites, spending much of their time hanging around in herds on the edges of streams in the park and feeding on riparian vegetation. They had to sharpen their act up quickly when wolves reappeared and soon reverted to more traditional elk-like behaviours, spending more time in forested areas where there was more cover and venturing out into the open less frequently. The unexpected consequence of this behavioural response was that elk impacts on streams within the park were substantially reduced, resulting in significant improvements in water quality and resulting benefits to both aquatic and terrestrial organisms. From a systems perspective, the reintroduction of a key system element and an important interaction led to a more sustainable usage of space and a reduction of pressure on key resources.

Plant-pollinator interactions are very different from predator-prey relationships in the sense that they involve mutualisms, defined as mutually beneficial interactions. Flowers that produce animal-dispersed pollen rely on their pollinators for mating (my favourite description of a honeybee is as a 'flying penis', although I can't recall where I first heard this); and pollinators in turn depend on flowers for food. Mutualistic success depends on pollinators finding plants, and so plants have developed some obvious signals – such as brightly coloured flowers – to attract pollinators (Barth and Biederman-Thorson, 1991). Flowers may benefit from occurring in clumps, because clumped resources are more likely to attract pollinators; but flowers in a clump may also receive reduced visitation rates if they can not compete effectively with their neighbours, and the risk of self-pollination or pollination from a closely related individual (with the resulting loss of genetic diversity) may be higher.

Although flowering plants and prey items do different things – one attracts pollinators, the other avoids predators – the spatial aspects of mutualisms and predator-prey interactions have a number of commonalities. For instance, resources (prey or flowers) are spatially dispersed in distinct ways, often in impermanent aggregations; both pollination and predation involve a tradeoff between search time and handling time; predators may be vulnerable to kleptoparasitism (other animals stealing their prey after a successful hunt), while flowers are vulnerable to pollen theft (animals that acquire resources from the flower without acting as pollinators); and there are similar tradeoffs involved between generalisation and specialisation, with specialising on a particular pollen source or prey item being a resilient strategy in some cases (e.g., aardwolves have survived on their termite prey for a very long time) and in other cases an evolutionary dead end (e.g., killer whales that have specialised on marine mammals are now verging on extinction; Springer et al. (2003)). A critical discussion of hypotheses about the relationship between specialization and extinction over evolutionary time scales is provided by Vazquez and Simberloff (2002).

Consideration of the elements that lead to sustainability in predator-prey and plant-pollinator relationships suggests some interesting principles for spatial resilience in social-ecological systems. In particular, long-term persistence of these relationships is maintained by a set of feedbacks that allow the system to adjust to variations in supply and demand. For example, when predator numbers get too high, prey items dwindle, leading to predator mortality. Conversely, pollinator populations must keep up with available flower resources if populations of flowering plants are to grow. In both cases, different speeds of population growth (i.e., prey populations growing faster than predator populations, and pollinator populations responding faster than plant populations) are an important component of the system's ability to reach a temporary equilibrium. Spatial variation in the environment, together with clustering of resources (such as prey items and flowers), creates the potential for space to play a similarly stabilising role in system dynamics; pockets of unexploited resources or particularly good 'hiding habitat' can create localised excess or scarcity, adding flexibility and resilience to the system by running counter to the dominant trend (Bakun and Broad, 2003).

In societies and in the business environment, fundamental resources include such things as human capacity, capital, consumers, contacts (or more generally, what Ranjay Gulati has termed 'network resources'; see Gulati 2007), and access to raw materials. Most of these resources have spatial locations and may be spread out through a given environment or highly clustered within it. The growing field of business GIS reflects the increasing awareness of the relevance of spatial patterns of consumption and demand for business-oriented decisions such as where and how to focus advertising and marketing campaigns or where to locate new outlets. Many of the basic principles of ecological interactions apply to spatial business interactions. For example, retail stores can be viewed as existing in a mutualism with customers; the well-known economic phenomenon of the concentration of stores of a particular kind in a particular area (as discussed in Chapter 2) is driven by what are essentially the same spatial feedback processes that lead to rich patches of synchronously flowering plants.

While naïve parallels between ecological and social or economic processes are beset with pitfalls, it is equally important that some of the general properties of complex adaptive systems that unite social and ecological perspectives should not be ignored. A particularly interesting set of spatially explicit models that deal with interactions between components comes from game theory. The spatially explicit analysis of such game theory problems as the prisoner's dilemma, rock/paper/scissors, and Maynard-Smith's (1982) Hawk-dove game was pioneered by Martin Nowak and Robert May in their 1992 paper (Nowak & May, 1992). The basic idea behind this paper (and the many excellent papers subsequently published on the same theme) was to explore what happens if individuals are assigned unique locations in space and interact only with their neighbours. Nowak and colleagues (Nowak, Bonhoeffer, & May, 1994; Nowak & May, 1992) found that spatial variation can alter the outcome of frequency-dependent selection and permit the coexistence of different strategies that could not coexist in a spatially homogeneous situation. Even more fundamentally, from the perspective of spatial resilience, local interactions appear to be one key to the development and maintenance of local diversity (Nowak, 2006; Nowak et al., 1994). Spatially explicit game theory analyses will be discussed in more detail in the next chapter.

Scaling Relationships

Scaling analyses require data that are collected in a consistent manner along a continuum of space, time, or (in the social sciences) a dimension of power or authority.

In many cases this involves measuring different individuals (e.g., animals, cities, protected areas, or plant comunities) that share a common property, such as size, growth rate, or species diversity. The basis for scaling studies is then to interpret variation in the shared property according to the location of individuals along a scale-determined axis.

The simplest form of scaling relationship is to plot a single quantity against scale; for example, to plot metabolic rate against body mass or the number of species in a vegetation transect against the area of the transect. A wide range of more detailed and more complex scaling analyses is possible, such as evaluating size distributions and searching for scale breaks; Stommel diagrams and related methods, which attempt to explore both spatial and temporal scaling relationships at the same time; geostatistical approaches to scale and scaling, such as semivariograms and kriging; fractal geometry, particularly with the potential for establishing non-linear fractal relationships using a boxplot approach; the multiscale analysis of landscape patterns; and lastly, consideration of the relationships between spatial and temporal feedbacks and the potential for space-time feedbacks to occur. These approaches to scaling are reviewed in more depth by Cumming and Norberg (2008). Scale break analyses in particular have seen some recent interesting advances, focusing on the questions of why certain body sizes should be untenable, whether the edges of scale breaks represent high turnover 'locations', and what scale breaks tell us about system resilience (e.g., Allen et al., 2006; Bessey, 2002; Garmestani, Allen, & Gunderson, 2009; Holling, 1992; Stow, Allen, & Garmestani, 2007).

Simple ecological models have produced some interesting results in the general sphere of scaling, particularly when looking at relationships between area and measures of populations and communities of organisms (e.g., species richness, population abundance). The species-area relationship is one of the most widely accepted generalities in ecology (Lomolino, 2000). It predicts that the number of species present in an area changes logarithmically with the area sampled, according to the simple relationship

$$\mathrm{S} = c\mathrm{A}^{z}$$

where S is the total number of species, A is the area, z determines the gradient of the curve, and c is a constant that describes the y-intercept (Rosenzweig, 1995). The species-area relationship together with a functional classification can also be used to generate a function-area relationship, and the spatial correlations between species richness and functional richness (as well as spatial patterns in within-group richness) may show some interesting and informative patterns (Cumming & Child, 2009).

A number of related empirical observations have been documented, including an intriguing relationship between species abundance and species range size; species with larger ranges also tend to be more abundant (i.e., to occur at higher densities per unit area of their range; Brown 1984). Ecologists have spent considerable amounts of time trying to understand the mechanisms that underlie these kinds of relationships, in many cases developing new approaches to modelling different aspects of ecological communities to help them explore the range of mechanisms that might underlie apparent generalities (e.g., Brown, 1995; Hubbell, 2001).

For the analysis of SESs, ecological approaches to scaling suggest some important general principles. They include the ideas that relatively clear-cut scale dependencies in richness and abundance may exist, even in highly complex systems; that scaling relationships may be explained by a variety of different mechanisms, and hence that additional tests of scale-dependent mechanisms must be undertaken; and that in order to successfully reproduce observed patterns in scaling relationships, mechanistic models may need to incorporate hierarchies and different scales of analysis explicitly (Kolasa & Waltho, 1998).

The social sciences have dealt with scale in a variety of different ways. In sociology, scaling often entails difficult measurements (e.g., who has the strongest preference for democracy?) and is often used in a different sense from physical scale; the dominant approach in the social sciences is more akin to what ecologists would think of as determining individual tolerance or response curves, particularly the creation and calibration of scales that determine where the averages and extremes fall for characteristics such as prestige, attittudes, or personality traits. For example, a Guttman scale arranges preferences in such a way that an individual who agrees with a particular statement will also agree with items of lower rank-order (see the recent review of ranking scales by Christ and Boice (2009)). The Bogardus Social Distance Scale (Bogardus, 1926) is a specific example of a Guttman scale; it was developed to measure how willing people would be to participate in social contacts of varying degrees of closeness with members of other social groups, such as those from different ethnic groups and homosexuals. In response to the question of how accepting people would be of other social groups, the Bogardus scale progresses as follows: as close relatives by marriage (score 1.00); as close personal friends (2.00); as neighbors on the same street (3.00); as co-workers in the same occupation (4.00); as citizens in my country (5.00); as only visitors in my country (6.00); and would exclude from my country (7.00). Here, agreement with any item supposedly implies agreement with all preceding items. In order to test hypotheses about social mobility, measures have also been created that rank occupational status on a scale. In addition, sociologists tend include dimensions of power or authority in scaling concepts (Cumming, Cumming, & Redman, 2006). In general, however, spatially relevant analyses of scale in the social sciences have primarily been derived from socially-oriented studies of human geography.

In economics, as in ecology, it is common practice to compare units of similar sizes or legal standing. For example, income is often considered across individual households or GDP across nation states. Fewer analyses have attempted to consider changes in economic production of comparable items from small social units to large social units; as in ecology, within-scale analyses are commoner than cross-scale analyses. A few exceptions do exist, including analysis of economies of scale (i.e., the reduction in unit cost that is achieved through bulk production) and measures such as the Gini coefficient (Gini, 1921), which is used to quantify inequality.

The Gini coefficient is often visualised as a Lorenz curve, in which the cumulative proportional increase in income (or other quantity of interest) per person, sorted from smallest to largest, is plotted against the number of people. A straight diagonal line (x = y) indicates a completely equitable distribution of resources, because each additional person adds an equivalent amount of wealth, health, or land, and will give a Gini coefficient of 0. A situation of complete inequity will yield a Gini coefficient of 0. Although they are typically used in economic contexts, Gini coefficients have also seen some use in ecology (e.g., Wittebolle et al., 2009). The Gini coefficient has the potential to be used in spatial comparisons, for instance between areas of different sizes, to calculate a form of scaling relationship. For example, the size of a protected area may be important to its long-term sustainability; it should be possible to gain insights into aspects of spatial resilience by calculating Gini coefficients for entire protected area networks (based on measures such as area size, total income, and minimum distance to next protected area) and then comparing these Gini coefficients to overall network performance measures (e.g., pathogen outbreaks, numbers of rare and endangered species, animal population trends, poaching levels, etc.).

The Role of the Environment

One of the oldest debates in ecology hinges on whether communities of organisms should be seen primarily as outcomes of abiotic variation – strictly 'dependents', in a sense – or whether communities should be accorded a dominant role in modifying their local environment and maintaining it within a particular range of biophysical conditions (Clements, 1916; Gleason, 1926). This debate has played out in various different arenas over the last 50 years and is fundamental to understanding the mechanisms of community establishment, succession, and non-equilibrium dynamics (Houlahan et al., 2007).

Communities in a given habitat or ecosystem are composed of members of the regional species pool. Conceptually, they can be viewed as being present at a given site as a result of passing successfully through a series of different filters at different scales – ranging from their ability to disperse at a regional scale through coarse-grained variables such as elevation and regional rainfall patterns to finer-grained variables such as microclimate and local habitat characteristics (e.g., Levin, 1992; Rappole & Jones, 2002). Abiotic and biotic variation both have significant influences on processes such as succession in plant communities (Pickett, Collins, & Armesto, 1987). Connell and Slatyer (1977) first proposed that plant succession is dominated by three competitive mechanisms: inhibition, facilitiation, and tolerance. Seen from a competitive perspective, facilitation occurs when the winning species can colonise only after the losing species has arrived; inhibition occurs when either species can prevent the other from colonizing; and tolerance occurs when the victor is the species that is most tolerant of reduced resource levels. Caswell and Etter (1999) developed a cellular automaton framework for thinking about Connell and Slatyer's (1977) mechanisms in patchy environments and found that although none of the mechanisms generates patchiness at equilibrium, patchiness decays most slowly in the inhibition model.

It is clear that abiotic variation drives the distributions of a great many species, and the success of species range models based on abiotic variables (even for such creatures as obligate ectoparasites; Cumming (2002)) lends credibility to this view. However, the demonstrated existence of alternate stable states and ecologically mediated thresholds in a range of communities (e.g., freshwater lakes, rangelands, and coral reefs) indicates that biological control of the local environment can also be a genuine phenomenon (Carpenter, 2003). The potential relevance of biological controls is further supported by some more speculative (but still plausible) arguments in favour of broad-scale biological interactions with abiotic processes (e.g., Rial et al., 2004; von Bloh, Block, & Schellnhuber, 1997). In many cases, ecologists have collaborated with climate scientists to develop spatially explicit models of feedbacks between climate and ecosystems. For instance, the case for biological mediation of community composition is strongly supported by the accumulating evidence that the African Sahel was once a rainforest and that the Amazon rainforest is kept in a wet state only by the presence of sufficient numbers of trees and their resulting transpiration, which sets in place a series of feedbacks between weather systems, rainfall, and tree communities (e.g., see Laurance & Williamson, 2001; Marengo, Nobre, Tomasella, Cardoso, & Oyama, 2008; Nepstad, Stickler, Soares-Filho, Brando, & Merry, 2008; Nicholson, Tucker, & Ba, 1998).

Given that most communities will be regulated by a combination of abiotic and biotic factors, with additional patterns arising from human influences, perturbations, and historical effects, attention has shifted in recent years towards considering overall properties of communities in relation to adaptation and persistence. The question here is not whether abiotic or biotic influences dominate but rather, whether biotic interactions can somehow compensate for the influences of changing anthropogenic and abiotic variation. This research paradigm will probably continue to grow as interest in the future impacts of climate change increases. One of its immediate offshoots has been to refocus ecologists on questions of community stability and the degree to which compensatory mechanisms exist that will maintain ecosystem function following environmental change.

The tension between biophysical and ecological controls is particularly apparent in studies that explore species diversity and community-level stability in relation to environmental variation. Leaving aside the difficulties of definitions (Grimm, Schmidt, & Wissel, 1992; Ives, Dennis, Cottingham, & Carpenter, 2003), the study of the relationships between the diversity and the stability of ecological communities is one of the areas of ecology with greatest relevance to the study of social-ecological resilience. More stable communities tend to show a greater ability to cope with environmental fluctuations and a stronger tendency to return to a local attractor. Community resilience can regarded from a classical perspective as the post-disturbance return time of both the number of species and the abundance of individuals of each species, or from a functional perspective as the time taken to return to pre-disturbance levels of production of a particular quantity (such as timber or bushmeat). Human communities in most social-ecological systems rely on a portfolio of ecosystem services, such as timber and fruit production from a neighbouring forest, fodder for livestock production in a rangeland area, and fish production in a nearby wetland system. Increased ecological stability in each of these instances results in a more continuous output of desired services, with likely effects on the structure of the human social and economic systems, the degree to which forward planning is necessary or possible, and general human wellbeing.

Diversity-stability analyses in ecology have tended to focus on the questions of (1) whether more diverse communities are more stable; and (2) whether more diverse communities are less prone to invasion by introduced species. An early modelling study by Bob May (May, 1972) produced the unexpected conclusion that more diverse communities were not necessarily more stable, setting in train a large number of subsequent investigations as ecologists battled to understand diversity-stability relationships (e.g., see Ives & Carpenter, 2007; Ives, Klug, & Gross, 2000; McCann, 2000; Rodriquez & Gomezsal, 1994; Tilman, Lehman, & Bristow, 1998). One of the central themes in this debate has been whether populations simply track environmental fluctuations in resource availability, or whether they show evidence of compensatory dynamics and interaction effects (such as the abundance of one species increasing as the abundance of another competing species declines (e.g., see Houlahan et al., 2007)). Progress in the diversity-stability debate was delayed for a while by debate over what constituted stability; the problem has been partly resolved by a gradual substitution of variation for true dynamic stability (Ives & Carpenter, 2007; Ives et al., 2003).

Curiously for questions that relate so clearly to spatiotemporal variation, the diversity-stability debate has typically been approached from a somewhat static and equilibrium-oriented perspective, with most authors invoking classical mechanisms of competition and compensation in alternative hypotheses (Houlahan et al., 2007). A more dynamic perspective on the same debate is provided by Holling's adaptive cycle (Holling, 1986, 1987, 2001; Holling & Gunderson, 2002), which implies that ecological communities are at their least stable when accumulated capital is high, because they are too 'rigid' to deal with disturbance without reorganization (a classic example being a mature stand of forest, which presumably would also have high diversity); and that they are at their most vulnerable to invasion following disturbance, which creates the opportunity for novelty to enter the system. Although the concept of a 'panarchy' (a nested set of adaptive cycles) introduces questions about the relationship between spatial scale and resilience (e.g., see Peterson, Allen, & Holling, 1998), the adaptive cycle largely ignores the potentially stabilising influence of spatial heterogeneity. A spatial perspective on stability is provided by many of the models and ideas discussed in this book, which offer various mechanisms by which internal system variation and the influence of neighbouring or connected communities can influence stability (including such things as subsidies, donor control, and source-sink relationships).

Another intriguing thread of research in ecology relates habitat area to the length of food chains (e.g., Post, 2002; Post, Chase, & Hairston, 2000; Schoener, 1989).

Keeping in mind that system size and boundaries are important aspects of spatial resilience, classical ecological theory predicts that in situations where more resources are available, there will typically be more niches and hence a greater potential for the development of a more diverse set of interactions. However, Post et al. (2000) found that in freshwater lakes, food chain length is determined by ecosystem size rather than by productivity. Post (2002) has argued that resource availability limits food-chain length only in systems with very low resource availability. Network models suggest that although longer or more complex food chains may be easier to disrupt, they may also be more resilient if nodes are interconnected to an appropriate degree (for example, if prey switching is possible). If biodiversity enhances resilience in a given context, then a higher degree of complexity of interactions provides another reason why larger habitats (e.g., larger lakes, forest patches, or protected areas) should be more resilient.

In general complex systems terms, these models imply a general principle by which larger patches of 'habitat' will exhibit more complex interaction networks, with attendant consequences for social-ecological resilience. For example, a larger economy might be expected to have supply chains that involve more different steps between producer and consumer. In ecosystems there is a level of spatial structuring within food webs, but the potential for such structuring is higher in human systems because energetic requirements do not dominate interactions to the same degree. These considerations suggest that larger social-ecological systems should show higher diversity and a greater degree of internal spatial structuring, depending of course on the openness of the system and the relative importance of external influences (for example, the potential to 'outsource' production chains to other countries, such as running shoes being manufactured in Vietnamese sweat shops, implies either a rethinking of the nature of the problem or a shift in scale in the system definition).

Disturbance Propagation and Its Interactions with System-Wide Properties

Ecologists have been interested in disturbance since the days of Charles Elton, one of ecology's founding fathers, who first suggested that invasions by non-native species were facilitated by disturbance (Elton, 1958). Considerable attention has been paid to the 'Intermediate Disturbance Hypothesis' (Connell, 1978), which suggests that diversity is highest at intermediate levels of disturbance, with low disturbance systems being likely to be dominated by a single competitor and high disturbance systems consisting primarily of good dispersers. The impacts of disturbance on ecological communities also appear to be subject to productivity, which varies systematically in space (Huston, 1994; Huston & Wolverton, 2009).

An integrative way of viewing disturbances and their impacts has been suggested by Turner, Romme, Gardner, O'Neill, and Kratz (1993), who gave a useful summary of expected relationships between disturbance extent and disturbance frequency as ratios of system size and duration (Fig. 5.3). This framework describes a set of possible outcomes that are equally relevant to plant communities and social-ecological

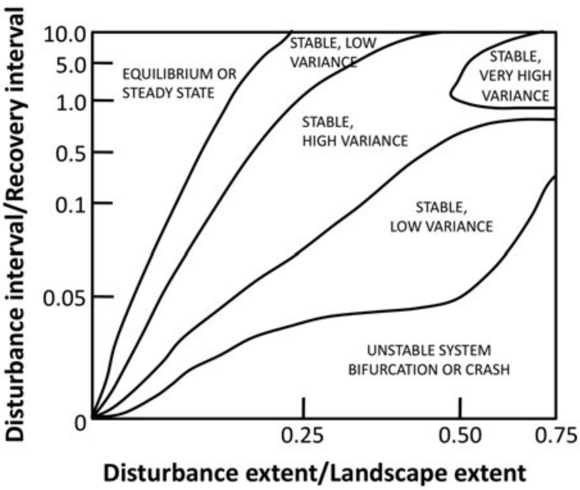

Fig. 5.3 A state-space diagram showing the expected relationships between the spatial and temporal scales of disturbance in a typical landscape. This diagram provides a hypothesis-oriented framework that connects disturbance and resilience. Redrawn from Turner et al. (1993)

systems. Under conditions of frequent, broad-scale disturbance, no equilibrium is reached and the community remains dominated by good dispersers, whether weeds or opportunistic businesses. Systems under conditions of infrequent, small disturbance tend towards dominance by good competitors, which may be woody plants or large companies. In between these two extremes lie a variety of possible outcomes that depend on both the disturbance regime and the properties of the system itself. Although exceptions to this framework can be identified, it offers a good example of an approach to thinking about different spatial aspects of disturbance.

Disturbances can be classified and described in a variety of different ways. A basic distinction is between 'press' and 'pulse' disturbances (Bender, Case, and Gilpin, 1984). Press disturbances occur over longer time periods and apply increasing stress to community; examples include droughts and reduction of variability in river flow regimes, as might occur after the construction of an upstream impoundment. Pulse disturbances occur over relatively short time periods and include such phenomena as fires and floods. One of the more important questions for the long-term sustainability of social-ecological systems is that of whether resilience to likely disturbances can in some way be enhanced or built, much as good engineering can produce buildings that withstand earthquakes or floods. For instance, some of the newly built houses from the central districts of New Orleans, following hurricane Katrina, look much like any other house in the southern USA but will float under flood conditions (Fig. 5.4). As this example illustrates, building resilience is often contingent on our understanding of disturbance regimes and our ability to develop ways of coping with change while keeping in place the properties of the system that we value most highly. Such coping mechanisms almost always have a strong spatial component; for New Orleans, proximity to existing waterways and location in relation to depth below sea level are of central importance in deciding how (and whether) to rebuild neighbourhoods.

Fig. 5.4 A floating house from New Orleans. Photograph by Joshua Lewis

Disturbances can also be grouped into different classes according to their ability to spread across a landscape. Some disturbances, such as dredging in shipping channels, are predictably localised and have little likelihood of spreading across a landscape (or in this case, seascape). Other disturbances occur in predictable locations and are non-contagious, but may have a larger impact than their location suggests; for example, volcanic emissions can influence local and global climate (Crowley, 2000), and floods may impact their floodplain to varying and unpredictable extents. Non-contagious disturbances can also be unpredictable in their location and trajectory, as with meteor impacts and hurricanes. In terms of spatial dynamics, however, the most interesting (and often the least predictable) disturbances are those that are contagious and have the potential to spread across a landscape or through a network. Contagious disturbances include such phenomena as fires, insect or pathogen outbreaks, and internet malware. These disturbances have the capability to spread through certain kinds of habitat, contingent largely on habitat type, amount, and arrangement.

The degree to which a system is vunerable to a particular kind of disturbance will often be a function of the degree to which the disturbance is contagious. There are various tradeoffs involved in contagious disturbance; for instance, a highly virulent pathogen may kill its host before the host can disperse, reducing its own rate of spread, and a hot fire will reduce fuel loads such that subsequent fires are less likely than they would be following a cool fire.

Fire is one of the most studied spatially contagious disturbances in ecosystems. Fire is relatively easy to simulate in a spatially explicit modelling environment, given some assumptions about its rate of spread and data on such things as spatial variation in vegetation type and fuel load, likely ignition points, and wind direction. A common approach to fire modelling is to use a cellular automaton in which burning cells can cause their neighbours to ignite (if fuel loads and wind direction permit) in each time step according to some predetermined probability.

A good example of the use of spatially explicit fire models to explore spatial aspects of resilience comes from the study by Leroux, Schmiegelow, Cumming, Lessard, and Nagy (2007) on fire dynamics in a reserve system in northern Canada. The authors used a fire and vegetation patch dynamics model, called CONSERV, to investigate the ability of six hypothetical reserve networks to maintain a set of 'targets' (i.e., the species, popuations, communities, and ecosystems that people would create the reserve network to protect). Networks were designed using static data and the reserve selection algorithm MARXAN (Ball & Possingham, 2000), as they would be in a typical conservation planning effort, and then subjected to fire. Interestingly, none of the six networks maintained all of its targets to the desired level, demonstrating how static approaches to conservation planning can easily overestimate the resilience of ecological communities.

The CONSERV model is a grid-based simulation model that uses age-based state transition rules, based solidly on an understanding of the ecology of the study area, to simulate vegetation successional dynamics. Fire itself is modelled as a three-stage stochastic process involving ignition, escape, and spread (Armstrong & Cumming, 2003). Ignitions and escapes occur within cells, while fire spread occurs between cells according to the fuel load in the adjacent cells and the probability of spread. Both ignition and spread probabilities are based on empirical estimates derived from real-world data for the study region. In addition to its direct relevance for management efforts in the study area, the model provides a useful example of one way in which empirical data and simple assumptions about spatial processes can be connected to produce useful conclusions about spatial resilience.

Conclusions: General Principles for Spatial Resilience

This chapter has cut a wide path through some of the central themes in spatial models of ecosystems. In many cases I have barely been able to scratch the surface of important topics. What the preceding discussion has hopefully made clear, however, is that ecological models – often based on a relatively simple set of principles and mechanisms – have been used to identify many fundamental principles and heuristics for thinking about spatial resilience in social-ecological systems.

In the introduction to the chapter, I suggested five complex systems themes that ecologists have considered in depth. They include (1) understanding the behaviour and functional importance of individual system components; (2) understanding interactions between components; (3) documenting scaling relationships and cross-scale feedbacks; (4) understanding the role of the external environment and its interactions with complex systems; and (5) understanding how disturbance affects system-wide properties and how it is propagated across a landscape.

We have seen that individual components of ecosystems have differing demands for resources and differing dispersal abilities. These differences have arisen from selective pressures that have enforced various tradeoffs in response to environmental variation, as in the tradeoff between competitive ability and dispersal ability in plant seeds. Dispersal is a particularly important response to environmental change and the potential for long-distance dispersal, even if only very occasionally, seems to be fundamental to the long-term persistence of system elements. Given that the parental environment is likely to be suitable for the offspring, and that entering new environments can be dangerous (e.g., until the number and nature of local predators have been identified), dispersal also carries high risks, suggesting an important strategic tradeoff (Levin, 1992) has a good discussion of this point). An interesting related point is made by Bakun and Broad (2003) with their suggestion that populations of animals that learn to exploit environmental 'loopholes' that periodically arise in space and time – such as low densities of predators in particular locations – may in this way be able to thrive in years that superficially seem harsh.

Individual components in an ecosystem interact with one another and with their environment to produce ecological communities. Classical ecological theory has focused on the ways in which ecological interactions limit membership in ecological communities. However, there is an increasing amount of evidence to indicate that ecological communities are heavily influenced by spatial effects, including external spatial structure (e.g., climatic regions or mountains) and the intrinsic dispersal abilities (and associated behaviours) of organisms. The theory of Island Biogeography, discussed in detail in the previous chapter, provides one framework from which to think about the role of habitat location and dispersal ability.

Interactions within ecological communities can be highly complex, with different trophic levels and spatial influences coming into play. Despite the complexity of ecological interactions, however, scaling analyses have identified some generalities (such as species-area curves) that appear to hold, even across a wide range of highly complex systems. The area or size of an ecosystem appears to set some basic constraints on the kinds of species and processes that it can contain. Scaling analyses thus offer an important way in which to start to make sense of spatial influences on complex systems.

In many cases, the external environment places constraints on what is possible within a given ecological community. Open, self-organizing systems are capable of sequestering and dissipating resources in such a way that they reduce rather than increase local entropy (Kay & Boyle, 2008). Higher diversity appears to provide greater stability in ecosystems, via such mechanisms as the insurance effect, which buffers system function against environmental change. Size and spatial arrangement are important components of spatial resilience.

Disturbance regimes are often determined by the context in which a given complex system exists. The occurrence and propagation of disturbances may be facilitated by the external environment as well as by the properties of the community; for example, fire will spread better in areas of continuous forest that contain highly flammable species.

The different insights that have arisen from ecological models suggest at least seven basic principles for thinking about spatial resilience, as follows: (1) Spatial effects and interactions are distance-dependent. Effects that are increased by exchanges between locations become smaller with increasing distance (e.g., colonisation from a remote source pool becomes less likely). By contrast, effects that are decreased by exchanges between locations become larger with increasing distance;

for instance, genetic divergence and technological innovations may be more likely in more isolated conditions (although we shall return to the hypothesis of intermediate connectivity and resilience towards the end of the next chapter). (2) The probability of extinction, or localised component loss, correlates with habitat and population size; larger populations and bigger areas tend to be more resilient. (3) As numerous data sets have shown, the decay of spatial effects is non-linear. For example, as habitat is lost, connectivity declines according to a sigmoidal function with a threshold around 47% habitat cover. (4) A range of ecological models have shown that spatial processes (such as limited dispersal) can produce spatial patterns, even in the absence of environmental variation. In testing for spatial effects in complex systems, this means that clearly defined null models are needed before one can be certain of a given effect. (5) Obviously, but often implicitly assumed, spatial variation in the environment is created by spatial processes. At the same time, spatial processes rely on spatial variation. Pattern and process are thus linked by feedback loops. More intriguingly, spatial and temporal variation are often confused in empirical studies, with spatial analyses measuring temporal variation and temporal analyses measuring spatial variation. Balanced sampling designs (i.e., in both space and time) will be important for the study of spatial resilience in complex systems. (6) Spatial variation can have a stabilising effect on system dynamics, because it creates the potential for a range of effects; e.g., differential extinction, reduction of predator impacts through increased search time, and the storage and rescue effects. (7) Localised interactions and uneven mixing help to maintain diversity in the nature of interactions and may have other important consequences, such as facilitating the evolution and spread of cooperative strategies. (8) Lastly, tradeoffs exist between dispersing, or moving, and staying put. Dispersal can be costly under some circumstances and beneficial under others. Long-term strategies for coping with temporal variation often hedge against environmental uncertainty by pursuing a mixed strategy.

These principles provide us with a starting point for thinking about the mechanisms that generate spatial resilience, as we move on to Chapter 6, which focuses on network analysis.

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Chapter 6
Spatial Resilience in Networks

Introduction

In recent times, and particularly since the advent of the internet, graph theory (and its sub-discipline of network analysis) has taken on a new importance as one of the branches of mathematics that is best suited to exploring questions of connectivity and relationality. Just about anything that involves exchanges between manageable numbers of distinct entities, in real or conceptual space, can be analysed as a network problem. This is not to say that network approaches should be applied in all cases; there is a set of problems for which network approaches are ideal, and a set of problems for which they are not. As a conceptual and analytical tool for the study of social-ecological systems, however, network analysis can not be ignored.

Networks consist of two primary elements, termed nodes (synonymous with vertices, locations, and actors) and links (edges, bonds, ties). The nodes of the network are typically comprised of discrete elements like towns, individuals, protected areas, or computer terminals. The links or edges capture the connections of nodes to one another. Links describe such things as roads, telephone lines, personal interactions, the movements of organisms, or virtually any other kind of exchange or flow that occurs directly between nodes. Links may be unidirectional, as in a river, or bidirectional, as in a road; they may have a spatially explicit or a spatially independent nature; they may exist permanently or only for short periods; and they may carry high or low volumes.

Network analyses have their origins in pure mathematics, dating back to a paper written in 1736 by the great Swiss mathematician Leonhard Euler on the Königsberg bridges problem. An English version of the paper is available in Newman (2003a). The city of Königsberg (modern-day Kaliningrad), in the then nation of Prussia, sat on the banks of the Pregel River. The town included two large islands and a network of seven bridges that joined different districts (Fig. 6.1). The problem of the bridges was to determine whether it was possible to find a path (today termed an Eulerian path or Euler walk) that crossed each bridge once only, without retracing any steps, and returned to the starting point.

Euler proved that there was no such solution in Königsberg by abstracting the problem to the fundamental elements of nodes and links – the first portrayal of the

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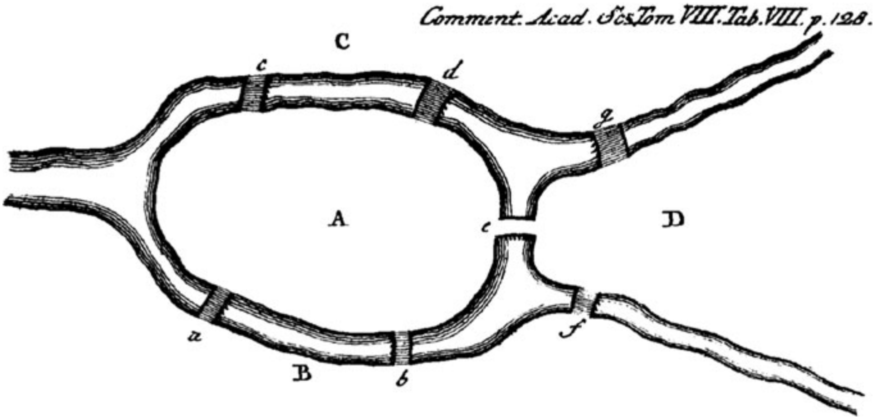

Fig. 6.1 Euler's sketch of the Königsberg bridges problem, taken from a copy of his original paper (*Solutio problematis ad geometriam situs pertinentus*). *A* and *D* are islands. The Latin original is available on line at http://www.math.dartmouth.edu/~euler/docs/originals/E053.pdf

kinds of network graphs that we are familiar with today – and then looking at the numbers of odd and even links associated with each node. The number of links touching a node is today termed its *degree*. Euler demonstrated that the necessary (and sufficient) conditions for a solution to exist are (1) that the graph be connected; and (2) that the graph should have exactly zero or two nodes of odd degree. In the case of the Königsberg bridges there were four nodes of odd degree, and hence no Eulerian path.

Euler's work provided not only a solution to the Königsberg bridges problem, but also a new and different way to think about networks. The degree of a node has remained an important quantity in network analysis, and for larger networks the statistical distribution derived from calculating the frequency of nodes with different degrees – 'degree distribution' – offers an important entry point to understanding the structure of a network. In a road network, for example, cities can be viewed as nodes and roads as links. A large city like Johannesburg that sits at the meeting point of a number of different highways will have a higher degree than a smaller town like Knysna, which sits on a single highway.

Degree distributions are often used to classify networks. For example, 'small world' networks (Milgram, 1967; Watts, 2004; Watts & Strogatz, 1998) are common in real-world systems and have the seemingly self-contradictory properties that (1) most nodes are not neighbours of one another (i.e., most nodes have a low degree); but (2) most nodes can be reached from others by a small number of steps. The second property derives from the fact that a subset of nodes connect different clusters within the network in a relatively efficient manner. The small-world structure has some interesting effects on signal transmission (including information flows and physical movement) within a network. If a simple network is assembled in which each member connects to just two other members (i.e., node degree is routinely low), and if the transmission capabilities of each link are identical, the total time that it takes for a signal to pass from one end of the network to the other will be proportional to the total number of links in the network. Errors at each stage will propagate and increase. You can imagine this situation as a game of 'Chinese whispers' being played in a circle by a group of 20 pre-school children; the teacher whispers a sentence in the ear of the first child, who passes it on to the second, and so on until it returns to the first child, who says both the original and the 'new' message aloud. Now imagine that instead of passing the message on to the next child in the ring, a child can cross the circle and communicate the message directly to someone on the far side. It takes only a few circle-crossers for the number of repetitions prior to return to the original signaller to become quite small, with the beneficial side-effect that the number of errors is substantially reduced. Small-world networks thus have the property that information (or other entities, such organisms or vehicles) can travel efficiently through them to get from one point to another; it is no coincidence that almost everyone at the office seems to know about your latest embarassing escapade within a few working hours.

A second important type of network is the scale-free network (Barabasi, 2002). Scale-free networks have the property that their overall connectivity appears the same regardless of the scale at which they are analysed; they are fractal in nature. More formally, scale-free networks can be defined as following power-law degree distributions. This means that if you were to select a piece of the network and plot out its degree distribution, you would find for a true scale-free network that the finer-scale distribution looked exactly like the distribution of the larger network and could be described by the same parameters. Various other kinds of network are of interest in network studies (Box 6.1).

Box 6.1 Network Terminology Unravelled

Network analysis uses a language all of its own. To assist in navigating this terminological zoo, I offer this brief summary of terminology as defined in several peer-reviewed articles (Janssen et al., 2006; Newman, 2003b; Webb & Bodin, 2008).

Networks are composed of *vertices* (nodes, actors, sites) and *edges* (bonds, links, ties). Edges can be *directional* or *undirected*. The number of edges connecting to a vertex is called the *degree* of the vertex. Plotting the degree frequency histogram (i.e., the total number of actual occurrences of each different degree against each possible value of the degree) provides the *degree distribution* of the network. If the graph is directed, a vertex may have in *in-degree* and an *out-degree* (i.e., numbers of incoming and outgoing edges). The *component* to which a vertex belong is a piece of the network that you can reach from it by travelling along edges. If most vertices fall into a relatively small number of components, with highly unequal sizes, the largest component is often called a *giant component*. The shortest path between two vertices is called the *geodesic path*; the longest geodesic path (measured in number of vertices) within the network is called the *network diameter*.

In a *random graph*, undirected edges are placed at random between a set of vertices to create a network in which each edge is independently present with a predetermined probability. The degree distribution of vertices follows a binomial (or, for large sample sizes) a poisson distribution. Random graphs are often used as null models against which to test hypotheses of structuring processes in networks. In a *small-world* network, most pairs of vertices are connected by a relatively short path. *Scale-free* networks have power law degree distributions. *Bipartite graphs* have two different kinds of vertex.

Edge density refers to the ratio of the actual number of edges to the possible number of edges (i.e., if every vertex were connected to every other vertex, creating a *saturated* network). *Reachability* describes the extent to which vertices in the network are accessible to one another. *Average path length* describes the average geodesic path length between pairs of vertices. *Network resilience* is generally used in this body of literature to describe the ability of a network to withstand deletion of vertices without being split into isolated subgraphs (separate networks).

The *betweenness centrality* of a vertex *i* is the number of geodesic (shortest possible) paths between other vertices that run through *i*. *Degree centrality* describes the number of edges connecting to a vertex; it is synonymous with 'degree' when calculated for a single vertex, but can be applied to an entire network by looking at the degree of each vertex relative to the average degree of vertices within the network. *Closeness centrality* is highest when vertices have short geodesic distances to other vertices in the same graph. Vertices with high levels of centrality are sometimes called *keystones* or *hubs*; they are of particular interest because they have a large impact on network function and may be both disproportionally responsible for network performance (e.g., computer network servers or influential politicians) and disproportionally at risk from things that move through networks (e.g., computer viruses, sexually transmitted diseases, invasive species, and corruption). A fascinating example of an application of centrality concepts to explore an ecological problem is provided by Rozenfeld et al. (2008).

Scale-free networks are common in social systems (Barabasi, 2002; Milgram, 1967) and ecosystems (e.g., Williams, Berlow, Dunne, Barabasi, & Martinez, 2002). The fact that they typically contain just a few well-connected individuals, or 'hubs', and many poorly connected individuals, means that while they are relatively resilient to the loss of weakly connected nodes, they can be disconnected quite quickly by the loss of just a few hubs. Travel networks offer a typical example of the relevance of this phenomenon. In the South African road network near Cape Town (Fig. 6.2), for example, a closure of the roads near Stellenbosch would mostly affect people travelling to and from Stellenbosch; whereas closure of the N2 through Somerset

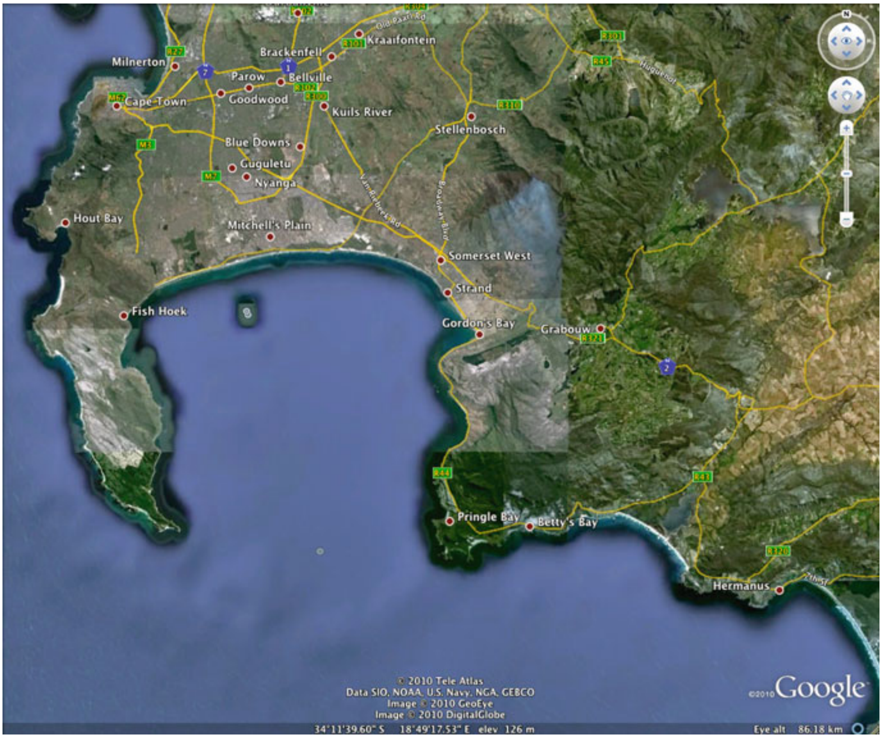

Fig. 6.2 Main roads near Cape Town, as viewed using Google Earth

West would alter the connectivity of Cape Town to the eastern coast of South Africa, affecting many more people.

A wide variety of both small-world and scale-free networks have been documented in the real world; and many networks that deviate from these assumptions, such as food webs, have also been described (e.g., Barabasi, 2002; Williams et al., 2002). One of the ongoing research threads in studies of real-world networks is to identify the mechanisms that lead to patterns like power-law degree distributions and to understand the relevance of degree distribution for network function and resilience. For example, preferential attachment ('the rich get richer', also called the Matthew principle (e.g., Merton, 1968)) provides one mechanism by which a small number of nodes becomes far more highly connected than average. The suggestion that networks as a whole may respond to external pressures by modifying their structure to 'solve' (passively or actively) a particular problem implies that the structures of existing networks can be viewed as the outcome of selective pressures. This implies in turn that if a certain network structure is frequent in a given context (for instance, if a particular kind of degree distribution occurs in most food webs), it may express a fundamental principle about the relationships between networks and their environment, thereby providing a key that allows us to use a simple explanation to unlock an entire class of problems.

Research by Geoffrey West, Jim Brown, and Brian Enquist (1997) on circulatory and respiratory systems in organisms offers a good example of an approach to connecting network structure and network function in a very general way. West et al. (1997) considered how materials that are essential for life (such as water and oxygen) are transported through networks of branching tubes. They developed a model which assumed that the networks are arranged in such a way that (1) minimal energy is lost during transport; and (2) the sizes of the ends of the tubules do not differ with the body size of the organism. Interestingly, they were able to use their model to predict both structural and functional properties of distribution networks (e.g., size and length of blood vessels in the human body) in vertebrates, plants, and insects.

Although theoretical and model-based analyses of networks have tended to dominate the field of network analysis, there have also been a large number of empirical investigations of the properties of real networks (Newman, 2003b). Sociologists have spent nearly a hundred years accumulating examples of social networks (Freeman, 2004). Published network analyses in recent years have considered a wide range of different systems and the scope of network analysis is very broad (Borgatti, Mehra, Brass, & Labianca, 2009). To offer a few examples to illustrate this breadth, network approaches have been applied to stakeholder networks in resource management (Prell, Hubacek, & Reed, 2009; Ramirez-Sanchez & Pinkerton, 2009); the movements of animals between patches of suitable habitat (Andersson & Bodin, 2009; Urban, Minor, Tremi, & Schcik, 2009); host-parasite and plant-pollinator interactions (Lafferty et al., 2008; Olesen, Bascompte, Elberling, & Jordano, 2008); assessment of academic collaborations (Moody, 2004); the transmission of pathogens within human and animal communities (Takeuchi & Yamamoto, 2006); the likelihood that power failures or deliberate attacks bring down electrical supply networks (Holmgren, 2006); and the architecture of the internet in relation to its function (Rosato, Issacharoff, Meloni, Caligiore, & Tiriticco, 2008). Some of these studies have supported model-based results and others have challenged accepted ideas (e.g., debate continues on the prevalence of scale-free networks). As with many of the fast-growing areas of research discussed in this book, network analysis is still in a period of rapid expansion and considerable turmoil.

One of the most exciting developments in network analysis is the potential to connect spatially explicit data of different kinds in ways that allow for an assessment of spatial aspects of resilience. Despite its high potential as a tool for exploring aspects of spatial resilience in social-ecological systems, however, network analysis has remained under-exploited in this context. In the remainder of this chapter I first discuss some detailed applications of network ideas in spatially explicit contexts and then try to tease out a few general principles for the network-based analysis of spatial resilience.

Three Spatial Applications of Network Analysis

Network analysis has a long history of use in the social sciences. In recent times it has been widely applied in economics; and its use in ecology goes back to the

1940s (e.g., Lindeman, 1942), although its most frequent application in ecology has been in studies of food webs. To illustrate the utility of network analysis for the analysis of spatial resilience in social-ecological systems, I will discuss three different applications of network analysis – one from each of sociology, economics, and ecology – in more detail.

Social Networks in Space: The Importance of Bridging Organizations

Social network analysis is used to understand both micro- and macro-level properties of social networks. Micro-level analysis involves understanding how individual characteristics – behaviours and attitudes, for example – combine to create a larger network and system-wide behaviours. For instance, individual values and preferences control the transmission of diseases like HIV or syphilis through self-organizing networks of sexual interaction (e.g., Liljeros, Edling, & Amaral, 2003). Macro-level analysis, by contrast, focuses on understanding how higher-level system characteristics (such as the size, structure, or connectivity of the network) influence or constrain the actions and attitudes of individuals. For instance, levels of sexual activity may be constrained by gossip and personal loyalties (e.g., deciding not to date a friend's ex-girlfriend) in smaller or more highly connected networks.

In many cases, the behaviours and interactions of nodes in a social network are a function of their spatial location. Actors (individuals or organizations) that are in close proximity in geographic space are more likely to interact than those that are far apart. At the same time, the geographic distance between locations influences the degree to which they share commonalities. In social systems, locations that are close to one another are more likely to be inhabited by people with shared values, culture, and language; and in ecosystems, nearer locations are (on average, although not inevitably) more likely to have biophysical properties and species in common. Location and geographic distance thus influence both social and ecological networks and have potentially important implications for social-ecological systems (Cumming, Bodin, Ernstson, & Elmqvist, 2010).

A good example of the use of social network analysis for considering problems of natural resource management in social-ecological systems comes from the doctoral research of Henrik Ernstson (2008). Ernstson focused on the generation and distribution of ecosystem services in urban environments, using the Stockholm National Urban Park as a case study. A social network analysis of 62 different organizations involved in the management and protection of the park suggested that social structures relating to the park included six core and semi-core groups that had deliberately built strong political connections to relevant authorities, with the result that they were capable of influencing planning decisions and potential threats to the park. Since these core groups also had weak links to more peripheral organizations, they received assistance in monitoring developments in and around the park and were capable of mobilising significant political pressure. Ernstson concluded that the diversity of different stakeholder groups and the different roles that they filled provided a source of resilience for the park (Ernstson, Sörlin, & Elmqvist, 2008). However, the relatively uncoordinated social organization relating to the park could also be viewed as a constraint to coordinated ecoystem management; for example, user groups with valuable local ecological knowledge had not been included in some collaborative arenas where their knowledge would have influenced decisions. Ernstson and Sörlin (2009) identified four factors that seemed to heavily influence actor networks relating to urban green areas: (1) the number and type of artefacts linked to an area; (2) the capabilities and numbers of actors involved; (3) the access of actors to social arenas; and (4) the social network position of actors.

Although many aspects of this analysis are not explicitly spatial, it has a strong spatial element. All actors were engaged in activities that centered on the park, and at a finer scale they were interested in different parts of the park. Actors were themselves located in space and their physical proximity to the park influenced their usage of the park and their social interactions with other users. In explicitly considering the spatial resilience of the broader network of green spaces in Stockholm, Ernstson and Sörlin (2009) argued that 'exploitation pressure... will seek out green areas for which a strong enough voice for resistance does not exist, or can not be created'. In general, understanding the social constraints and incentives that affected the network of people with interests in the conservation of urban green space thus suggested that the resilience of the biophysical network would be highest in cases where all four of Ernstson and Sörlin's conditions were met for many of the nodes (green spaces) in the physical network. Obviously, meeting his conditions would be most important for the well-connected nodes, or hubs, in a small-world actor network.

Economic Interactions and Spatial Games: Cooperation and the Prisoner's Dilemma in Network Applications

The effective management of social-ecological systems requires that individuals cooperate with one another and/or act in the interests of the greater good. What is best for a society or family group, however, is not necessarily what is best for an individual. Cooperation and sociality in the societies of other animals (as in ants, termites, mole rats, or cooperatively breeding birds) can often be explained by relatedness; animals commit altruistic acts that ultimately serve to enhance the persistence of their own genes in the population (Hamilton, 1972). In an evolutionary context, however, other kinds of associations and mutualisms can evolve; flowering plants and their pollinators, for example, are heavily interdependent (Barth & Biederman-Thorson, 1991). These cooperative interactions have intrigued evolutionary theorists because the mechanisms by which they might evolve and be retained via natural selection – which acts on individuals – are not immediately obvious (Maynard Smith, 1982).

In human societies, cooperation often involves interactions with people who are unlikely to be related to the actor in any meaningful way. The fact that cooperation is widespread in human society suggests that selective processes other than natural selection can favour the formation and persistence of cooperative strategies. It is obvious that cooperative behaviour can have a huge impact on the overall resilience of a human society. We depend for our daily wellbeing on the fact that other people do not only act in their own immediate self-interest; and the resolution of collective action problems (such as climate change and deforestation) is only possible through cooperative behaviours. One of the central issues in understanding the mechanisms that drive the dynamics of SESs is therefore that of how, and why, cooperative behaviour arises and how it can be either lost or maintained in a population. The study of cooperative behaviours has been of particular interest within economics (Beinhocker, 2007).

The tradeoffs involved in cooperative behaviour have been captured in a number of simple 'games'. The best known of these is probably the prisoner's dilemma, but there are many others, including 'hawks and doves' (Maynard Smith, 1982) and 'rock-paper-scissors'. The prisoner's dilemma revolves around making a simple choice. It envisages a situation in which two suspects are apprehended and kept in jail in separate cells. Both prisoners suspect that the police don't have enough evidence to convict them, but they can't be sure. Each is offered the option to either confess and inform on the other, or not. If both prisoners refuse to inform on each other, both will be released – the best outcome for both. If one informs on the other without being informed on, the person who keeps quiet will go to jail for 10 years while the other receives a lesser sentence of 5 years. If they both inform on each other, both receive the maximum penalty of 10 years. They therefore have to decide, individually and in the absence of additional information, whether to cooperate or defect.

Von Neumann and Morgenstern (1944) were the first to propose that the prisoner's dilemma offered a good model for economic interactions, which can be heavily dependent on a set of complex tradeoffs between different forms of cost and benefit. Dixit and Nalebuff (2008) provide a good example of the prisoner's dilemma in action in a business situation. They envisage two firms that sell a similar product – in their example, Coca-Cola and Pepsi. If both charge a high price for their product (cooperation), they maximise their profits. If one company decides to lower their price (defect) then it can win customers away from its rival. If both companies set low prices, they will each make less profit. If keeping prices low is the dominant strategy, both firms end up worse off.

The game becomes more interesting when it is repeated several times with the same players, giving each individual a chance to gain insights into the other's strategy and to try to second-guess their decisions. It has many commonalities with typical human interactions, including a typical economic transaction such as buying a car. The buyer pays money in good faith and stands to lose some or all of her money if the car is in reality broken or dysfunctional, while the dishonest dealer stands to either gain unfairly, or, if exposed, to lose further business and face prosecution. Following a successful purchase of a second-hand vehicle from a car dealer, the same customer is more likely to return to the same dealer because of the basis of trust that has been established.

Early models of the prisoner's dilemma assumed homogeneous mixing in larger populations. In these instances the Nash equilibrium, also termed an evolutionary stable strategy (Maynard Smith, 1982), applies; each player knows the equilibrium strategies of each of the other players, and no single player gains by changing only their own strategy unilaterally. Homogeneous mixing is a dubious assumption in many ecological contexts, but it is worth noting in passing that many of the other assumptions on which solutions to games like the prisoner's dilemma are based are not tenable in many real-world situations (Gibson, Andersson, Ostrom, & Shivakumar, 2005). For example, game theory predictions are commonly based on a rational choice model, which assumes that actors have complete and well-ordered preferences, complete information, unlimited computational ability, and the single goal of maximising the net value of their expected returns (Gibson et al., 2005). Nonetheless, theories based on rational choice do generate empirically confirmed predictions under some circumstances, and can serve as useful tools for generating testable hypotheses, in the sense that deviations from rational choice can offer insights into real-world mechanisms (Gibson et al., 2005). These simple models offer one good starting point for exploring spatial resilience in SESs.

Robert Axelrod (1984) first realised that the prisoner's dilemma could be played out on a spatial lattice (i.e., a regularly spaced grid, in which each player is assigned to a single cell) in which decisions to cheat or cooperate were made by locally interacting neighbours. This realisation, together with the development of fast personal computers that could be used to run large numbers of repetitive operations, triggered an explosion of interest in spatial aspects of cooperative behaviour.

Axelrod also hosted a famous competition in the late 1970s in which he invited researchers to develop different strategies (in the form of computer programmes) for competing in a game of prisoner's dilemma (Axelrod, 1984). Each model was paired with each other model and competition ensued over 200 iterations, with the outcome being tracked using a points system. The competition was won for 2 years in a row by the mathematician Anatol Rapoport, with a program that consisted of just five lines of code. Rapoport called his programme 'Tit For Tat', or TFT. The strategy behind TFT was simple: cooperate in the first round, and thereafter, repeat whatever action the competitor had taken in the previous round. Interestingly, Rapoport went on to make major contributions to the study of peace and global cooperation before his death in 2007 at the age of 95. He would probably have been intrigued to see the demonstration, published by Choi and Bowles (2007) just 10 months after his death, that a tradeoff between local cooperation (altruism) and external aggression (parochialism) can create a rational route to war.

Exploration of the spatial aspects of the prisoner's dilemma game was further advanced by Robert May and Martin Nowak (1992). They demonstrated that cooperators and defectors can coexist indefinitely if interactions are spatially localised. A level of stability arose through cooperators forming clusters that could lead to a higher payoff for cooperators inside clusters than for defectors at the boundaries. Subsequent research restricting games to local interactions can lead to a huge variety of different outcomes (e.g., Fig. 6.3), including the spread of competing strategies through populations and the capture of situations (i.e., formation of a locally stable state consisting of one strategy) by cooperators or defectors (e.g., Nowak,

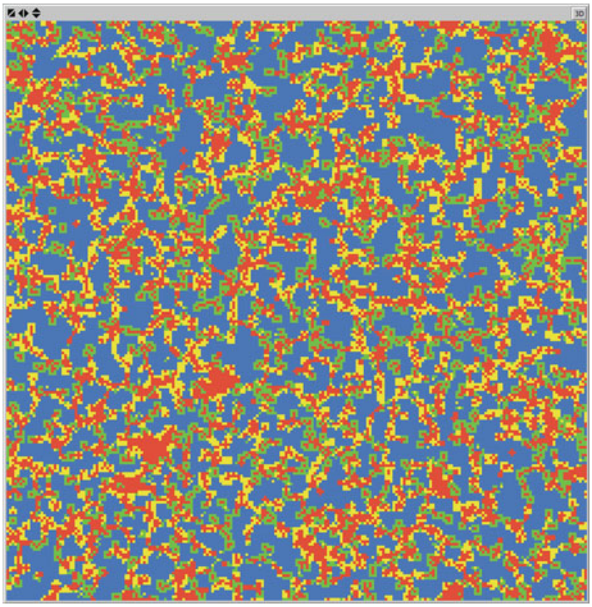

Fig. 6.3 Spatial depiction of an implementation of the prisoner's dilemma game in NetLogo (Wilensky, 1999, 2002). Each pixel in this 150 × 150-pixel world represents an actor who can interact with his/her eight neighbours in each iteration of the model. Actors cooperate (*blue*) or defect (*red*) with equal probability at the start of the model. From then on, if an actor has cooperated, its score will be the number of its neighbors that also cooperated; if it defects, its score will be the product of the defection-award ratio and the number of cooperating neighbors (i.e. the actor has taken advantage of the patches that cooperated). For the next iteration of the model, each actor will adopt the strategy of its highest-scoring neighbor from the previous round. In this figure, *blue shading* means that the actor cooperated in the previous and current round; *red*, that it defected in the previous iteration as well as the current round; *green*, that it cooperated in the previous round but defected in the current round; and *yellow*, that it defected in the previous round but cooperated in the current round. This particular simulation used a defection-award ratio of 1.58, which results in a dynamic pattern with similar proportions of defectors and cooperators. Netlogo can be downloaded or run on-line at http://ccl.northwestern.edu/netlogo/4.1.1/

Bonhoeffer, & May, 1994; Ohtsuki & Nowak, 2006; Ohtsuki & Nowak, 2007; Pacheco, Traulsen, Ohtsuki, & Nowak, 2008).

Although early work on spatial aspects of the prisoner's dilemma focused on lattice models (i.e., in which actors occupy a cell in a regularly-spaced grid), the same ideas have been applied to cooperative interactions in which network location matters. Some valuable insights have emerged from these models. In particular, for cooperative behaviours to persist in a population, the benefit-to-cost ratio of an altruistic act has to be greater than the mean number of neighbours per individual (Nowak, 2006; Ohtsuki & Nowak, 2006). According to Ohtsuki and Nowak (2006), this very simple rule seems to work for many different kinds of graph, including lattices, regular graphs, random regular graphs and scale-free networks. It also makes good practical sense; if each cooperative interaction carries a certain cost for the actor, costs become too high once the number of links that demand cooperation becomes too large. Ohtsuki and Nowak (2006) draw parallels to related research (e.g., West, Pen, & Griffin, 2002) which suggests that cooperation is a better strategy when the scale of competition is greater than the scale of interaction. For example, cooperation may be more likely if competition for resources takes place at a global or regional scale while social and economic interactions occur locally between small numbers of people (West et al., 2006). While these ideas may not appear particularly novel to people who have been thinking about transaction costs in real-world systems, it is important to note that game theory now provides a quantitative framework that can be used to analyse and model such tradeoffs in spatially explicit contexts, including networks of interactions.

Ecological Networks: Resilience of Endangered Species and Reserve Networks

There has been a large amount of interesting ecological research that has involved applying network analysis to food webs and mutualistic networks (e.g., Bascompte, Jordano, & Olesen, 2006; Dunne, Williams, & Martinez, 2002; Pascual & Dunne, 2006; Solé & Bascompte, 2006; Tylianakis, Tscharntke, & Lewis, 2007). Relatively few food-web studies, however, are explicitly concerned with spatial dynamics. Spatial analyses of ecological networks have been commoner in biogeography and conservation, and they are increasingly being applied to the study of metapopulations in spatial networks that consist of patches of habitat surrounded by an inhospitable matrix (Andersson & Bodin, 2009; Cantwell & Forman, 1993; Keitt, 1997; Urban & Keitt, 2001). Urban et al. (2009) offer a recent review of the details of network analysis in fragmented (or naturally patchy) landscapes. They provide a useful summary of some important technical details, including different approaches to quantifying relevant aspects of networks and verifying, validating and interpreting the results of network models.

Some of the most obviously spatial applications of network analysis have addressed such problems as the adequacy of reserve networks that are intended to protect populations and metapopulations of species that are of conservation interest. The value of describing spatial patterns as networks is most apparent when species of interest have clear-cut preferences for a particular kind of readily mappable habitat, such as patches of old-growth forest or seasonal ponds.

A good example of a network analysis relating to spatial resilience in a population of a single species comes from research by Örjan Bodin and colleagues (Bodin, Tengö, Norman, Lundberg, & Elmqvist, 2006) on the ring-tailed lemur, *Lemur catta*. Ring-tailed lemurs are forest-dwelling primates that play an important role in seed dispersal for forest trees, spending around 30% of their time on the ground. In the district of Androy in southern Madagascar, historically extensive areas of forest have been reduced to a set of small patches (1–95 ha) that offer islands of ring-tailed lemur habitat within an agricultural matrix. Many of the remaining patches are kept intact by virtue of their being used as burial sites; but local customs, which forbid entry into sacred groves, are being eroded by western values and immigration in many places and taboo-based habitat protection may not provide a long-term conservation solution (Bodin et al., 2006; Tengö, 2004).

In this landscape, network analysis can be usefully applied by treating forest patches as nodes and quantifying connectivity between patches based on the dispersal ability of the lemurs. A literature review suggested that ring-tailed lemurs occasionally move as far as 1 km (Bodin et al., 2006), suggesting a reasonable ballpark figure for vagility (i.e., the distance that a typical animal will move to find food). Patches (or patch clusters) $\leq$ 10 ha were considered unlikely to be permanently occupied. Bodin et al. (2006) varied their vagility assumption over a reasonable range around 1 km. Their analysis showed that if patches within 900 m of one another were considered connected, the landscape effectively split into two different compartments (giant clusters) of similar size.

Network-related metrics for each patch, such as the number of neighbours and the degree distribution, were also used to quantify the relative importance of each patch for the larger network. In a situation where connectivity is vital to population persistence, large patches may act as reservoirs, but smaller patches may play an ecologically important role by acting as 'stepping stones' – patches of habitat that may not on their own be able to sustain a viable population, but that provide temporary food and shelter that allows dispersing animals to move between larger patches. Network analysis provides a natural approach with which to explore scale dependencies and identify key tension points within fragmenting landscapes (Bodin & Norberg, 2007; Janssen et al., 2006).

Similarly, Urban and Keitt (2001) used satellite telemetry to map out a network of forest patches that constitute suitable habitat for the threatened Mexican spotted owl *Strix occidentalis lucida*. They explored the resilience of the network to patch loss using an approach based on minimum spanning trees and three different kinds of node removal (respectively involving pruning nodes at random, starting with the smallest, and starting with the smallest end node). Their approach enabled the authors to determine which individual patches had the largest overall impact on network connectivity, and hence to focus conservation action (and limited resources) on conserving the most important patches.

For small spatial networks, many of the conclusions derived from network analysis will be obvious from inspection of the network. The benefits of formal network analysis become more obvious when large networks are under consideration. The quantitative network analysis of spatial patterns, and the derivation of various different network metrics (e.g., see Box 6.1), can yield informative insights in cases where the number of nodes and connections is well beyond the ability of a human observer to cope with.

Network Analysis and Spatial Resilience

As these examples from three different fields suggest, network analysis offers a potentially useful tool for making links between the spatial properties of different kinds of network. The way in which a network is represented is the same for both social and ecological systems, despite differences in the nature of the nodes and the connections. Network analysis thus offers a way of quantifying similarities and differences between relational patterns in social and ecological systems in terms that can be directly compared (Cumming et al., 2010; Janssen et al., 2006). In addition, combined analyses of social-ecological systems have the potential for the development of fully integrated social-ecological models, and hence for understanding linkages and feedbacks within social-ecological systems (discussed in Cumming et al., 2010).

Network analysis offers a powerful tool for thinking through many aspects of spatial resilience. Some of its most interesting implications come from its potential to be combined with other approaches, such as different ways of quantifying landscapes, detailed studies of movement through networks, and linking network-based system descriptions to dynamic programming techniques such as neural networks and genetic programming. For example, given a conservation problem, a suitable optimization criterion, and a set of realistic test data that incorporated some stochasticity and surprises, it would be possible to use genetic algorithms to piece together network motifs (small sub-units with different functions) to evolve alternative network solutions that were robust to stochastic change.

Network analysis also suggests some novel ways of linking system architecture to system function. In a particularly interesting recent publication, Stouffer and Bascompte (2010) asked how the structure of a food web influences its long-term persistence. They assessed the roles of different 'trophic modules', each of which was comprised of recognisable structural units within a typical food web, to understand their relevance to the resilience of the broader system. Intriguingly, they found that those modules which are most commonly found in real-world food webs are also those that contribute the most to community persistence. The study also suggests a way of linking mechanistic approaches, based on detailed analyses of network subsets, to broader-scale comparative statistical analysis of food web architecture. I am not aware of any studies that have attempted to define similar 'modules' or motifs based on spatial relationships rather than trophic relationships, but the approach should in theory be equally applicable to questions of spatial resilience in biogeography and conservation.

Consideration of nodes, modules, and networks highlights one of the central questions in understanding any social-ecological system: what is the impact of the node on the network, and of the network on the node? In a spatial network, the broader network provides a set of constraints and opportunities that may heavily influence local events. At the same time, local activities may have knock-on effects that spread through the network, altering it from within. In spatial networks in particular, the physical location of a node (relative to the broader network) can have a disproportionately high influence on node importance. Seemingly insignificant patches of habitat or weak social links may be fundamental to social-ecological resilience if they act as stepping stones or serve to bring together different pieces of a network.

Mark Granovetter (1973, 1985) asked nearly 40 years ago whether there is a general relationship between the relative degree to which nodes in a network are connected and the overall resilience of the network. This is an important question because it implies that an understanding of network size, connectivity, and scaling properties could yield some valuable insights into network dynamics and the likely influence of the broader network on individual nodes and edges (Box 6.2). For example, road developments alter the geographical and social connectivity of local communities and will in turn influence their ability to maintain their identity (Cumming & Collier, 2005; Cumming et al., 2005).

Box 6.2 Intermediate Connectivity and the London Tube

Transport networks are often data-rich and can offer useful insights into spatial resilience. The London tube, London's underground rail transport system, is one of the oldest underground networks in the world. As part of an unpublished project on infrastructure connectivity, I looked at network change through time and current network resilience to delays using two tube maps, one from 1921 and the other from 1999 (Fig. 6.4a, b; see http://www.clarksbury.com/cdl/maps.html and the official tube site at http://www.tfl.gov.uk/tube/maps/). The connectivity of each line in the tube network can be quantified as

$$\gamma = \frac{L}{3(V - 2)}$$

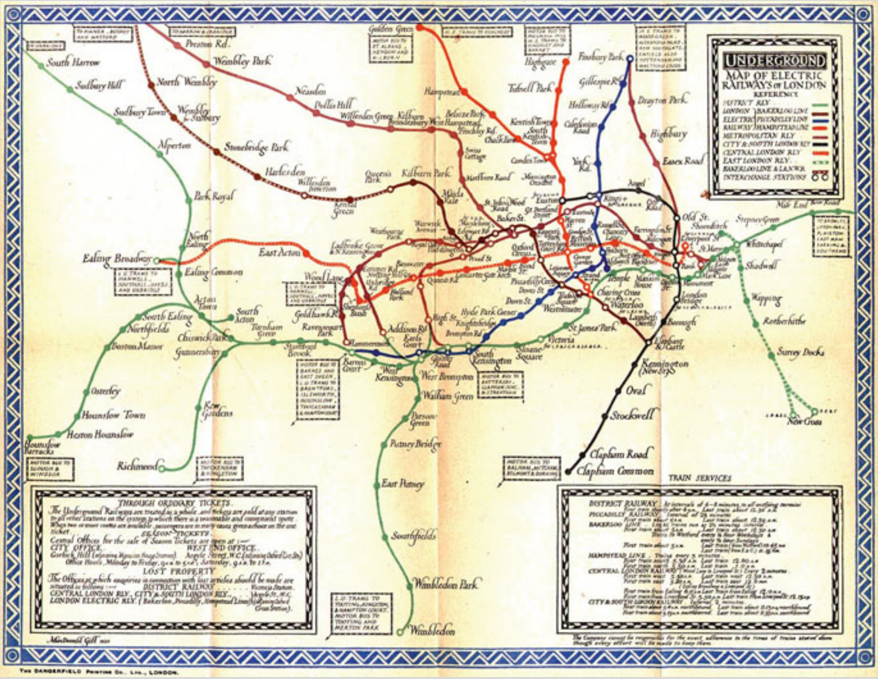

Fig. 6.4a London tube map from 1921

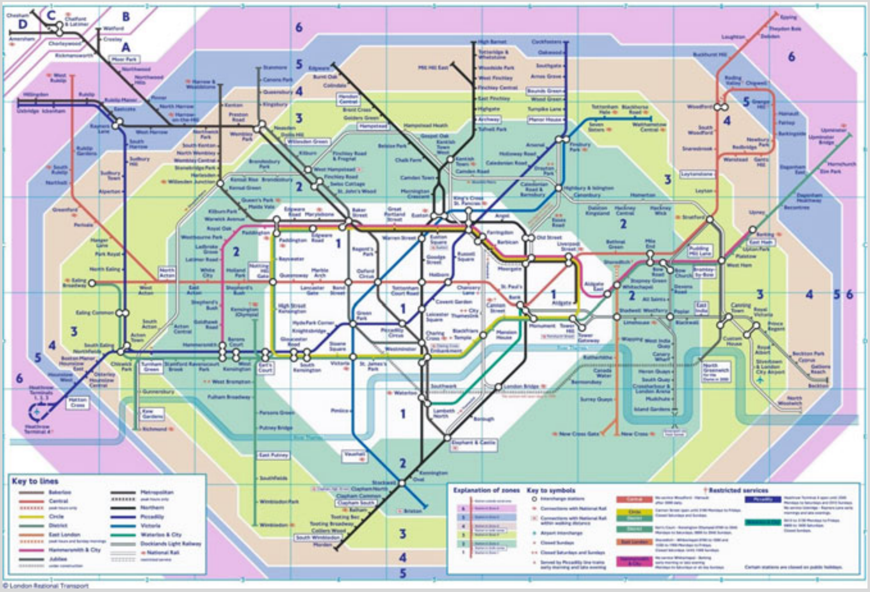

Fig. 6.4b London tube map from 1999

Where γ is network connectivity, L is the number of links, and V is the number of vertices.

Delay data reflect a summed response by the management of the tube system to local perturbations (such as mechanical failures of locomotives and signalling systems, customers behaving inappropriately, and the need for repair work), and so incorporate direct and indirect measures of both the degree to which the entire system is perturbed and its ability to respond, adapt, and self-organize. Data were obtained from the official web site of Transport for London, http://www.tfl.gov.uk/tfl/. I used the number of delays per month per line for the 55-month period from the 5th January, 2002 to the 4th March, 2006. The 11 lines included were Bakerloo, Central, Circle & Hammersmith, District, East London, Jubilee, Metropolitan, Northern, Piccadilly, Victoria, and Waterloo & City.

I plotted total vertex and edge numbers for 1921 and 1999 respectively against zone location to characterize how the spatial pattern of vertices and edges had changed over a 78-year time period (Fig. 6.5). When the spatial pattern of network spread is viewed by zone (i.e., in relation to distance from the city centre), the tube network has maintained a remarkably consistent, loglinear form through time. This stability can be attributed to the inflexibility of the city landscape and the high costs of modifying infrastructure, although >20 stations have been removed and several lines closed during the tube's history.

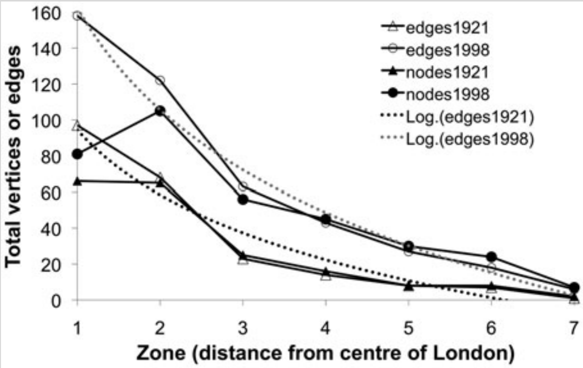

Fig. 6.5 Plot of number of vertices (tube stations) against distance from centre of London, as defined by tube zones

For the 11 different lines used in the delays analysis, there was a significant correlation between the number of delays experienced on the line between 2002 and 2006 and the numbers of nodes and edges that the line contained ($r_S = 0.709$ and 0.702 respectively, $p < 0.016$ in both cases, $n = 11$). Larger networks experienced more total delays, as would be expected if disruptions are random and independent of network size, but were not more connected. Despite the significant influence of network size on delay occurrences, the linear correlation between connectivity and delays was weak and insignificant, even with two outliers (Waterloo & City, and East London) excluded ($r_S = 0.477$, $p < 0.194$, $n = 9$). By contrast, a non-linear curve provided a significant fit to the plot of mean delays per month against connectivity (Fig. 6.6; $y = -118504x^2 + 81943x - 14135$; $R^2 = 0.684$; $n = 9$), supporting the idea that the relationship between resilience and connectivity is non-linear. Interestingly, the shape of the curve was opposite to what I expected, with the least and most connected networks being more resilient to disruptions than networks with intermediate connectivity. One possible explanation is that networks with intermediate connectivity experience more disruptions than low connectivity networks while lacking the capacity of highly connected networks to find alternative solutions. Some support for this view is provided by other studies (e.g., Mao, Panwar, & Hou, 2006).

The relationship between network size and number of disruptions was linear in this case, but has the potential to exhibit scale-dependent thresholds in resilience – for instance, if a network that crosses a critical size boundary suddenly becomes more (or less) vulnerable to a particular kind of perturbation. The nodes of physical networks exist in space and their spatial context may also be key to their dynamics and that of the network at certain times. For example, the Bakerloo tunnels that run under the Thames were temporarily sealed with concrete during the period of the second World War when London was being bombed (Day & Reed, 2001).

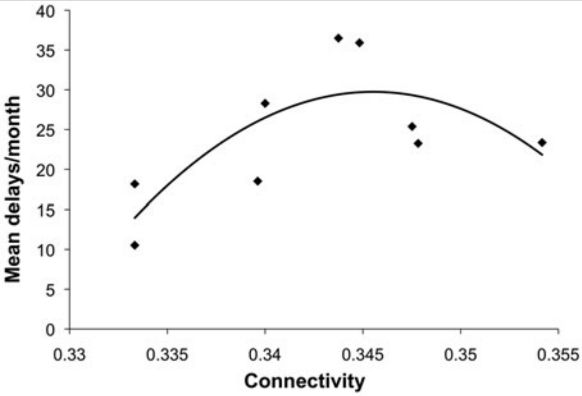

Fig. 6.6 Plot of mean number of service delays per month (i.e., late trains) against the connectivity of individual tube networks. Each point in this plot represents a different tube line

In ecology and conservation biology, the potential for a general relationship between connectivity and resilience has important implications for conservation and the maintenance of protected areas. Much of the ecological literature has assumed that increasing habitat connectivity through corridors and protected area networks will increase the resilience of ecological populations and communities of interest. However, connections between protected areas are also conduits for pathogens, parasites, and invasive species. If a general relationship between connectivity and resilience exists, it may have profound implications for determining how connected a particular protected area should be, and how best to spread the range of management and protection strategies (e.g., how best to apportion high vs. low connectivity nodes) within the regional network. Similarly, the structure and arrangement of networks (e.g., simple versus hierarchical branching) may have a significant impact on ecological dynamics (Cumming, 2002).

The resilience of a social-ecological system might be expected to be highest under conditions of intermediate connectivity (Bodin & Norberg, 2007; Cumming et al., 2005; Webb & Bodin, 2008), because the system is neither isolated from changes and perturbations nor overwhelmed by them. We would expect that more isolated modes are less likely to receive help from other nodes in a network, and so will not benefit from 'rescue effects' or spatial subsidies; nor will they have much need to adapt to changing external conditions, and so are likely to fall behind in any kind of 'arms race' situation and hence to be vulnerable to later increases in connectivity. By contrast, very connected nodes will be open to most of the influences that travel through the network, making it difficult to achieve any kind of local stability and potentially resulting in a boom-and-bust cycle. These two extremes are exemplified by Amazonian rainforest tribes on the one hand and the 9/11 destruction of the twin towers in New York on the other. The degree of isolation or connectivity of a given node will also have a range of indirect effects on such system properties as diversity and adaptive capacity.

In closing, I should make it clear that this brief discussion of network analysis has only scratched the surface of some of the more important topics in the study of spatial aspects of resilience. While network analyses at present raise more questions than they answer, the field is a rapidly growing and exciting area of research in many different disciplines. Although it is not yet possible to list out a set of network analysis-derived principles for spatial resilience in SESs, this area of research holds great promise, both as a possible source of new ideas and techniques and as a way of testing fundamental hypotheses about spatial resilience.

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Chapter 7
Spatial Resilience and Landscape Analysis

Introduction

The view from an aeroplane window on a clear day gives a good flavour of the perspective of a landscape ecologist or a geographer with an interest in land cover. From high above the earth's surface a different perspective on space presents itself. Even the casual observer will notice such things as gradients from hills to valleys or cities to farmlands; the ways in which large rivers cut across landscapes, carrying with them pieces of each of the areas through which they flow; and the unusually abrupt breaks, straight lines, and repeating patterns that are generated by human agency.

The different patterns within a landscape can be described and measured in a number of different ways and at a range of different scales. Depending on the goals of the analyst, landscapes can be viewed in different ways. For example, they may be approached as ecological entities (focusing on habitat types and organisms); as social or economic entities (focusing on people and their influences on landscape features, including 'cultural landscapes', which are defined as culturally significant landscapes fashioned by people); or as social-ecological entities (focusing on interactions and feedbacks between people and nature). Social-ecological landscapes are composed of people, abiotic and biotic variation, and the interactions between them, cohesively defined in space and time. A social-ecological landscape can contain multiple ecosystems, economies, and human social systems. It is thus a natural unit in which to address interdisciplinary questions of resource management, human wellbeing and ecosystem integrity from a spatial perspective.

Landscape ecology is the branch of ecology that deals most directly with social-ecological landscapes. As a discipline, it has relied heavily on a patch-matrix paradigm in which discrete features in the landscape are viewed as patches and the more continuous habitat in which they sit is termed the matrix (Turner, Gardner, & O'Neill, 2001). Patches are defined as nonlinear, contiguous areas that differ from their surroundings (Forman, 1995). They can be described quantitatively using patch metrics, which capture details about their size, shape, perimeter, and relationships to other patches of the same type and the broader landscape (e.g., Franklin, Dickson, Farr, Hansen, & Moskal, 2000; Leitao & Ahern, 2002; Shao & Wu, 2008).

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Linear features, such as roads and rivers, fall into a different analytical category from patches and are typically measured in different ways, although many of the same concepts remain relevant (e.g., Cumming, 2004; Wiens, 2002). Landscape ecologists have often ignored point features, such as nesting sites or salt licks or wellpoints, but these can also play an important role in landscape dynamics (e.g., Ruggiero & Fay, 1994; Smit & Grant, 2009).

The analysis of social-ecological landscapes is an important theme in geography, particularly in the area of remote sensing. Remote sensing describes the collection of data without direct contact between subject and observer. In the same way that a person in an aeroplane can obtain information about the landscape from the light that features on the earth's surface reflect, an aeroplane- or satellite-borne camera can collect detailed, spatially explicit information about spatial patterns of solar radiation as it is absorbed, stored, or reflected. The methods for capturing and interpreting remotely sensed data about the earth's surface are the focus of the current body of knowledge on remote sensing. There are many good published introductions to remote sensing (e.g., Campbell, 2002; Richards & Jia, 2006), to which the interested reader is referred for a comprehensive introduction.

A typical satellite image, such as an image taken by NASA's Landsat 7 Thematic Mapper, will simultaneously capture information across different parts of the electromagnetic spectrum. Different kinds of surface feature interact differently with different wavelengths of radiation. For example, the green leaves of plants absorb energy for photosynthesis at the red and blue ends of the spectrum, and the radiation that they reflect differs from that reflected by a green roof. Just as lakes, houses and forests reflect light in different ways and hence look different from an aeroplane, so the differences in the radiation reflected by different objects provide a signature that can be used to differentiate surface features from one another (Richards & Jia, 2006). In practice, following the collection of a reference or 'training' data set (i.e., ground measurements to establish the signatures of different features occurring in the image), multivariate statistical methods are used to classify each pixel as belonging to a particular land cover type – for example, forest, grassland, water, sand, or built environment. In this way, land cover maps can be created that provide detailed and accurate descriptions of spatial patterns in landscapes (although categorical classifications do have some weaknesses; see, e.g., Arnot, Fisher, Wadsworth, & Wellens, 2004; Fassnacht, Cohen, & Spies, 2006; Peng, Wang, Ye, Wu, & Zhang, 2007).

Another important use of satellite remote sensing data is to describe variation in continuous variables, such as vegetation greenness, based again on spatial variations in the amount of reflected radiation. Continuous data provide a different way to view the world (Fig. 7.1). For example, vegetation indices and greenness metrics can be quantified for every cloud-free pixel in a Landsat image and may give a different perspective on vegetation communities from that offered by a categorical classification (Fassnacht, Cohen, & Spies, 2006; Southworth, Munroe, & Nagendra, 2004). These data are potentially very powerful because they capture slight differences within areas that might be viewed as the same patch type in a standard landscape ecology analysis.

Fig. 7.1 The earth in 2005, as seen as a composite from MODIS satellite images. This image, which is freely available on-line from NASA's Earth Observatory web site, has been shaded to match the natural colours of the earth. Note the staggering amount of highly accurate spatial information that remote sensing technology can provide

Land cover refers to the habitat type that is present at a given location. The way in which a pixel is used by people is termed its 'land use'. For example, a forest pixel (land cover type) might be a conservation area (land use type) or a timber plantation (land use type). Land cover and land use are particularly interesting in analyses of spatial resilience because they depict two different aspects, the environmental and the socioeconomic, of the same area at the same grain. Land cover and land use maps together provide an 'interface' data set – that is, one that reflects spatial aspects of both ecological and social dynamics (Cumming et al., 2005).

Advances in remote sensing have provided numerous ways of quantifying spatial patterns in landscapes, and consequently have been integral to developments in landscape ecology (Newton et al., 2009). Landscape ecology and other branches of geography have in turn provided remote sensing with problems and questions that have pushed remote sensing researchers to new heights. In recent years there has also been an increasing move towards integrating landscape ecology and remote sensing analyses with socioeconomic data, and towards using remotely sensed data to guide the management of natural resources (e.g., Gaughan, Binford, & Southworth, 2009; Guyer et al., 2007; Kennedy et al., 2009; Nagendra, Munroe, & Southworth, 2004). These trends are gradually producing a wide-ranging science of landscape analysis.

Further interdisciplinary integration of approaches to landscape analysis has considerable potential for improving our understanding of spatial resilience. Land cover patterns over most of the earth's surface (e.g., Fig. 7.2) are a direct reflection of land use and a broader, multi-scale interaction of physical, ecological and

Fig. 7.2 A patchy landscape; aerial photograph of the periphery of Harare, the capital of Zimbabwe. Photograph by Graeme S. Cumming

societal processes ('societal' here including such things as economics, institutions, social learning, and policies). In the phrasing of Herbert Simon, one of the fathers of complexity theory, 'process is what maps pattern onto pattern' (Simon, 1962, 1976): changes in landscape patterns reflect variations in the processes that have produced them. At the same time, patterns influence and sometimes limit the kinds of process that can occur within a landscape. For example, extensive fires will not occur where the spatial configuration of patches that contain fuel does not allow fire to cross between patches. Landscapes have some patterns that are symmetrical, in the sense that pieces of the landscape are effectively interchangeable; and other patterns that are asymmetrical and linked to gradients or distinct, organized spatial variation (e.g., Kessler, 2002). Different kinds of pattern asymmetry can interact with landscape processes to create feedbacks, thresholds, and other typical properties of complex systems (reviewed in Cumming, Barnes, & Southworth, 2008). For example, differential heat reflectance between different tree species in boreal forests can influence the incidence of lightning strikes, which in turn determines the fire regime, which in turn can influence species composition, which in turn influences reflectance; and in this way fire-tolerant or fire-suppressed vegetation can effectively self-organize to create a local 'regime' that keeps a system locked in to a particular state (Bonan, Chapin, & Thompson, 1995; Higgins, Mastrandrea, & Schneider, 2002; Kasischke, Christiansen, & Stocks, 1995).

The demonstration that some landscapes are capable of self-organization raises the question of whether we can think of landscapes as complex systems. To clarify, there is no doubt that complex processes occur within landscapes, and that these processes influence land cover and land use, but the question here is posed at a higher level of analysis: can entire landscapes can be seen as complex systems, with different land cover and land use types exhibiting emergent properties and complex interactions in their own right?

There are at least two reasons why this is an important question. First, if landscapes are complex systems, then studies of landscapes should offer deep insights into the nature of spatial aspects of complexity; research on the emergent properties of social-ecological landscapes has the potential to make useful contributions to complexity theory and the further development of interdisciplinary frameworks. Second, we need to determine how (and whether) to apply existing theories and methods from the study of SESs to studying landscapes. If landscapes are passive reflections of external drivers, or if they can not be viewed as complex systems, then it is possible (in the worst case) that each landscape must be analysed individually and that few or no overarching generalities exist by which we can connect seemingly disparate case studies. Alternatively, we may have to restrict ourselves to being content with teasing out separate ecological, economic and sociological generalities, with little or no true exchange between disciplines. By contrast, if landscapes can be analysed as complex systems, we can bring the set of theoretical and analytical tools that have been developed for other complex systems to bear on the analysis of landscapes; and we can immediately make some far-reaching generalisations about change in landscapes.

Viewed as a research process, an analytical approach in which ecologists and social scientists develop separate models and provide one another with inputs and outputs is quite different from a truly integrated framework, such as that offered by complex systems theory, in which different disciplines refer to a broader underlying set of concepts and explore how these explain social-ecological system dynamics in different locations. For example, if landscapes are complex systems, we can expect the populations and communities of pixels in land use and land cover maps to exhibit non-linearities, thresholds, and feedbacks; to display some capacity to adapt and self-organize; and to exhibit a multi-scale, hierarchical structure with scale breaks in different variables arising as a consequence of the interactions between fast and slow variables. Identifying landscapes as complex systems thus provides a broader context for disciplines like landscape ecology and geography and suggests a range of new ways of looking at, studying, and understanding dynamic change in landscapes.

An important step in building the theory that links landscapes and complexity will be to develop ways of working with remote sensing products that allow us to bring the increasingly powerful body of complex systems theory into landscape analysis, and vice-versa (Turner, Lambin, & Reenberg, 2007). In the rest of this chapter I will focus on (1) the case for analysing landscapes as complex systems; and (2) building a bridge between ecological and remote sensing (geographic) perspectives by drawing out some of the parallels between pixels and species.

Landscapes as Complex Systems

Most landscape ecologists would accept that a landscape can be defined as an area that contains spatial heterogeneity in at least one property of interest. It would be possible to argue indefinitely over the details of such a definition, but I refer here to 'a landscape' as it is typically used and applied in the ecological literature (e.g., Turner et al., 2001; Wiens, 2002). In thinking through applications of complexity theory to landscapes, we need to address a logical progression of questions that include (1) whether landscapes are systems; (2) if so, whether they exhibit the hallmarks of complexity; (3) if so, whether they should be considered as complex systems or complex *adaptive* systems; and (4) whether landscapes exhibit other, unique properties that should be taken into account when applying ideas about complex systems to landscape analysis.

Can an appropriately bounded area qualify as a system? The different parts of a typical complex system derive their membership in the system through one or more shared properties that provide cohesion (Collier & Hooker, 1999; Collier, 1986), bring them into contact with one another, and create interdependencies. In a person, for example, different organs contribute to the persistence of the entire system; cohesion is provided by transport networks (blood, lymph, digestive system) and by the skeleton, muscle, and skin, which create a bounded structure on which and within which organs are arranged. Such arrangements also demand spatial proximity of different parts.

Most landscapes lack the equivalent of a physical 'skin', but strong parallels to other complex systems exist; social-ecological systems typically contain hierarchies of administrative institutions that range from the nation state down to the municipality, and in many ecosystems important edge or transition zones (such as those between biomes or vegetation types) or bounding features (such as oceans, catchment boundaries, or large rivers) can be identified across a range of different scales (e.g., Cadenasso, Pickett, Weathers, & Jones, 2003; Pickett et al., 2008; Wiens, 2002). Steve Carpenter, an eminent limnologist, refers to the shoreline as 'the skin of the lake' (Carpenter, personal communication). There are also transport networks (e.g., rivers, roads, power lines, prevailing winds) that flow through or over landscapes and provide a level of cohesion (or in some cases, disruption) between different parts of the landscape (e.g., Alexander & Waters, 2000; Schurr, Bond, Midgley, & Higgins, 2005; van Bohemen, 1998; Wilkie, Shaw, Rotberg, Morelli, & Auzel, 2000). As with organs in a body, the resilience of different kinds of land cover (e.g., forests, golf courses, or housing developments) may relate closely to their proximity to particular kinds of transport network (e.g., Laurance et al., 2002). Spatial proximity and connectivity are probably the single most obvious causes of cohesion in most landscapes. Very different parts of a landscape (e.g., forests and drylands) can influence and interact with one another simply because they are near to each other (e.g., Soderberg & Compton, 2007). Proximity also means that features within a landscape tend to experience similar broad-scale environmental regimes. Key drivers such as droughts or periodic disturbances can affect large areas at the same time, leading to a degree of synchrony in the timing of land cover and land use change (e.g., Holmgren & Scheffer, 2001). For example, a substantial amount of citrus production in northern Florida ended abruptly following a series of freezes in the 1980s, with the long-term consequence that pieces of the landscape now consist of abandoned citrus groves in similar successional states (Cumming & George, 2009).

These considerations suggest that social-ecological landscapes can indeed be considered as systems. It is also clear that they share with other complex systems a number of other important properties. For instance, the role of diversity (i.e., the differentiation of components) in landscapes is critical, with both the average amount of heterogeneity at a particular scale and the extent to which heterogeneity varies across a broader landscape being important for system processes and stability (Levin, 1992; Scheffer & DeBoer, 1995). Asymmetries in landscapes can drive processes (Cumming, Barnes, & Southworth, 2008), and boundaries and flows (of materials, organisms, or people) matter (e.g., Polis, Power, & Huxel, 2004; Schindler, Leavitt, Brock, Johnson, & Quay, 2005). Landscapes have a hierarchical arrangement in common with other complex systems (Simon, 1962), contain a finite range of possible variation, can exhibit a number of markedly non-linear pattern-process interactions (e.g., Kasischke et al., 1995; Scheffer, 2009), and may show strong path dependency in terms of the influence of their past history on current and future trajectories of landscape change (e.g., Cumming & George, 2009; Lugo & Helmer, 2004).

Landscapes as Complex *Adaptive* Systems

It is slightly harder to answer the question of whether social-ecological landscapes (considered as populations of pixels) are complex *adaptive* systems. Several aspects of landscapes do, however, suggest that they can be considered adaptive. They exhibit many of the classical features of adaptive systems, including the creation of novelty, the presence of diversity, and the removal or restoration of some land cover or land use types by the actions of competition and selection (e.g., Marignani, Rocchini, Torri, Chiarucci, & Maccherini, 2008; Turner et al., 1993, 2007). New forms of social-ecological landscape component include such things as new cropping systems, new tenure systems, and new habitats. For example, extensive planting of biofuels may alter landscape patterns; extractive reserves are a relatively recent form of landscape element that seems likely to have differing resilience from exclusive reserves; and invasive species can significantly alter habitat composition in urban green spaces (e.g., Dures & Cumming, 2010).

Land cover types exhibit differential mortality. Selective processes remove (convert) pixels that are 'unfit' within the current social-ecological environment. For example, if the global economy places a high value on hardwoods, patches of hardwood trees are likely to be selected against by human agents (whether from inside or outside the system) and removed from the landscape (Laurance et al., 2002);

economic pressures favouring certain crops, such as coffee, may alter spatial patterns of forest cover (Nagendra, Southworth, & Tucker, 2003); and forests are often cut down to make way for farmlands (Gaughan, Binford, & Southworth, 2009). The fact that the composition of a landscape can respond to selective pressures, together with the fact that the composition of a landscape will influence the magnitude and nature of many of the selective pressures that it experiences (e.g., Bellamy & Lowes, 1999; Daniels & Cumming, 2008), suggest that entire landscapes can be expected to exhibit a range of complex system dynamics that match the standard definitions of adaptation and self-organization. As in any other complex adaptive system, the relevance of feedbacks from pattern back to process depends largely on the scales of different influences, with endogenous processes (i.e., those occurring completely within the system) being more likely to lead to two-way pattern-process feedback loops.

Feedbacks and related self-organizing processes are of high interest in the study of complex systems because they create the possibility for alternate stable states, regimes, and regime shifts. An understanding of regimes and regime shifts is integral to understanding the resilience of a system (Carpenter, Walker, Anderies, & Abel, 2001; Holling, 2001), and spatial self-organization is an important aspect of spatial resilience. Self-organizing processes occur in many landscapes, often quite independently of external drivers. For example, people tend to construct their houses in particular places relative to city centres, and housing densities increase faster near to cities (Ulfarsson & Carruthers, 2006; Yu & Ng, 2007). City sizes have a multimodal distribution, with aggregations and 'gaps', suggesting that there are certain city sizes that are unsustainable and others that constitute relatively stable states (Garmestani, Allen, & Gallagher, 2008). The creation of a sufficiently large city sets in train a series of processes that often result in further increases in city size; and cities tend to grow faster when they are small relative to their market potential (Garmestani, Allen, & Gallagher, 2008; Ioannides & Overman, 2004). Large cities can in turn create environmental influences that differ from those of small cities (Box 7.1). Similarly, the fine-scale processes involved in clearing rainforest for commercial timber or the creation of pastures can result in a regular 'herring-bone' pattern of tree loss (Fig. 7.3) as people construct and use access roads (Cochrane, 2001). The occurrence of autonomous processes and pattern-process feedbacks, together with a hierarchical system structure, means that certain parts of the landscape can end up following a different trajectory from other parts. This kind of dynamic is common in many complex adaptive systems and equates to the processes of compartmentalisation and modularity that have been described in other systems (Cumming & Norberg, 2008; Dicks, Corbet, & Pywell, 2002; Levin & Lubchenco, 2008).

Compartmentalisation usually occurs when top-down feedbacks are weak at higher levels of a hierarchy and interactions within and/or below a level of interest are strong. For example, deforestation in Acre (Amazon Basin, Brazil) can be partially explained by the weakness of enforcement of laws that demand that landowners maintain a proportion of forested land on their property (see overview in Laurance, 2000). Landscapes have in common with many other complex systems the property that local interactions and exchanges between components are important. The potential for compartmentalisation means that artifical boundaries,

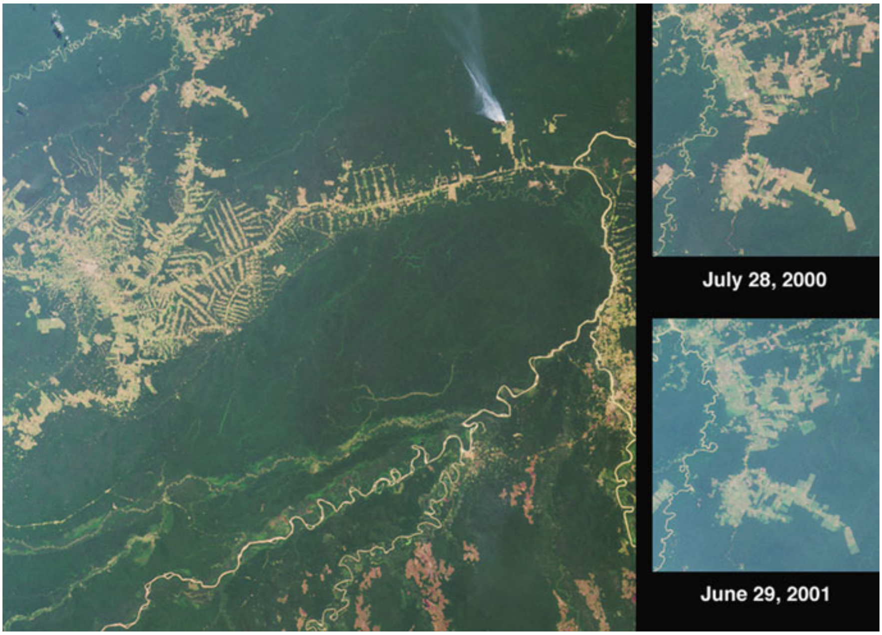

Fig. 7.3 Area in which rainforest has been removed from the Amazon, surrounding Rio Branco, Brazil, show the classic herring-bone pattern that often accompanies deforestation. The large overview image was acquired by NASA's Multi-angle Imaging SpectroRadiometer on the 28th July, 2000, and covers an area of 333 km^2. This image was provided by NASA's Earth Observatory

such as those of nation-states, can constrain local interactions across the boundary and can gradually entrain divergent but neighbouring systems. For instance, the island that contains Haiti and the Dominican Republic has a single biophysical environment but two vegetation compartments: in simple terms, a deforested half (Haiti; e.g., see Dolisca, McDaniel, Teeter, & Jolly, 2007) and a forested half (the Dominican Republic). As this example shows, political systems are tied to particular locations and can be important influences on broader-scale spatial patterns (and ultimately on spatial resilience).

Local interactions and compartmentalisation contribute in various ways to the potential for non-linearities and thresholds in landscapes. One of the most widely documented thresholds in landscape ecology occurs when habitat is removed at random from a simulated landscape; connectivity between patches declines according to a sigmoidal relationship with a tipping point at approximately 46% habitat loss (Turner et al., 2001). Such non-linearities can play important roles in pattern-process relationships (Richardson, Cowling, & Lamont, 1996). For example, if forest regeneration is contingent on the dispersal of seeds by small mammals, decreases in connectivity beyond the 46% threshold can ultimately result in further attrition of forested patches. As this example shows, structure and function in landscapes can have strong influences on one another, as in other complex adaptive systems.

Box 7.1 Urban Heat Islands

An intriguing example of the feedbacks between pattern and process at the scale of an entire landscape is that of the urban heat island effect. The primary source of heat in most environments is the sun. Different surfaces have different capacities for absorbing, storing or reflecting solar radiation.

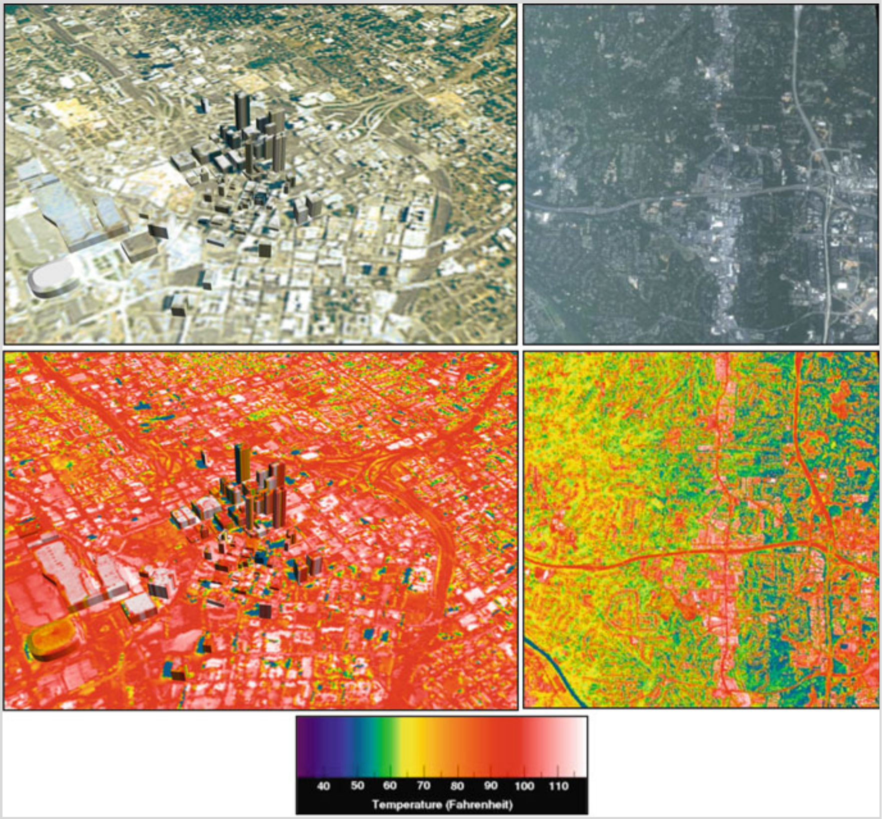

Fig. 7.4 The urban heat island of Atlanta as revealed using thermal imagery. These figures show the city downtown area on the *left* and an adjacent suburban area on the *right*. The *upper pictures* are in true colour and the *lower pictures* in 'thermal colour'. Temperatures in Fahrenheit are given in the bar at the base of the figure. Note how the roads and the roofs of buildings stand out. These photographs were taken by NASA's Earth Observatory and can be viewed in full colour (if you are reading the print version of this book) at the Earth Observatory web site

The proportion of reflected radiation is termed the albedo of a surface. For example, snow has a high albedo and forests tend to have a low albedo. Vegetation absorbs sunlight for use in photosynthesis, but it also keeps itself cool by evapotranspiration. When humans build over extensive areas of formerly vegetated land, they often use materials that have high albedos (e.g., one-way glass and aluminium) or materials with low albedos that rapidly become warm (e.g., tarred road surfaces and roofs). Buildings change the structural properties of the surface, and the release of stored heat at night can reduce night-time cooling. These changes alter the thermal properties of the earth's surface, changing patterns of reflection, conduction, and convection of solar energy, and influencing the heatrelated dynamics of the surrounding landscape in a variety of ways (Shepherd, 2005).

A classic example of an urban heat island comes from the city of Atlanta (Fig. 7.4). As these figures show, Atlanta's relative lack of downtown greenery has resulted in the creation of a higher-temperature zone in the middle of the city. A number of studies have shown that this zone not only experiences temperatures some 2–10°C higher than the surrounding countryside, but also that it causes increased convection, which in turn influences downwind precipitation patterns and thunderstorm activity (e.g., Diem & Mote, 2005; Dixon & Mote, 2003). As a result, Atlanta and some areas downwind of Atlanta now experience greater rainfall relative to control sites and historical data. Urban heat islands provide a fascinating example of how the fine-scale activities of people can accumulate to cause larger-scale effects that can have profound consequences for ecosystems.

Lastly, it is worth noting that landscapes contain many overlapping systems within the same space. Like ecosystems, landscapes usually lack a restrictive boundary or semi-permeable membrane. This means that movement in and out of a given landscape, whether at random or on a regular basis, is easy. Some key processes may be performed by infrequent visitors, such as migratory species or other long-distance dispersers (e.g., Green, Figuerola, & Sanchez, 2002; Helfield & Naiman, 2001); and other key processes, such as the regeneration of grasslands, may occur when mobile individuals or species are temporarily absent. There are, however, differences in the accessibility of different landscapes, and some kinds of landscape feature (such as mountain ranges, forests, or grasslands) can provide impermeable barriers to the movements of animals and plants. Over long time periods these barriers can play an important role in the formation and maintenance of diversity (Box 7.2).

Box 7.2 Highland Bird Distributions in Africa

Bird communities in montane regions of Africa, such as the Albertine Rift and the Eastern Arc mountains, show some striking similarities. Many of the true forest specialists occur only in isolated, high-altitude pockets of habitat; but these pockets may be thousands of kilometres apart and not linked by dispersal.

Similarities between bird communities in disjunct (spatially separated, as by the Rift Valley) locations result from a combination of dispersal, convergent evolution, and isolation. During the Pliocene, Africa's increasingly drier climate caused dramatic reductions in the extent of Afrotropical lowland forest. Since highland areas tend to get more rainfall, forests were lost from low-lying areas of the landscape and many of the connections between forested regions were broken.

How did bird communities respond to such widespread land cover change? Montane forest regions were left relatively unchanged by late Pliocene-Pleistocene climate change, acting as stable regions within a changing landscape. They may have acted as temporary refugia for formerly lowland forest birds, a hypothesis which is supported by species that are currently found in several different highland areas with disjunct distributions, such as the green-headed oriole *Oriolus chlorocephalus* (Crowe & Crowe, 1982; de

Fig. 7.5 Mount Gorongosa, as viewed from near the 'Renamo hut' near the base of the mountain. The only population of green-headed orioles in southern Africa lives in a forested belt on the upper slopes of the mountain. Photograph by Graeme S. Cumming

Klerk, Crowe, Fjeldså, & Burgess, 2002). Alternatively, separation of existing populations into smaller pieces may have resulted in increased rates of local adaptation and speciation, as for the (derived, relative to lowland species) forest robin genera *Cossypha* and *Sheppardia*, implying a role for montane areas as centers of endemism (Voelker, Outlaw, & Bowie, 2010). Much of the high diversity of Africa's montane biodiversity hotspots (e.g., Fig. 7.5) probably derives from the combination of these two effects: persistence of ancestral lineages on the one hand, and increased speciation rates (resulting from isolation of small populations) on the other (Fjeldså & Bowie, 2008).

Landscapes as a Unique Class of Systems

Despite their many similarities to other complex systems, landscapes have some unique features that must be taken into consideration when applying complex systems theory to problems of spatial resilience. Probably the single most important difference between a landscape and most other kinds of complex system is that landscapes offer a zero-sum game in terms of area (although not necessarily in other relevant quantities, such as biological diversity or the production of ecosystem services). In other words, every part of a landscape must be occupied by some kind of land cover type, whether by natural habitat, buildings, or bare earth. Closely allied to the zero-sum game is the lack of mobility of different parts of the landscape; although elements within the landscape may move, the biophysical configuration of most landscapes changes at geological time scales (although rapid climate change and sea level rise may yet make this statement untrue). Continental drift, volcanoes, earthquakes, floods, glaciers, and erosion are the primary drivers of changes in landform (Fig. 7.6). By contrast, human elements of landscapes, such as cities and transport networks, can change at time scales of years and decades.

Considering the immobility of many landscape elements and the fact that the primary basis for landscape cohesion is proximity, it is clear that membership within a given landscape is more a boundary condition than a systemic condition. Incompatibility of membership within a landscape (i.e., the presence or attempted entry of a land cover type that is unsustainable within the larger configuration of the landscape) will probably result in landscape change, but may occur more frequently than would be expected in a complex system in which membership is contingent at all times on fitting in with a more process-oriented criterion (such as survival of the unit as a whole). Another important consequence of the organizing role of space in landscapes is that most important interactions will evidence some kind of quantifiable decay in their strength as proximity and/or connectivity decreases. This property makes landscapes a good study system for exploring spatial influences in complex systems research, as discussed in Chapter 6 (understanding networks) and in Chapter 8 (understanding fragmentation). Some detailed examples of specific

Fig. 7.6 A typical post-glacial landscape in southern Germany. Gently rolling hills in this area reflect the grinding action of ice. Photograph by Graeme S. Cumming

hypotheses about spatial resilience that studies of landscapes could contribute to addressing are presented in Chapters 3 and 10.

It is also worth noting that social-ecological landscapes per se differ from many other complex systems in that their biophysical elements have no unified decision making capacity, no central information processor, and no intentionality. A particular kind of land cover class or habitat can only expand at the expense of other elements within the landscape; large-scale landscape patterns are often emergent properties of local mechanisms, rather than a consequence of selective pressures at a landscape scale. Obviously, some forms of centralised information processing and response capacity have arisen within social-ecological landscapes, such as national land use policies, urban planning, and the deliberate creation of areas with particular tenure regimes.

I have dwelt at some length on how landscapes are similar to other complex adaptive systems and how they differ. This discussion is necessary to help us decide which ideas from complex systems theory can be borrowed in the analysis of spatial resilience and which ideas must be modified, or qualified, or completely rejected. If we accept that social-ecological landscapes are complex adaptive systems (CASs), we need to broaden the scope of investigations of landscape pattern-process interactions to include CAS-specific phenomena (such as feedbacks and thresholds) and to modify spatial planning processes to take better account of path dependencies, uncertainties, non-linearities, and the potential for surprises. Some early suggestions of these new directions are already in place in published studies (e.g., Foster et al., 2003; Gordon, Peterson, & Bennett, 2008; Gunderson & Holling, 2002; Lambin, Geist, & Lepers, 2003), but they are far from being widespread or even widely accepted in LULCC analyses. Consideration of landscapes through a complex systems lens suggests a number of fertile areas for future research; both landscape ecology and land use and land cover change analyses will benefit enormously from looking more intensely, with detailed empirical data, for certain kinds of landscape dynamic. Chapter 10 contains some detailed examples of some of these areas in the context of understanding the spatial resilience of large river basins. Ultimately, therefore, this kind of analysis should help us to overcome the problem of the correlative but largely mechanism-free approaches that have so far been one of the greatest weaknesses of landscape analysis (Cumming, 2007).

Land Cover Maps as Populations of Pixels

As explained above, changes in the values of pixels in land cover maps can be viewed as emergent outcomes of a set of social-ecological dynamics. Most mechanistic studies of landscape change have focused on understanding correlations between land cover change and the underlying drivers of change (e.g., Dai, Wu, Shi, Cheung, & Shaker, 2005; Lambin et al., 2003; Munroe, Southworth, & Tucker, 2002). While these analyses have yielded some important insights into individual case studies, they are often difficult to generalize from; and spatially correlated interactions between different land cover types are often ignored.

The observation that pixel values represent an emergent 'summation' of underlying causal relationships suggests that perhaps analyses focusing on pixels, as interacting units in their own right, may offer some valuable generalities. Pixels of different types can be viewed as populations of 'species' (land cover or land use types) that interact via mechanisms similar to those common in ecological communities (Table 7.1). Although Geography as a discipline has a long history, land cover change analyses (and particularly those that incorporate the spatial detail that can be obtained from satellite remote sensing data) are relatively recent. Consideration of land cover change dynamics from the perspective of ecological mechanisms offers the potential for novel insights as well as for drawing on a longer history of thought and quantitative research on spatial dynamics of animal and plant populations and communities. Many of the methods and models that are routinely employed in ecology for population and community analyses could have valuable applications if adapted appropriately to the analysis of land cover data. In addition, as discussed in Chapter 5, ecologists have already made considerable progress in understanding ecological interactions in space and some of their likely implications for spatial resilience.

As a word of caution in pursuing this line of thought, it is important to note that there is a fine line between naïve analogies and genuinely shared mechanisms underlying pattern-process relationships. Naïve analogies focus on superficial similarities to draw parallels that often break down under more intense scrutiny. Shared

Table 7.1 Examples from ecology and LULCC research, illustrating some similarities in processes that occur between and within ecological communities and pixels and/or pixel types respectively

Ecological interaction or dynamic	Mechanism underlying population or community dynamic	Mechanism underlying pixel change from one land cover class to another
Competition, competitive exclusion (different parties fight for the same resources)	Mussels, limpets and barnacles compete for space on a rocky shore	Urban areas and housing developments compete for space with conservation areas (natural vegetation) and farmland
Facilitation (environmental modification by one party supports growth or colonization of another)	Canopy trees provide the environment needed by shade plants	Conversion of natural land to agriculture or mining provides resources for establishment of towns (e.g., Johannesburg)
Parasitism (extraction of resources from one party by another)	Cattle productivity is reduced by high tick burdens; arctic reindeer waste energy fighting mosquitoes; tapeworms extract heavy metals from birds	Urban areas suck resources from surrounding countryside while sending them waste and pollution (e.g., footprint of London)
Mutualism (beneficial interaction for both parties)	Pollination systems, such as bees and flowers. Typically linked dynamics with correlated increases or decreases in abundance (although not necessarily at the same time scales)	Seasonally flooded wetlands improve water quality in adjacent lakes; water is essential for maintenance of wetland plants that appear as distinct land cover classes (e.g., reed beds), and so total numbers of pixels tend to grow or shrink together. Persistence of both types of land cover is inter-related because cleaner water is given higher value by people
Predation, predator-prey cycles (consumption of one party by another; typical cycles engendered by different consumption and recruitment rates between predator and prey)	Numerous classical studies based on Lotka-Volterra model	Clear-cuts for cattle pasture ‘swallow’ a rainforest; regeneration of rainforest is slow, but can engender cycles of felling and regrowth

Table 7.1 (continued)

Ecological interaction or dynamic	Mechanism underlying population or community dynamic	Mechanism underlying pixel change from one land cover class to another
Succession (progression in time and space of predictable community stages)	Classical Clementsian progression from bare ground through weedy colonisers to shrubs and forest	Individual pixels in LULCC research follow 'trajectories' that are often similar to (or indeed, based upon) those of vegetation communities. For example, a pixel in a classification might move from pasture to shrub to forest over different dates. Other less 'ecological' pathways also exist, such as forest to pasture to urban, but the principle is the same
Selection (reduction of diversity by pressures that act differently on different kinds of system component)	Species that are unsuited to their local environment are removed by processes that cause mortality to exceed recruitment. Examples of such processes include predation, disease, and environmental extremes of temperature or drought	As the landscape changes, some land cover types become unsuited to their context – for example, natural grassland in cities or wetlands in extensive farming areas – and are gradually driven to extinction
Dispersal (movement away from location of origin)	Plant propagules are released by sessile parents and disperse in different ways depending on their size, mobility, and germination requirements; note tradeoff here between propagule size (larger tending to be more effective competitors), dispersal distance, and number of propagules; also between the higher likelihood that the parental environment is suitable versus competition with parent and siblings	Contagious land cover types, like urban sprawl or deforested areas, tend to spread slowly through space – much like an invasive but dispersal-limited species. New agricultural practices and technological innovations that alter pixel type will also spread gradually through a landscape via social networks, which influence rate and extent of spread. Examples include changes in ploughing technology (hand to horse to tractor), chain saws, pesticide and fertiliser use patterns, and changes in extent and kind of crops planted. Infrastructure plays a key role in dispersal of land cover types; humans create their own corridors (and resource patches) before and during dispersal

mechanisms, by contrast, are based on the idea that the same general principles underlie pattern formation across a range of complex systems. A good example of the value of thinking about shared mechanisms comes from the demonstration by Beinhocker (2007) that principles of diversification and selection, similar to natural selection (if different in some equally important ways), can explain some important aspects of the incredible expansion of the human economy over the last 200 years.

Considered at the right level of analytical generality, shared mechanisms (rather than just intriguing analogies) almost certainly do exist between ecological interactions and land cover change. The mechanisms by which species within ecological communities interact (labelled by ecologists with such terms as predation, competition, parasitism, and mutualism) have some important general properties that are echoed in other complex systems. For example, 'predation' typically evokes an image of a large carnivore, such as a lion, messily devouring a hapless antelope. But a more general way to view predation is as a term that describes the transfer of resources from the antelope to the lion. Predation as used in ecology carries the added assumption that the antelope will not survive the process (or at least, will experience pain, lose its identity, and become part of the lion), and hence that being preyed upon is not in the best interests of the antelope. For the antelope population as a whole, however, predation may play an important role by weeding out the weak and diseased members of the population, and by preventing the population from becoming sufficiently large to exhaust its own resource base (in this case, vegetation).

Transfers of resources occur in many different spheres, including economies. Labelling a hostile business takeover as 'predation' may sound overly dramatic, but the outcome in a general sense is similar; resources are transferred from the weaker business to the stronger, and amalgamated into it. 'Predation' interpreted in this way is thus a convenient (if perhaps overly value-laden) label for something that happens in many different kinds of complex systems.

Some independent support for the notion of the transferability of basic ecological concepts between contexts comes from the social sciences. The 'Chicago School' of sociology, under the leadership of Ernest Burgess and Robert Park, was active from roughly 1917–1942 and developed a spatially-oriented approach to the study of human societies. Setting aside for the moment the inevitable sociological debates over the details of the Chicago School's approach (sociologists like to argue with one another, to the point that even the validity of terming the group 'the Chicago School' has been questioned), it is indisputable that Park and Burgess had a substantial impact on analyses of urban environments in both sociology and geography. Burgess (1925) argued that cities were arranged, and expand, in a series of concentric circles away from their central business district (CBD). Outside the CBD were, in sequence, a zone of deterioration; a zone of 'workingmen's homes'; a residential area; and a zone in which commuters lived. Burgess considered that the main mechanism of expansion was that each zone in turn expanded, 'by the invasion of the next outer zone', in a successional manner. According to this model, competition for space by different actors leads to increasing mobility of certain sectors of the population. Burgess further argued that mobility could explain social problems: 'Where mobility is the greatest, and where in consequence primary controls break down completely, as in the zone of deterioration in the modern city, there develop areas of demoralization, of promiscuity, and of vice' (Burgess, 1925). As Abbott (1997) summarizes it, '. . .the cornerstone of the Chicago vision was location, for location in social time and space channeled the play of reciprocal determination. All social facts were located in particular physical places and in particular social structures. . . within the temporal logic of one or more processes of succession, assimilation, conflict, and so on'.

Although some elements of Burgess's original ideas have not stood the test of time, the basic argument that cities have spatially distinct zones that interact via the 'ecological' mechanisms of competition, invasion and succession has survived in a number of forms. Hudson (1980), for example, considered that an expanded concept of invasion and succession could provide a good foundation for understanding patterns of land use change. Current research in urban geography includes numerous studies of 'spillover effects' (e.g., Pacheco & Tyrrell, 2002), which occur when changes in one area (such as increases in wealth, gentrification of neighbourhoods, or growth rates) impact an adajcent area. The ecological perspective on urban environments thus is still very much alive, and in an interesting twist, is finding additional parallels in studies of the land-use impacts of protected areas (e.g., Serneels, Said, & Lambin, 2001).

If this kind of generalization of mechanisms can be justified and sustained, one of the largest potential benefits of adapting ideas from ecology in land cover change research (and by extension, in the analysis of spatial resilience) is that in many cases, ecological methods provide a clearer mechanistic framework than the typical correlative or descriptive land cover change approaches. As an area of research with its origins in a set of methods, land cover change research still sits on the fence between tool and scientific discipline. Ecology, by contrast, has a much stronger tradition of analysing very simple models that are based on clearly defined, theory-derived mechanisms. If such mechanisms and theoretical insights can be transferred or adapted to the analysis of changes in populations of pixels, they can offer useful insights into ways of viewing and understanding landscapes.

For example, ecologists use the term 'spatial synchrony' to describe synchronous changes in the numbers or abundance of disjunct (spatially separate) populations. Spatial synchrony is a potentially important issue in land cover change analyses (e.g., hypothetically, a synchronous change in deforestation rates in the Amazon and the Congo forests would be important to describe and understand) but it has received relatively little attention. In ecology, spatial synchrony in population dynamics has been attributed to one or more of three fundamental processes (Leibhold, Koenig, & Bjornstad, 2004): (a) dispersal of individuals between populations, which evens out numbers across space; (b) dependence of population dynamics on a single broader-scale driver, such as temperature or rainfall (a phenomenon known as the 'Moran effect'); and (c) ecological interactions (such as predation or parasitism) with populations of other species that are themselves spatially synchronous or mobile. These mechanisms are equally relevant to understanding synchronous changes in land cover composition, and looking for synchronous change in land cover types and understanding its drivers may provide important ways of quantifying the scales of interactions and processes across landscapes.

The ecological frameworks of island biogeography (MacArthur & Wilson, 1967) and metapopulation ecology (Hanski, 1999) relate the dynamics of source pools, dispersal and extinction events (among others) to community composition in weakly connected patches. Many of the spatial implications of island biogeographic mechanisms have already been carefully and thoroughly explored in the ecological literature (e.g., Anderson & Wait, 2001; Holt, 1992; Hubbell, 2001), providing a wealth of analysis, statistical methods, models, and conceptual insights on which to draw in understanding LULCC. Island biogeographic events are apparent in many landscapes, not only in pixel composition but also in changes in tenure types, which relate closely to land use and land cover. If dispersal is seen as the arrival of a pixel of a particular type in an area in which it has not been previously present, at a relevant scale of analysis, then populations of pixels can also be described as undergoing colonizations, dispersal events, and extinctions. Despite the unprecedented connectedness of global society, some of the processes by which landscapes change their composition are still dispersal-limited; for example, large cities are seldom built until the infrastructure that is needed to service them is in place.

Many kinds of landscape change should be considered as population growth rather than dispersal. For example, the dynamics of urban sprawl can be viewed as a situation in which there is increasing population of urban pixels and a level of spatial subsidy from the centre to the periphery. If the centre is too small relative to the total amount of sprawl, the burden imposed by the edges on the centre (in practice, arising from the need to provide infrastructure and services to new housing units) will exceed the productivity of the centre and the city will experience a period of decline (Hortas-Rico & Sole-Olle, 2010). If pixel mortality is measured by decreases in neighbourhood revenue rather than simple loss of pixels, the basic process is essentially the same as one in which edge effects cause increased mortality in an animal or plant population, setting up a sink area on the periphery, and movement from source to sink is frequent (e.g., see Breininger & Carter, 2003; Gundersen, Johannesen, Andreassen, & Ims, 2001). An ecological parallel would be a situation in which unregulated hunting occurs on the edges of forest patches and prey species are slow to learn to avoid edges. Under such conditions an animal population can decline quite rapidly. Population viability analysis (PVA) is one ecological tool that can, with the addition of two spatial compartments and some directional exchange between them, be used to model this kind of dynamic (e.g., see Akcakaya, 2000; Harding, 2002; Lindenmayer & Lacy, 2002; Wiegand, Moloney, Naves, & Knauer, 1999).

Ecological approaches thus have considerable potential in the analysis of spatial resilience in landscapes from land cover maps. They also have some potential weaknesses. One of the central challenges in bridging the gap between ecological approaches and land cover analyses is to unravel the different mechanisms that are expressed simultaneously in the same kinds of land cover type. For example, a new, isolated 'built environment' pixel on a lake shore in Wisconsin might simply indicate the addition of a boat ramp by a conservation agency; or it might be a harbinger of a period of rapid colonisation of a lake shore by holiday homes. Where the mechanism under consideration is consistent, and where the land cover map can accurately distinguish the differences between these kinds of structure, one would expect a farly clear relationship between colonisation (construction of new houses and purchases of existing houses), dispersal distance (e.g., from Illinois-based Chicago suburbanites into Wisconsin), home abandonment or sale, and 'equilibrial' final population size. Effective broad-scale analysis of such dynamics, however, depends on careful ground-truthing and validation of the larger land cover data set. It is important that the classification has the right resolution, in the sense that while the number of land cover types should reflect the dominant processes in the area, and it should not be excessively complicated (for instance, the number of possible trajectories in a 5 time-step analysis increases very quickly as a function of the number of possible land cover classes).

Fig. 7.7 The city of Brasilia, the capital of Brazil, is a rare example of a developing-country capital city in which planners have attempted to stick rigidly to zoning regulations. In this 2001 image, note the relatively intact riparian corridors (appearing as forested branching patterns running through the suburbs) and the largely development-free area of Brasilia National Park to the northwest of the city. As the city grows, limiting spillover from the city into its natural areas – and maximising the benefits of being in close proximity to a functional ecosystem – will need to remain important priorities for city planners. Image from NASA's Earth Observatory web site

A second important distinction to keep in mind when applying ecological approaches to the analysis of land cover and spatial resilience lies in the differences in the mechanisms driving land use and land cover as opposed to those driving changes in plant and animal communities. While the majority of ecological mechanisms have parallels in populations of pixels, the converse is not necessarily true. Land cover change in the twenty-first century is largely anthropogenic, and human social systems are capable of extremely complex dynamics. There are some kinds of land cover change that arise uniquely out of the interaction between social and ecological systems, that have a strong influence on landscape change, and for which no obvious parallel exists in solely ecological analyses. For example, the implementation of regional zoning plans – and violations of such plans, such as housing developments constructed outside official residential zones or in green belts – can leave distinctive human imprints on landscape patterns and processes (Fig. 7.7).

Landscapes and Spatial Resilience

In this chapter I have so far argued that (1) landscapes are complex adaptive systems that can be analysed via a complexity theory framework, with a few modifications; and (2) pixels in land cover maps can be considered using many of the same conceptual and methodological approaches that have been developed for spatial analysis in ecology. The final step in this argument is to clarify the link between these two points and the analysis of spatial resilience in social-ecological systems.

Spatial resilience in this context is dominated by the maintenance of important patterns and processes through time. This is not to say that landscapes are expected to stay constant. Rather, it means that a given landscape or land cover type can only be considered resilient if variation in land cover composition occurs within the range where important pattern-process relationships are maintained (for a closely related perspective, see Poiani, Richter, Anderson, & Richter, 2000). For example, if the connectivity of forest patches declines to the point where seed dispersers can no longer move through the landscape, the forest can not be considered resilient. Careful quantification of spatially explicit influences on process-related thresholds should facilitate the development of a more general set of theories and approaches.

A useful conceptual framework for thinking about land use and land cover change (LULCC) was developed by Agarwal, Green, Grove, Evans, and Schweik (2002) for the US Forest Service. Models of LULCC encapsulate current ideas about pattern-process relationships. Agarwal and his coauthors evaluated a set of 19 representative land-use models, classifying each model along axes of space, time, and human decision making. The classification scheme provides a way of thinking through the central elements of LULCC problems. Spatial and temporal resolution and extent are generally well specified in LULCC studies that use remotely sensed data, but human decision making in models is trickier to tie to a particular scale. The authors assessed human decision making in terms of both the agent and the jurisdictional domain over which decisions were made, as well as the time horizon. They further characterized human decision-making along a scale of six different levels of complexity, ranging from 'biophysical only' with no decisions being made in the model through to 'Multiple types of agents whose decisions are modeled overtly in regard to choices made about variables that affect other processes and outcomes… [and] changes in the shape of domains as time steps are processed, or interaction between decision-making agents at multiple human decision-making scales' (Agarwal, Green, Grove, Evans, & Schweik, 2002). More than half of the models that they considered provided for spatial interaction in some form; and some included multi-scale temporal phenomena, such as lagged effects. The authors concluded with a discussion of a range of issues but focused in particular on the needs of policy makers and the ways in which LULCC models can address these.

As the Agarwal et al. (2002) review and other more recent reviews (e.g., Matthews, Gilbert, Roach, Polhill, & Gotts, 2008) demonstrate, there are many current models that can be used to test and explore ideas about LULCC and how complex systems work. Interestingly, however, the focus of most land use models (multi-agent studies excluded) has been on developing applications that facilitate decision making in a particular context; and the majority of land use and land cover models ignore the potential for feedback mechanisms (Matthews et al., 2008). Although numerous exceptions do exist, the pressure to produce concrete recommendations for particular circumstances appears in many cases to have overshadowed the development of a broader, deeper, and ultimately more useful science. Relatively few LULCC studies have asked what generalities for our understanding of SESs emerge from these models; and as a result, most of what we have learned about spatial resilience from LULCC models is buried in single paragraphs and isolated sentences in the discussion sections of published articles. Shifting towards a more general approach (and one that is more oriented towards learning about the system through the model, rather than simply simulating change) will require an explicit focus on theory-derived hypotheses and seems like a logical next step in this fast-growing discipline (Lambin & Geist, 2006).

Ultimately, one of the central aims of this agenda is to be able to undertake a priori analysis of spatial resilience and use the resulting insights to generate predictions and insights that will facilitate the development of policies and management strategies that will in turn prevent a critical loss of resilience in desirable landscape attributes. Understanding non-linear relationships and thresholds in seed dispersal processes, for example, provides us with an important insight into the likely effects of deforestation on forest recruitment. This kind of insight can in turn help us to quantify alternative scenarios for future landscape changes and to be ready to sound the warning bells if thresholds of potential concern (Biggs & Rogers, 2003) are approached. Modelling pixels as populations, from a complex adaptive systems perspective, may help us to phrase a particular set of problems clearly and concisely and explore some of their subtleties using minor modifications of existing approaches. As proposed by Bennett, Cumming, and Peterson (2005), minimal models can offer a valuable platform from which to explore resilience in a social-ecological system.

In this chapter I have explored the potential for analysing entire landscapes as complex adaptive systems, using satellite imagery as the basis for capturing spatial patterns and ecological models for inferring and/or simulating process. Existing studies focusing on land use and land cover change have so far offered many case-specific insights but relatively few general principles for understanding spatial resilience (Lambin & Geist, 2006). In the next chapter I delve more deeply into a range of detailed empirical studies, specifically those that have used broad-scale experimentation, that offer some detailed insights into the mechanisms that produce spatial pattern and the ways in which spatial pattern influences process. These studies suggest a range of predictions and hypotheses that could be tested using existing land use and land cover change models.

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Chapter 8
Spatial Resilience, Landscape Experiments, and Fragmentation

Introduction

The majority of theoretical development and the testing of principles relating to the influence of spatial variation on processes in social-ecological systems has been either on paper or in silico (which is to say, through analytical mathematics and/or the use of computer-based models). This chapter provides a counterpoint to mathematical and model-oriented approaches by discussing rigorous empirical studies of spatial effects in ecosystems. Its primary goal is to offer an overview of the body of work in ecology that uses different forms of experimentation to test ideas about the relevance of space for resilience (as discussed in the previous four chapters). It also offers an introduction to a set of concepts that provide important background for Chapter 9.

As discussed in the last chapter, while there have been many potentially relevant case studies of patterns of land use and land cover change, these have seldom yielded or tested general principles that can be transferred between landscapes. Controlled experiments, by contrast, offer one of the strongest of available approaches to understanding causal relationships. Indeed, experimentation (together with replication and prediction) remains one of the most important distinguishing features of science. The philosophical principles underlying experiments as a way of learning and testing ideas remain valid at broad scales. What changes with increasing scale is, of course, the number of variables under consideration and the ease with which experimental manipulations can be undertaken. Attempts to undertake broad-scale experiments are beset by such concerns as the time and expense involved; the ethical dilemmas raised by indirectly experimenting on societies, or with people's livelihoods; and the potentially enormous costs of events that may be improbable, such as the collapse of an entire ecosystem, but are still possible outcomes of experimental manipulations.

Despite the many barriers to broad-scale experimentation, there are some notable studies in which scientists have been able to take advantage of suitable windows of opportunity to undertake broad-scale habitat manipulations (e.g., Carpenter, 2003; Carpenter et al., 2001; Holmgren & Scheffer, 2001; Monserud, 2002). One of the important benefits of an experimental approach is that it allows direct tests of theory through the exclusion or control of problem variables that may confound the results

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of correlative studies. As a result, some of the strongest principles that we have about complexity in ecological systems have been derived from experiments on entire ecosystems. Broad-scale experiments have also resulted in many important recommendations for ecosystem management.

The dominant focus in spatial experiments in ecology has been on understanding the impacts of fragmentation, connectivity, and dispersal on local ecological populations and communities (and associated processes), although there have also been experimental attempts to understand the influence of terrestrial systems on aquatic systems (e.g., Bernhardt et al., 2005; Likens, 2004); the effect of variation along environmental gradients or between biomes on local community composition and turnover (e.g., Suding et al., 2005); and contrasts between 'modified' and 'intact' areas, such as fenceline contrasts and exclusion plots (e.g., Cumming et al., 1997; Richardson-Kageler, 2003) that often require only a greater degree of replication under different conditions of spatial variation to produce meaningful conclusions about the contributions of space to resilience. Given that different experimental approaches typically offer different kinds of insight, a convenient way of organizing a discussion of the different results obtained by broad-scale experiments is to consider findings across the range of different approaches that have been applied.

Experimental Approaches to Spatial Processes in Ecology

Spatially-explicit experiments in landscape and community ecology have generally adopted one of three different kinds of approach, which I categorise loosely as distributed experiments, whole-ecosystem experiments, and fragmentation experiments. The first approach, and possibly the commonest, has been to try to understand the relevance of location by undertaking manipulations of small units that have been deliberately dispersed over larger extents (hereafter termed 'distributed experiments'). Since scale is considered relative to the size and dispersal capabilities of the study organisms and/or the ecological interactions and functions of interest, 'large extents' for microorganisms or insects may imply a spatially structured experimental design that can fit within a single room or greenhouse. For example, a distributed experiment might consist of planting the same five species of tree seedlings in a standard 2×2 m plot at different distances away from a potential source of leaf-mining insects; or laying out a series of bottles, filling them with nutrient solution and two competing plankton species, and varying the number and location of connecting pipes.

Distributed experiments include both the creation of deliberately simple systems and the erection of exclosures that exclude key system drivers, such as herbivory or rainfall. The simplest systems to set up as distributed experiments are microcosms and mesocosms, which, despite their many weaknesses (Carpenter, 1996), have yielded some interesting insights into the nature of spatially relevant processes. Jessup et al. (2004) provide a spirited defence of microcosm approaches. They argue that microcosms are well suited to exploring such questions as how local interactions can lead to pattern creation at larger spatial scales; how ecological patterns are generated and maintained across multiple spatial and temporal scales (e.g., Cadotte & Fukami, 2005); what the consequences are of manipulating ecological complexity; and how ecological characters evolve. The potential contributions of microcosm and microorganism studies to our understanding of evolution as a spatial process seem to me to be one of the most important contributions that microcosms can make to the study of spatial resilience, given that larger organisms tend to have slower generation times, higher dispersal ability, and greater behavioural flexibility. For example, Friedenberg (2003) used experimental manipulations of populations of the soil-dwelling nematode *Caenorhabditis elegans* to demonstrate that random environmental variation in space and time can favour the evolution of increased dispersal propensity, while in more constant environments dispersal propensity offered individual worms no particular advantage.

Many micro- and mesocosm spatial experiments in ecology have focused on understanding the tradeoffs between different traits, with one trait confering a relative advantage and another a relative disadvantage in a particular environment or set of conditions. Dispersal ability is often viewed as a trait that is traded off against competitive ability or vulnerability to predators, because traits that support high mobility may include being smaller, weaker, or easier for predators to find. Kneitel and Chase (2004) review mechanisms of local coexistence and summarize coexistence-related tradeoffs at two different scales and within homogeneous and heterogeneous communities. They suggest that the nature of tradeoffs may differ at different scales. For example, at a regional scale, sufficient habitat heterogeneity is likely exist for species to avoid competition for food by specialising on obtaining food in different habitats; while at a local scale, within a single habitat type, tradeoffs between competitive (e.g., food-finding) ability and predator avoidance may be more important. It is also important to note that empirical studies focusing on quantifying differences in competitive and dispersal ability can be confounded by differences in habitat preferences and use, making it surprisingly difficult to quantify dispersal-competition tradeoffs in heterogeneous habitats. The consideration of tradeoffs within a single community across a range of scales offers a potentially valuable way of bringing together ideas about fundamental ecological mechanisms, diversity, scale, and spatial resilience.

Although many spatially-explicit experiments have supported hypotheses that rely on differences in dispersal ability to explain coexistence between competing species, other experiments have identified important non-spatial mechanisms. For example, Amarasekare (2000) used experimental manipulations to explore the ways in which harlequin bugs *Murgantia histronica* interacted with two competing specialist parasitoids in a spatially-structured mesocosm, contrasting what he termed the local hypothesis and the metapopulation hypothesis. The local hypothesis, intraguild predation, suggested that coexistence between parasitoids could occur if the inferior larval competitor (i.e., the one whose larvae get eaten by the other) is superior at finding unparasitized hosts. By contrast, the metapopulation hypothesis predicts coexistence if the inferior competitor is a superior disperser. Amarasekare (2000) demonstrated that coexistence did not require the inferior larval competitor to have a dispersal advantage; parasitoid coexistence could occur via local interactions.

The search process is of course spatial in nature, but his findings suggest more generally that although the relevance of dispersal and connectivity for competition is undisputed, local mechanisms can also play important roles in determining coexistence (and ultimately, community-level resilience).

Exclosure experiments have a long history in ecological studies of the impacts of herbivory, fire, and soil type on vegetation composition and structure. Exclosures include deliberately fenced areas (e.g., Staver, Bond, Stock, van Rensburg, & Waldram, 2009) as well as fenceline contrasts (e.g., Todd & Hoffman, 2009). Exclosure-based studies have offered a wide range of important insights into ecological dynamics, particularly in situations in which multiple interacting causes make the effects of a single management strategy hard to tease out. They are also useful for understanding the impacts of different kinds of anthropogenic land use on ecological communities, particularly in situations where livestock pastures are fenced and adjacent to less perturbed areas. In northern Zimbabwe, for example, we were able to use a fenceline contrast to explore the impacts of high densities of elephant on communities of other organisms (Cumming et al., 1997; see also Fig. 8.1). Interestingly, we found that elephant appeared to be reducing biodiversity within protected areas, probably as a consequence of their negative impact on structural diversity in the vegetation community. Fenceline contrasts have also been used to show that declines in large native carnivores may have ultimately resulted in a decline in hardwood tree populations in the USA (Ripple & Beschta, 2007).

Distributed experiments include translocation experiments, in which animals are either reared in captivity under controlled conditions and then taken to new environments, or collected from one part of their range and translocated to another part. These experiments can offer insights into local adaptation and limitations on niche breadth as well as testing the ability of animals to find their way through unfamiliar landscapes and/or to return to their home range. Belisle (2005) has suggested that translocation experiments should play an important role in quantifying and

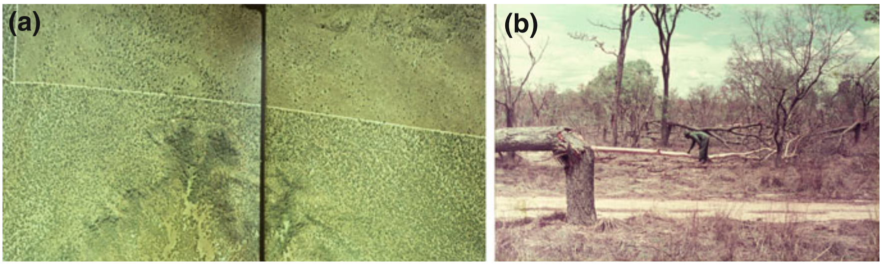

Fig. 8.1 (**a**) The northern (*upper*) half of this figure shows the south-west corner of the Sengwa Wildlife Research Area (SWRA), just south of Lake Kariba in Zimbabwe. These two colour aerial photographs were taken just 10 years after the construction of a game-proof fence, erected in an attempt to control tsetse fly, separating the SWRA from the adjacent communal land. The lower tree cover inside the park is directly attributable to herbivory, particularly from elephants. (**b**) A patch of *Colophospermum mopane* trees that were ring-barked and felled by elephant in Hwange National Park, Sinamatella region. Mopane trees are slow-growing hardwoods that provide important habitat for many smaller species of mammals and birds. Photographs by David Cumming

understanding how animals move through fragmented landscapes. Translocation experiments are likely to see increasing application in the next decade as a way of understanding the likely responses of communities to climate change, in relation to both dispersal to new habitats and their ability to persist under novel environmental conditions. For example, Hellmann, Pelini, Prior, and Dzurisin (2008) used translocation experiments to test how populations of two different butterfly species, a small-bodied specialist (*Erynnis propertius*) and a large-bodied generalist (*Papilio zelicaon*) responded to warmer conditions. Their experiments showed increased larval production at warmer temperatures for both species, and greater larval production for *P. zelicaon* in drier locations. These results suggest that the species will respond positively to climate change, although in subtly different ways, and offer some mechanisms that could be used to model likely species range shifts.

Another variant of distributed experimental approaches is to attempt to correct for spatial variation by creating experimental systems according to a spatially randomized design. A good example of the value of this approach comes from the work of David Tilman. Tilman was interested in understanding the relationships between plant diversity, ecosystem function, and overall primary production. He and his co-workers established a set of 147 different experimental plots in nitrogen-limited pairie regions in Minnesota, planting each plot with either 1, 2, 4, 6, 8, 12, or 24 different plant species (Tilman, Reich, & Knops, 1996). The results supported a number of classical ecological theories, including ideas first formulated by Charles Darwin and Charles Elton. Tilman et al. (1996) found support for three important hypotheses: the diversity-productivity hypothesis (i.e., that increasing diversity leads to better exploitation of existing resources, and hence greater productivity), the diversity-stability hypothesis (i.e., that more diverse communities are less likely to enter alternative states, here interpreted as communities showing less temporal variation) and the diversity-sustainability hypothesis (i.e., that more diverse communities are more likely to maintain ecosystem functions through time). Subsequent analyses of the same experimental treatments (e.g., Tilman et al., 2001) further supported initial findings and showed, for example, that plots with 16 species attained a 2.7-times higher biomass than monocultures.

Tilman (1994, 1999) placed some of his ideas in spatially explicit contexts, arguing that models that include spatial effects, particularly neighbourhood competition and dispersal between sites, allow for the persistence of higher levels of diversity. Coexistence is possible in such cases because species with higher dispersal rates are often poorer competitors. Taken together with the results of his experimental manipulations of diversity, these findings suggest that connectivity will not only be an important direct influence on biodiversity, but also an important indirect influence on the long-term resilience of an ecological community, the functions that it performs, and the ecosystem services that it provides.

Distributed experiments have thus yielded a wide range of useful results. However, they may eliminate or ignore important real-world feedbacks and processes because of the simplifications imposed by experimental design and practical constraints. A second approach to broad-scale experimentation has been to undertake a single manipulation of an entire system, often with a single control and without additional replication. The best examples of this kind of study come from aquatic systems. The defoliation of the Hubbard Brook catchment was one of the first strong pieces of evidence for terrestrial control of food webs in streams (Likens, 2004; Likens, Bormann, Johnson, Fisher, & Pierce, 1970; Likens, Bormann, Pierce, & Reiners, 1978); and in the northern lakes region of Wisconsin, several entire lakes were manipulated in different ways to understand the roles of nutrient inputs, habitat structure, and food web dynamics (Carpenter et al., 2001). For example, in one experiment, a large plastic curtain was placed across a single lake; half the lake was acidifed, and the other half was not. The acidifed half soon diverged from the control and substantial changes in the aquatic food web were seen. These kinds of experiment have provided some of the strongest approaches to exploring and understanding the effects of acid rain and other forms of nitrification on freshwater lakes (e.g., Schindler et al., 2008).

While single manipulations of entire systems can yield a good understanding of whole-system dynamics, they ideally need to be repeated in different locations – and within different spatial contexts, such as in areas that differ in the composition of the surrounding landscape or at different locations along an energy gradient – to give insights into the relevance of spatial variation for system dynamics (Huston, 1997). Since whole-system manipulations tend to be time-consuming and expensive, not to mention charged with political difficulties, relatively few such studies exist.

The third approach has been to experimentally create spatial variation within the bounds of an extensive, relatively homogeneous landscape. The tradition of deliberately creating statistically amenable spatial patterns in plant communities started in earnest with a series of carefully designed agricultural experiments on crop production, initiated in the 1920s by the statistician and geneticist Fisher (1926); these experiments also provided the basis for the original development and application of the spatially explicit 'Latin square' layout for experimental treatments. Later ecologists built on these early experimental manipulations through larger, more ambitious manipulations of different habitats, often by fragmenting areas that were historically forests or grasslands through regular clear-cutting and/or mowing (see reviews by Debinski & Holt, 2000; Lindenmayer & Fischer, 2006). In other high profile studies, ecologists were poised to take advantage of natural fragmentation events that created interesting natural experiments, such as those at Barro Colorado (Hubbell, 2001) and Lago Guri (Terborgh et al., 2001).

From the perspective of understanding spatial resilience, although experimental fragmentation approaches have been less commonly applied (Lindenmayer & Fischer, 2006), fragmentation experiments have been one of the most productive approaches to understanding the relevance of location, connectivity and context for ecological patterns and processes. A widely cited review of 20 different landscape fragmentation experiments was undertaken by Diane Debinski and Bob Holt (2000). Debinski and Holt found that most fragmentation experiments have focused on a small set of questions that are central to classical landscape ecology, including (1) the impacts of fragmentation on the species richness and abundance of animals and plants within the study sites; (2) the effects of fragmentation on interspecific interactions, such as predation and competition; (3) the influence of corridors and other forms of connectivity on individual movements and community composition; and (4) the influences of edge effects on organisms. For example, Holt's Kansas fragmentation experiment was undertaken with the initial aim of understanding how proximity to propagule sources influenced the successional trajectories of woody plants (Holt, Robinson, & Gaines, 1995).

Interestingly, Debinski and Holt (2000) found that the results of fragmentation experiments lacked consistency across taxa and across experiments. They proposed a number of reasons why theoretical expectation were not met. The most important of these included (1) the possibility that most of the fragmentation experiments in their review had not continued for long enough for the more profound effects of fragmentation to become evident; (2) the confounding influence of relaxation effects, particularly the idea that if species were lost from isolated fragments at different rates and over different time periods, predictions based on simpler models might not be met; (3) the possibility that the spatial scale of fragmentation may have been inadequate to limit the movements of highly mobile species, leading to the creation of idiosyncratic patterns in community composition by these organisms; and (4) the increasing importance of social interactions as patch size declined.

Lindenmayer and Fischer (2006) have pointed out that all of the experiments that Debinski and Holt (2000) reviewed were based on the standard landscape ecology model of a patch-matrix-corridor view of habitat. The standard model is not necessarily easy to generalise from because local uniqueness and context can play a large role in determining final outcomes. Prugh, Hodges, Sinclair, and Brashares (2008) reviewed over a thousand different studies of patch dynamics and concluded that the importance of the matrix (i.e., the more continuous habitat in which patches sit) had been substantially overlooked in many landscape ecology studies; in many cases, the nature of the matrix offered a better descriptor of within-patch community composition than patch size or arrangement. These objections notwithstanding, fragmentation experiments have been incredibly useful tools for learning about spatial relationships in ecosystems. Even though classical expectations were not met in many fragmentation experiments, the reasons *why* they were not met offer a number of insights that have high relevance for ideas about spatial resilience. Some of the more general principles for spatial resilience in ecosystems that have emerged from fragmentation experiments include the following:

Different System Components Respond to Changes in Spatial Patterns and Processes Differentially

Some species are more sensitive or more specialised than others, and species loss from isolated habitats occurs at different speeds. Populations that are no longer viable may persist for the length of a single generation until 'relaxation' occurs (Kuussaari et al., 2009). This time interval could be quite long, for example in the case of a tree population that has lost its pollinators, making it less simple than one might think to detect the 'standing dead'. Because organisms have different lifespans, even in the absence of direct mortaility events there will be a loss of unviable populations at different speeds within a particular fragment, creating the potential for surprises and unexpected effects. This principle is particularly well illustrated by the results of John Terborgh's study of islands that were created by flooding in Lago Guri (Venezuela), where the loss of predators on small islands led in several cases to spectacular ecological collapse (Box 8.1; Terborgh et al., 2001). As noted by Debinski and Holt (2000), it is critically important to continue fragmentation experiments for long enough to observe these kinds of effect and their aftermath.

Box 8.1 Ecological Meltdown at Lago Guri

Lago Guri is officially called Central Hidroeléctrica Simón Bolívar and was completed in two stages, which ended in 1968 and 1983 respectively. The final water level, subject to rainfall, was attained in October 1986. Although the lake provides around 73% of Venezuela's power, its creation was an ecological disaster that flooded large tracts of highly biodiverse forest. Higher-lying areas became islands, creating a fascinating natural fragmentation experiment that has been taken advantage of by a number of researchers.

John Terborgh and his co-workers have provided some fascinating insights into the impacts of fragmentation through their study of the Lago Guri Islands (e.g., Terborgh et al., 2001; Terborgh, Lopez, & Tello, 1997). They studied 12 islands, four 'near, small' islands (each around 1 ha in size); four 'far, small' islands of the same size; three 'medium' islands (around 10 ha); and one 'large' island (350 ha). By 1997, the bird communities were already peculiar relative to mainland study sites. Densities of birds were about twice as high on the 1-ha islands as on the mainland; whereas two of the three medium islands, which retained relict populations of capuchin monkeys *Cebus olivaceus*, supported bird densities that were only about a fifth of that on the mainland. Experiments with artificial nests suggested that the moneys were raiding bird nests, keeping numbers low. For both the small and medium islands, Terborgh et al. (1997) concluded that the founding communities that were present when the waters of Lago Guri reached their final level had already collapsed.

Looking beyond birds, other fascinating patterns were discovered (Terborgh et al., 2001). Correcting for area, rodent and iguana populations were respectively 35 and 10 times larger than mainland populations. Leaf cutter ant populations had exploded to two orders of magnitude (100 times) greater than reference populations. On other islands, howler monkey densities attained 1,000 animals per square kilometer, a striking contrast to mainland densities of 20–40/km^2. These high densities of herbivores were having a strong effect on the vegetation of the islands, with tree mortality rising and the numbers of inedible and toxic plants increasing under the high selective pressure for resistance to herbivory.

The study provides a fascinating illustration of the relevance of scale and connectivity for ecological dynamics. As the authors argue, predators appear to provide a form of ecological stability, contributing to the resilience of their prey populations. The resilience of the Lago Guri island communities has a scaledependent threshold. Herbivore communities on islands that were too small to support vertebrate predators seemed doomed, in the near future at least, to extinction. Hypothetically, if one wanted to deliberately increase the resilience of the island communities, the most effective solution would be to enhance spatial resilience – for example, by increasing connectivity between islands and lowering the water level to increase island size.

In the context of social-ecological systems, it is hard not to ask oneself a question with an unwelcome answer: what is the relevance of these results for human societies?

Spatial Resilience at a Community Level Is Influenced by Local Components

Building on the first point, the differences between organisms can translate into systemic resilience or vulnerability. The degree to which the local animal community is resilient to landscape change and capable of adapting or responding to fragmentation events – through such mechanisms as altering their feeding or breeding habitats or their social structure – can have a profound impact on patch dynamics. Fragmentation experiments have demonstrated convincingly the importance of dispersal capability and dietary breadth as two variables that have a strong influence on the post-fragmentation persistence of animal populations.

In passing, I should also point out that I am not aware of any studies that have tried to analyse community data from broad-scale fragmentation experiments explicitly from the perspective of community-level resilience to fragmentation, although many studies have travelled some way down this path by quantifying changes in species richness, ecosystem function, and/or covariance in the populations that make up a community (e.g., Houlahan et al., 2007).

As Fragments and Communities Become Smaller, the Idiosyncracies of the Local Community Become More Important and the Consequences of Fragmentation Become Harder to Predict

The kinds of species present and the nature of their ecological interactions become more important when the community is small. From a food web perspective,

Fig. 8.2 White-backed vultures fight over the carcass of a dead elephant in Chobe National Park, Botswana. Note the (less common) Egyptian vulture in the foreground. As an upper trophic level species, vulture populations are in decline in many parts of southern Africa. Photograph by Graeme S. Cumming

as species are removed from an ecosystem, the number and strength of interactions (links) between species are altered. We should expect particular kinds of species and possibly particular functional groups to be lost first (Child, Cumming, & Amano, 2009; Cumming & Child, 2009; Dobson et al., 2006). For instance, local extirpation in a small fragment is more likely for species that depend on scarce resources and/or resources that rapidly become limiting within a patch, that are more vulnerable to predation, or that are intolerant of overcrowding or edge effects (Fig. 8.2). Depending on the ecological functions performed by sensitive species, and the degree to which species loss is systematic or random, reductions in fragment size are likely to amplify some kinds of trophic interaction and remove others. These uncertainties make accurate prediction of changes in community dynamics a lot harder for small fragments. For example, if predators are generalist and less sensitive to fragmentation than their prey, a trophic cascade (e.g., local extirpation of preferred prey, followed by prey switching by the predator and successive extirpation of primary consumers, followed by extirpation of the predator and release of primary producers) may easily follow. By contrast, if predators are specialised on a single prey source (e.g., a weasel that primarily hunts voles) and unable to switch prey, local extinction of the predator-prey pair following prey extinction is more likely and the rest of the primary consumer community may be left relatively intact, resulting in heavy impacts on primary producers.

Patch Surroundings (Local Context, Matrix) Matter

As mentioned previously, a large number of landscape ecology studies have found that what happens within a patch is determined not only by the location and number of adjacent patches, but also by local and regional context; the degree to which organisms can obtain essential resources from areas imediately outside their core habitat, and the degree to which the matrix is permeable to movement, can have large effects on community composition (e.g., Debinski & Holt, 2000; Prugh et al., 2008). Forest patches are not oceanic islands.

Landscapes that Appear Fragmented May Not Be Fragmented for All System Components

The assumption of fragmentation is usually made from a human perspective. In several of the fragmentation studies considered by Debinski and Holt (2000), the possibility arose that for some species the 'fragmented' habitat would have been better described as a 'patchy' habitat. Animals perceive and use landscapes at different scales (Holling, 1992), influencing their responses to fragmentation, and the same principle can be expected to apply more generally to different components of social-ecological systems. For example, people who can afford delivery vans or bicycles may be able to interact with different communities and reach different markets from those who have to use public transport and/or travel by foot.

As these examples should make clear, landscape experiments and manipulations of different sorts – and particularly broad-scale fragmentation experiments – have yielded numerous insights into the kinds of process that drive changes in complex systems following changes in their spatial relationships to their surroundings. The relevance of these results for understanding ecologically-focused aspects of SESs, such as the provision of ecosystem services by forest fragments, is obvious. More generally, and equally interestingly, many of the insights that ecologists have obtained from landscape experiments are exemplars of more general processes that also have potential relevance for studies of social and economic systems, and for social and economic aspects of social-ecological systems. Some of these generalities are discussed in the next chapter.

In closing, it is worth considering the relationship between large-scale experimentation and ecosystem management. The relative scarcity of large-scale ecological experiments is at odds with the fact that adaptive management is very much a buzz-word in conservation at the present time, with many organizations claiming to be managing adaptively. Adaptive management in its original conception is based squarely on a philosophy of broad-scale experimentation as a way of learning (Holling, 1978; Walters & Holling, 1990). Carl Walters, one of the gurus of adaptive management, reflected on his experiences in an article in the journal *Conservation Ecology* (now *Ecology and Society*) in 1997 (Walters, 1997). By the time of writing the article, Walters had participated in no fewer than 25 different attempts to do adaptive management. He noted that of these 25, only 7 resulted in broad-scale experimentation and only 2 of those 7 were well designed in terms of controls and scientific method. Walters summarized the problems with big-scale experimentation under the categories of (1) problems with the science; (2) problems with assessing the costs and risks of experiments; (3) problems with self-interest in research and management organizations; and (4) fundamental conflicts in ecological values between different ecological-interest groups. His analysis suggests that achieving large-scale experimentation is as much, or more, a political problem as it is a scientific problem.

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Chapter 9
Spatial Resilience and Fragmentation in Social Systems

Introduction

One of the dominant themes of this book has been the broader relevance of many 'disciplinary' concepts and approaches. Chapter 8 focused on the relevance of broad-scale ecological experiments and related ideas about fragmentation, for our understanding of the spatial aspects of ecological resilience. Experimental approaches are generally inappropriate in social systems, for obvious reasons, but there is a growing realization across many of the social sciences that spatial arrangement can have profound impacts on social systems.

In this chapter I introduce a set of ideas from the social sciences that have strong parallels to ecological ideas about fragmentation (and indeed, are directly related to ecological fragmentation through their influences on land use). I then link these concepts to the ideas discussed in the previous chapter by suggesting a set of general principles for an interdisciplinary synthesis of social-ecological fragmentation and spatial resilience. Prior to entering the realm of the social sciences, however, a word about fragmentation is necessary.

Clarifying Fragmentation Concepts

The term 'fragmentation' is used in ecology to capture a loss of continuity within a particular kind of habitat, or a loss of connectedness to an external environment (Lindenmayer & Fischer, 2006). Habitats in which connectivity was never present are considered to be merely 'patchy' and animals that live out their lives in naturally patchy environments have evolved successful strategies for dealing with patchiness (those that have not are, for obvious reasons, no longer with us). While fragmentation does occur as a consequence of natural processes – for example, forest fragments may be created by fire – fragmentation has risen to particular prominence in ecology and conservation because of it is one of the characteristic signatures of a human-modified landscape and hence is a problem

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that is important to understand for landscape design and management as well as for its theoretical interest (Cumming & Spiesman, 2006; Lindenmayer & Fischer, 2006).

Fragmentation in its strongest sense entails a loss of both physical and process connectivity. For example, it is possible that a new bicycle path that divides a meadow into two distinct patches does not have important ecological consequences. The key question is whether or not spatially dependent processes, particularly dispersal, can still occur between fragments. In addition, organisms perceive a landscape at different scales; what constitutes fragmentation for a relatively sessile organism, such as a chamaeleon, does not necessarily constitute fragmentation for a mobile organism like a falcon.

In the same general sense, the strongest forms of fragmentation in social and economic contexts have relevance for social processes as well as involving a loss of connectedness or a separation of some component of a system that 'should' (perhaps for functional, ethical, or historical reasons) be incorporated within the broader system. The concepts of connectivity and fragmentation are widely used in areas of both sociology and economics, although they are given a range of different labels (as discussed later in this chapter) and the emphasis in the social sciences tends to be more on processes and interactions – whether social or economic – than on strictly physical fragmentation, even though physical fragmentation is both a frequent driver and a frequent consequence of social dynamics.

Analysis of the causes and consequences of fragmentation in social systems introduces some additional complexities that are generally ignored in studies of ecosystems. Chief among these is the question of power and its structuring role in societies and social-ecological systems (Robbins, 2004). For example, in an apartheid system like the one that I witnessed during visits to South Africa when I was growing up, spatial segregation was enforced by an obvious power relationship; the ruling class held legislative power and enforced spatial separation in where people from different ethnic groups could live, which beaches they could go to and even which public toilets they could use. In the situation that now prevails, some 15 years after the transition to majority rule, racial segregation still exists but is linked more directly to income, education and culture. The legacies of apartheid remain influential and will take a long time to fully escape (Adato, Carter, & May, 2006). There is no obvious ecological parallel to apartheid-like power relationships and it is important to keep in mind that in many instances, including such notably spatial questions as the determinants of settlement patterns in post-apartheid South Africa (Ramutsindela, 2007), power relationships are critical to understanding spatial patterns in social-ecological systems. Indeed, many of the patterns that we see in human-influenced ecosystems are a result of power dynamics in the social system.

It is easy to forget that power dynamics and spatial changes resulting from social processes are not unique to human systems. A wide variety of animal societies exhibit social dynamics and some of these societies may provide good test cases for exploring and understanding the relevance of social interactions for spatial resilience in SESs (Box 9.1).

Box 9.1 Social-Ecological Systems Without People?

The focus in most studies of social-ecological systems is on people and the problems of natural resource management by humans. Many other animals, however, exhibit social behaviours. Research on animal societies includes such themes as power relationships and dominance hierarchies, cooperation, altruism, collective action, conflict and aggression. For example, vampire bats *Desmodus rotundus* must feed every 2–3 nights to survive and foraging success depends on finding a suitable mammalian host species. Vampire bats will often share blood meals (via regurgitation) with other colony members who have not found food, but if individuals beg without donating to others for too many nights in succession, they may be blackballed by other colony members who refuse to feed them (Wilkinson, 1984).

The societies of other animals offer models that we can use to better understand the general principles of spatial relationships between social and ecological systems. The social insects, for example, have long been of interest in the study of cooperation and emergence (Nowak, 2006). Individuals in ant, honeybee and termite colonies appear to follow relatively simple behavioural rules that allow them to efficiently and effectively accomplish complex tasks relating to foraging, colony defense and nest construction (e.g., Beekman & Bin Lew, 2008; Perna et al. 2008; Portha, Deneubourg, & Detrain, 2002). The emergence of complex behaviours from simple rules has served as one of the inspirations for mechanistic approaches to understanding complexity, including such important developments as multi-agent models (Holland, 1994).

Social behaviours in vertebrates can have profound impacts on the resources that they depend on, particularly when the animals concerned are ecosystem engineers (Jones, Lawton, & Shachak, 1994). In the case of elephant, for example, a tendency to travel in herds results in greater heterogeneity of impacts. Elephant societies are organized hierarchically into four different tiers: individual, family, group and herd (Wittemyer, Douglas-Hamilton, & Getz, 2005). Group and herd sizes respond to environmental influences, with the roles of dominance and other relationships in elephant societies being more pronounced in the dry season when resources are scarce (Wittemyer, Getz, Vollrath, & Douglas-Hamilton, 2007). Elephant thus provide an example of a flexible but consistent social structure that responds adaptively to environmental conditions.

One of the best studied examples of social interactions in grazing herbivores is that of sheep (*Ovis* spp.). Sheep grazing can influence vegetation composition (Oom, Sibbald, Hester, Miller, & Legg, 2008) and soil properties (Shand & Coutts, 2006). The influence of sheep on vegetation and fire dynamics has been shown to impact sage grouse (Pedersen, Connelly, Hendrickson, & Grant, 2003) and voles and their predators (Wheeler, 2008).

The spatial pattern of sheep foraging behaviour is influenced by group membership, relatedness and gender as well as the 'personality' of the individual (Cassinello & Calabuig, 2008; Sibbald, Erhard, McLeod, & Hooper, 2009). Spatial memory and flock leadership can also play an important role in sheep foraging decisions and group behaviours (Dumont & Hill, 2001; Ramseyer, Boissy, Dumont, & Thierry, 2009). Sheep prefer to graze at certain distances apart and in heterogeneous habitats this preference can be an important factor influencing their choice of patch in which to forage, with larger patches being preferred because they allow the requisite spacing (Sibbald, Oom, Hooper, & Anderson, 2008). Collectively, the social system of sheep flocks thus creates a set of feedbacks between social and ecological systems that play out in space, potentially influencing not only the spatial resilience of the sheep flock but also that of the ecosystem.

It would be possible to fill several books with fascinating examples of spatially relevant social interactions in other animals. As this brief introduction suggests, studies of social-ecological systems that include non-human societies may offer valuable insights into the fundamental reasons why human social behaviours arise, the ways in which they interact with and influence spatial patterns in ecosystems and the conditions under which certain kinds of social-ecological system may become unsustainable.

My focus in this chapter is on presenting some of the more relevant aspects of well-established social science research on human societies. Given the wide scope of the social sciences and the relevance of many social interactions for spatial patterns and processes in SESs, I have aimed for depth over breadth by focusing my discussion on three of the sub-disciplines that deal most directly with social fragmentation (as distinct from the social drivers of ecosystem fragmentation): urban geography and planning, the study of social capital and social exclusion, and the study of conflict.

Urban Geography and Planning

Spatial perspectives on the development of cities date back at least as far as the writings of the Chicago School of Sociology (e.g., Burgess, 1925), as discussed in Chapter 7. Urban geographers and planners have strong interests in understanding the genesis and the consequences of spatial patterns of city growth and change, including such trends as the differential gentrification or decline of neighbourhoods in relation to spatial patterns of settlement and resources (e.g., Dooling, 2009), the spillover effects that occur between different neighbourhoods within a city (e.g., Pacheco & Tyrrell, 2002) and the increase of urban sprawl (e.g., Hortas-Rico & Sole-Olle, 2010). I will focus on the topics of urban sprawl and political fragmentation as informative examples.

Cities are thought to grow in extent as a consequence of expanding populations, rising incomes, falling commuting costs and lifestyle choices such as a preference for single-family housing units (Brueckner, 2000; Downs, 1999). Urban growth under these conditions is not necessarily a problem, but sprawl may result if (1) the benefits of open space are not accounted for; (2) commuting becomes excessive because of a failure to account for the social costs of congestion; and (3) new developments are not made to pay for the infrastructure costs that they generate (Brueckner, 2000). These three conditions are considered to be market failures (the assumption being that if a more complete accounting were undertaken and humans behaved rationally, economic interests would eliminate them). The relationship between the degree of urban sprawl in an area and the cost of service provision to residents is non-linear, making sprawl disproportionately expensive for municipalities (Hortas-Rico & Sole-Olle, 2010).

According to Irwin and Bockstael (2002), recent changes in patterns of urban development in the USA include the formation of new 'edge cities' around traditional urban centers and increasingly scattered residential development in the outer suburbs and urban-rural fringes. The authors propose that scattered development is the consequence of a tradeoff between 'attracting' and 'repelling' economic forces. For example, service provision and social benefits may be higher in developments (attractive forces) while congestion may increase with increasing size or number of developments (a repelling force). Irwin and Bockstael (2002) use a multi-agent simulation model to demonstrate that scattered development patterns could arise purely from negative interaction effects between residential developments. In other words, scattered urban development can be explained by endogenous (internal, self-organizing) forces, independently from existing landscape structures (roads, fields, etc) – much as vegetation patches can be formed independently of underlying variation in the biophysical environment (Tilman & Kareiva, 1997). Interestingly, Irwin and Bockstael's (2002) analysis of urban sprawl also provides a strong challenge to the view that sprawl is an efficient outcome of rational economic decisions (e.g., Wheaton, 1982), raising some important questions about the role of regulation in determining efficient and equitable land use.

Although traditional explanations for urban sprawl focus on market failures, as discussed above (Brueckner, 2000), sprawl has also been linked to political fragmentation. Carruthers (2003) describes political fragmentation in suburban areas as resulting from the pursuit of small local governments by local residents. Once formed, these regulatory structures attempt to support the lifestyle demands of locals, often at the expense of the larger city and community. For example, the construction of multi-family housing units that might help neighbouring poorer communities may be actively resisted (Downs, 1999). Byun and Esparza (2005) similarly argue that the responses of residents and developers to the local regulatory environment can create spillover effects that result in sprawl, particularly in metropolitan regions in which local growth management has been imposed in the absence of regional coordination. Their argument is supported by Ulfarsson and Carruthers (2006), who conclude that the inadequacies of political (regulatory) structures may be as much to blame as market failures for undesirable patterns of urban development.

These examples are particularly relevant for understanding spatial resilience because they run counter to the prevailing wisdom that decentralised and/or devolved local governance structures ('polycentric institutions') can address environmental problems more readily than centralised governance because they have a greater variety of response capabilities (Ostrom, 1998) and can encourage innovation and experimentation by allowing a diversity of problem-solving approaches to develop (Imperial, 2004). The distinction between 'polycentric' and 'fragmented' is clearly important for urban development and the spatial resilience of cities, but little on this topic has been published. It appears in any case that the spatial relations of political entities and the tradeoffs between centralisation and decentralisation may play out differently in different circumstances, with the consequences for system resilience at different scales being different and strongly context-dependent.

This discussion also suggests that urban sprawl and other patterns of urban development relate closely to economic and political equity. Where equity is low, differential power relations are likely to exacerbate the problem of social exclusion, resulting in further feedbacks to spatial pattern.

Social Capital and Social Exclusion

A reasonable working definition of social capital is that it describes 'the ability of actors to secure benefits by virtue of membership in social networks or other social structures' (based on the extensive review by Portes, 1998). Note that social capital is distinct from human capital, which captures education, skills and knowledge. As we have already seen in Chapter 6, social networks typically have a spatial structure; this structure influences social capital because it influences the kinds and frequencies of both benefits and transaction costs that actors receive or incur (see Rutten, Westlund, & Boekema, 2010 for an introduction to a recent special feature on spatial dimensions of social capital).

Social capital can play an important role in resilience, because innovations, information and resulting economic opportunities – as well as various forms of assistance – often move through networks, with membership being a prerequisite to benefitting from spatial transfers of knowledge (Gulati, 2007). According to a review of 65 firms by Westlund and Adam (2010), for example, there is strong evidence that possession of social capital increases a firm's economic performance. Social capital is generally perceived as a positive benefit of membership of a social network. The converse, restriction from membership in social networks, is captured by the idea of social exclusion.

Social exclusion occurs when an individual or sub-set of individuals are restricted from access to socially-related benefits such as employment, health care, commodities, housing, or membership in particular kinds of group. Unemployment in particular is considered a major driver of social exclusion, affecting not only a person's financial standing but also their social status, their feelings of self-worth and their access to social networks of like-minded people (e.g., Mayes, 2002; Mohan, 2002). The roles of infrastructure and public transport in creating the connectivity that allows people to reach key 'resource patches' (without having to spend excessive time, money and effort to get there) has strong and obvious parallels to the importance of corridors and habitat connectivity in fragmented ecosystems. It is thought that improving connectivity via public transport can contribute to overcoming problems of social fragmentation that may arise through an inability to access health care services, schools, or employment opportunities (e.g., Currie, 2010).

Spatially relevant restrictions in societies may occur informally or more formally through the deliberate creation of institutions, such as passports, work permits and professional qualifications (e.g., certificates, memberships and degrees) that serve to create distinct groups (in landscape ecology jargon, these could be viewed as social 'patches' that are internally homogeneous and differ from the surrounding or matrix community). Some groups are comprised of people who have deliberately distanced themselves from mainstream society (e.g., through the formation of gated communities and communes; Litz, 2000) while others are prevented from full participation in society because they differ through appearance, disabilities (e.g., autism), or age (Gartrell, 2010).

Even where there is no deliberate attempt to create a spatial structure to match process- or interaction-oriented social fragmentation, the multi-scale socioeconomic processes that serve to entrench the existence of excluded groups often result in spatial segregation (e.g., Dangschat, 2009; Dzambazovic, 2007). For example, many large towns in developed countries have slum areas or ghettos that are dominated by particular racial groups, often immigrant minorities. In the USA, Canada, western Europe and Scandinavia, these could be African Americans, Latinos, Jews, Chinese, or East Europeans (e.g., Arbaci & Malheiros, 2010; Nelson & Hiemstra, 2008; Vasquez-Leon, 2009). Attempts to provide low-cost housing typically create spatial aggregations of wealthy and less wealthy households; and spatial differences in house prices (generated by such variables as size, age, proximity to the city centre, proximity to factories or markets and access to social services and high quality schools) lead almost inevitably to social and economic segregation, even within societies that are striving for equality (e.g., see Arbaci & Malheiros, 2010; Szczepanski & Slezak-Tazbir, 2007; Wang & Murie, 2000; Watson, 2009).

As in ecosystems, social fragmentation develops as the result of processes that occur over a range of different scales and may be driven by a combination of broad-scale and local-scale policies (Dangschat, 2009; Gordon & Monastiriotis, 2006; McNamara, Tanton, Daly, & Harding, 2009). For instance, refugees fleeing from political or economic problems in Africa or Eastern Europe may make their way to Western European countries and end up living in ghettos, lacking work permits or recognized qualifications and often being unable to speak the local language. Even in South Africa, economic refugees from other parts of Africa often experience social isolation and become the victims of aggression during times of economic turmoil (as witnessed by the outbreaks of violence against Somali shopkeepers in 2008).

Social exclusion is a contested term (Fangen, 2010; Jahnukainen & Jarvinen, 2005; Silver, 1995; 2007). There is a plethora of similar but subtly different terms that capture aspects of fragmentation-like processes in societies, including alienation, disenfranchisement and marginalisation; and on the positive side, social inclusion, social recognition (e.g., Fraser & Honneth, 2003), citizenship and economic integration and empowerment. To further confuse things, the term 'social exclusion' is itself used in different and potentially conflicting ways; just as Lindenmayer and Fischer (2006) complain that 'fragmentation' in ecology has so broad a meaning that it has become virtually meaningless, so sociologists complain about the difficulties of achieving a single coherent definition of social exclusion. The concept of exclusion is intimately related to ideas about discrimination, inequality and poverty; it also tends to imply an active 'keeping-out' by society, rather than a deliberate withdrawal from society, thereby making it value-laden and politically challenging for governments that claim to be democratic and inclusive.

Some of the clearest writings about social exclusion are those of Hilary Silver. In a seminal review, Silver (1995) recognised three different paradigms that have used and developed the concept of exclusion. She labelled them solidarity, specialization and monopoly respectively. The paradigms differ in their attributions of the causes of exclusion and in the political philosophies on which they are based (Table 9.1).

Although the majority of work on social exclusion and related topics has viewed social fragmentation in a non-spatial context, many aspects of exclusion are fundamentally dependent on space (e.g., Murtagh & Shirlow, 2007; Siegrist, 2000; Vaughan, Clark, Sahbaz, & Haklay, 2005). Marginalised individuals may have their own identifiable residential areas, such as slums, ghettos, or homelands

Table 9.1 Paradigms of exclusion in sociology. Reproduced, with a few minor modifications, from Silver (1995). This table summarizes the major political and philosophical themes within the more general discourse about social exclusion, as well as giving some examples of key thinkers in each paradigm

	Solidarity	Specialization	Monopoly
Concept of integration	Group solidarity/cultural boundaries	Specialization/separate spheres/ interdependence	Monopoly/social closure
Source of integration	Moral integration	Exchange	Citizenship rights
Ideology	Republicanism	Liberalism	Social democracy
Discourse	Exclusion	Discrimination, underclass	New poverty, inequality, underclass
Seminal thinkers	Rousseau, Durkheim	Locke, Madison, utilitarians	Marx, Weber, Marshall
Exemplars	De Foucauld Douglas, Mead	Lenoir, pluralism, chicago school	Room, Townsend
Model of the new political economy	Flexible production	Skills, work disincentives, networks, social capital	Labour market segregation

(Ramutsindela, 2007; Schierup, 2001; Szczepanski & Slezak-Tazbir, 2007); they may be forced to divide their time between two or more locations on a regular basis (Koch, 2008); or they may be homeless, with attendant concerns of being perceived as criminals and/or 'not being wanted' in many urban locations (Alvarez, de Alvarenga, & Della Rina, 2009; Silver, 2007). In each case, physical separation from the rest of society serves to reinforce a group identity and emphasize other forms of exclusion (Dangschat, 2009). Silver (2007) further points out that 'migration is a process that easily can be cast as transgressing a boundary, becoming excluded and slowly integrating anew'. Many societies have rigid rules about residency and work and these and related rules can serve to reinforce social segregation between long-time residents and new arrivals.

As with fragmentation in ecosystems, social exclusion is closely related to resilience. De Haan (2000) makes an important distinction between poverty and social exclusion when he states that 'Notions of vulnerability are closer to the concept of social exclusion... vulnerability is not a synonym for poverty. Whereas poverty means lack or want and is usually measured for convenience of counting in terms of income or consumption, vulnerability means insecurity, defencelessness and exposure to risk and shocks.' Socially excluded groups tend to be vulnerable to many kinds of disturbance, both economic and physical and are likely be less resilient to perturbations (e.g., natural disasters, disease outbreaks, or econcomic recession) than the larger society that they are adjacent to (or embedded within) because they lack access to the same range of coping mechanisms and support systems (e.g., Chaves, Cohen, Pascual, & Wilson, 2008). De Haan's distinction is nicely illustrated in many parts of southern Africa by the contrast between rural and slum-dwelling people with similar income levels; those who live in traditionally organized villages and are not socially 'excluded' (despite possibly being 'marginalised' in a political sense (Robbins, 2004)) have the added resilience that is provided by traditional institutions (such as tenure rights and recourse to traditional law) and the proximity of old friends and family. In townships where many of these cultural norms have been lost, problems such as theft, drug abuse, rape and murder are worse than in rural areas and the quality of life is lower. For example, according to statistics provided by the South African Police Service, during the period April 2008–March 2009 a total of 18,148 South Africans were murdered. In a country with a total population of 47.9 million, this equates to a per capita murder rate of 0.00038, or (rounded to the nearest whole number), 4 out of every 10,000 people. The city with the highest murder rate is Cape Town. A breakdown of murders by precint for the area of greater Cape Town (Gie, 2009), however, shows that in Cape Town, over 44% of murders occurred in just five districts, all of them townships with socially excluded people: Nyanga (13.18%), Harare (which sits in Khayelitsha; 8.67%), Khayelitsha (8.47%), Gugulethu (7.58%) and Delft/Belhar (6.1%). These locations define a high-risk cluster of sites to the east of the city (Fig. 9.1).

Excluded segments of society are often perceived as being sources of criminal activity, of drug dealing and drug abuse and of other kinds of activities that are viewed as being anti-social (Palloni, 1999). While these perceptions are not

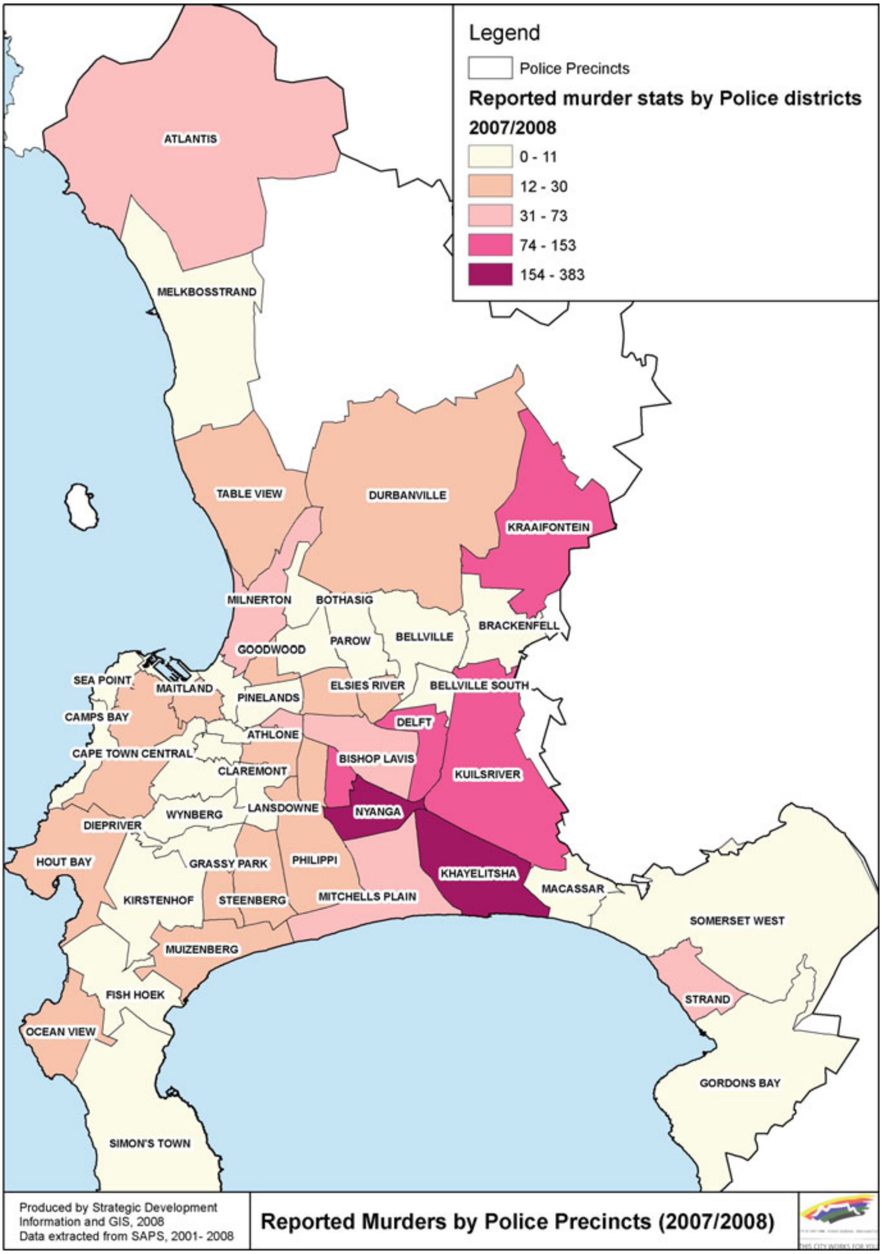

Fig. 9.1 Murder rates, by police precinct, in the city of Cape Town. As this figure shows, the worst violence in South Africa occurs within socially excluded communities. In this instance a 'cluster of fear' exists in a location on the city's periphery with high poverty, little infrastructure and an often transient population. Figure provided by (and used with permission from) Janet Gie, of the city of Cape Town

inevitably false (e.g., Martens, 1997; Paoli & Reuter, 2008), excluded groups may also bring additional resilience to the societies in which they are embedded – even if only through their willingness to do jobs that the rest of society considers beneath them, or to work for relatively low wages. For example, in richer countries where the population is declining, immigrants provide a source of labour for factory jobs. Turkish labour helps to keep German car factories productive and in the USA a variety of less skill-dependent industries (such as car manufacturing, construction and agriculture) have relied on African and Hispanic labour pools to achieve and maintain their current levels of global prominence (e.g., see Palacios, 2010; Vasquez-Leon, 2009). These trends have implications for spatial resilience at national and regional scales, with industry and labour availability influencing city sizes, economic growth rates and the accumulation and use of different kinds of capital.

Socially excluded or marginalised groups can also be powerful voices for societal change, forcing societies to confront difficult problems and entrenched attitudes (Green, 2008); the push for Black civil rights in the USA, for example, had the beneficial effect of forcing American society to consider and revise its attitudes towards minorities and marginalised groups in general. By adding a diversity of new views, approaches and skills to a society, socially excluded groups may ultimately contribute to its economy, its institutions and its resilience to larger shocks.

Social exclusion can also, if unaddressed, result in discontent and ultimately in conflict (e.g., Webersik, 2004). Ostby, Nordas, and Rod (2009) found that conflict was more likely in regions that had low levels of education; strong relative deprivation regarding household assets; strong intraregional inequalities; and the combined presence of natural resources and relative deprivation. Social exclusion, marginalization and inequity can thus be drivers of conflict, to which I now turn.

Conflict as a Spatial Process

Conflict can be viewed as a form of perturbation in social-ecological systems because it disrupts social processes and may result in the loss of key system components. Like most perturbations, war and other forms of conflict generally have a high degree of spatial structuring (e.g., Braithwaite, 2005; Braithwaite & Li, 2007; Flint, Diehl, Scheffran, Vasquez, & Chi, 2009). Conflict can create spatially discrete fragments in social and ecological systems, both through formal boundary creation and through the displacement of people. Conflict and related human migrations can have significant spatial effects on land cover, land use and ecosystems (e.g., De Vos, Jongerden, & van Etten, 2008; Suthakar & Bui, 2008). Obvious examples of spatial outcomes from conflict include such events as the erection of the Berlin Wall, which created a physical and social divide through the middle of a formerly continuous community; the division and active separation of Israel, Palestine and Lebanon; the separation of India, Bangladesh and Pakistan; the impacts of the civil war in America; and the ongoing fighting in Somalia, which has resulted in a set of self-contained fragments controlled by different warlords (Webersik, 2004). An intriguing example of the relevance of space and social capital in war comes from the conflict in Mozambique, in which Renamo rebels appear to have deliberately used terror to destabilise villages and thus prevent political activity by villagers (Lunstrum, 2009).

Conflict tends to be spatially clustered (Buhaug & Rod, 2006) and may be contagious (Braithwaite, 2010; Buhaug & Gleditsch, 2008), depending partly on the degree of social-ecological similarity and connectivity (e.g., shared ethnicity and infrastructure) as well as the capability for governance within the system. The direct impacts of conflict are often obvious (e.g., scorched fields and empty villages), but conflict can have indirect spatial consequences too; for instance, spillover effects from failed states may negatively affect their neighbours (Iqbal & Starr, 2008; Murdoch & Sandler, 2002). Conflict is often linked to access to resources (Le Billon, 2001; Lujala, Rod, & Thieme, 2007), which may in turn be distributed in space in non-random ways, further entraining spatial patterns of social-ecological fragmentation.

Conflict can create long-lasting path dependencies, with current spatial patterns of ownership and resource access by different ethnic groups being influenced by past conflicts (e.g., Daley, 2006; Korf & Funfgeld, 2006). The occupation and colonisation of one nation by another frequently creates ongoing problems, as in Southern Africa and Australia, where land tenure and ownership are still contentious issues centuries after colonisation began (e.g., Ramutsindela, 2007).

Assuming that conflict in general (and war in particular) is generally an undesirable event for the majority of elements of social-ecological systems (Keshk, Pollins, & Reuveny, 2004), the spatial resilience of a given system to conflict is influenced by a wide range of both biophysical and social variables. Landscape pattern and topography serve to make some places more vulnerable than others; and the ability of a particular location to withstand attack or to serve as a base for military action, together with its proximity to potential enemies, has had a notable impact on the political geography of many countries. For example, the location of Ottawa, the capital of Canada, was selected by Queen Victoria to be close to the border between Canada's French- and English-speaking Canadian communities but also sufficiently far from the American border, where towns were considered vulnerable to attack following the 1812 war (Sheppard, 1994). The fact that a considerable amount of conflict occurs on or close to borders (Braithwaite, 2005) has also facilitated the cross-country movements of refugees, many of whom may become members of socially excluded groups, including rebel organizations, in the countries that they flee to (Salehyan & Gleditsch, 2006).

Additional resilience to conflict appears to reside in institutions that govern spatial interactions such as trade, access to international markets and water extraction. In large river basins the likelihood of conflict is demonstrably related to the institutional environment, with levels of conflict apparently being reduced by the presence of international treaties and other institutions that help to resolve conflict peacefully (Yoffe, Wolf, & Giordano, 2003). Braithwaite (2010) similarly argues that increased state capability (such as better governance and law enforcement capability) reduces the potential for nearby conflict to become contagious. While such institutions are not themselves explicitly spatial, they interact with and regulate spatial processes.

In general, the spatial resilience of social-ecological systems to conflict appears to be related to variables across a range of different scales, including the internal properties of the system (Braithwaite, 2010; Ostby et al., 2009) as well as its immediate neighbours (Iqbal & Starr, 2008), its regional context (Goldsmith, 2007) and the location of key biophysical resources that may be of interest to external actors (Le Billon, 2001). Although direct approaches to reducing the likelihood of conflict (such as increasing military capacity) can obviously contribute to social resilience, the most effective approaches to improving resilience to conflict appear to be the provision of less extreme ways to resolve inequities (e.g., democratization; Gleditsch & Ward, 2000) and the creation of conflict-resolving international institutions.

Conclusions from Social Science for Spatial Resilience

It is obvious from this discussion that spatial location, context and connectivity can have important implications for social resilience. Some of these ideas have already been discussed in Chapter 6, where I argued that spatial resilience can be influenced by the social relationships between actors in a network. The examples discussed in this chapter suggest, however, that social fragmentation has a more complex relationship to social-ecological resilience than membership in key networks alone would suggest. Whether social fragmentation increases or decreases social-ecological resilience depends on the context and the nature of both the society and the perturbations of concern. Perhaps the biggest difference between social and ecological fragmentation is that social fragmentation often tends to increase regional social and cultural diversity, hence increasing rather than reducing the number of ways that a system can respond to new challenges. Conversely, social resilience is also dependent on collective action and social fragmentation may reduce system resilience by reducing the ability of societies to respond collectively to change.

In general, the spatial resilience of social systems appears to be facilitated by (1) finding the right geographic balance between centralization and decentralization (‘polycentric’ rather than ‘fragmented’), including the resolution of scale mismatches between system components (Cumming, Cumming, & Redman, 2006); (2) the development of additional institutions that regulate spatial processes in sensible ways, including (amongst others) processes relevant to urban development, social exclusion and conflict; and (3) the formation of informal networks that increase social capital, build trust and provide benefits and a level of insurance for members. For social-ecological systems, it further appears that (4) governance networks that cross different scales are particularly important (Brondizio, Ostrom, & Young, 2009; Ernstson, Barthel, Andersson, & Borgström, 2010; Olsson, Folke, Galaz, Hahn, & Schultz, 2007).

Integrating Fragmentation Concepts Across Disciplines

Each of these examples of social fragmentation has relevance for understanding spatial resilience in social-ecological systems. Separation or segregation in space within a community will affect a range of interactive social processes, including various forms of collective action, politics, the development of relationships of trust or suspicion and economic transactions (e.g., Gibson, Andersson, Ostrom, & Shivakumar, 2005; Ostrom, 2003; Poteete & Ostrom, 2004). Changes in these processes will often impact the management of natural resources and patterns of land use (Nagendra et al., 2004). Changes in land use and land cover in turn impact ecosystems and ecosystem services. If some sectors of society respond to changes in ecosystem services, for example by introducing payments for ecosystem services or by lobbying the government for more effective flood control or farming subsidies (e.g., Hediger, 2003; Schindler, Leavitt, Brock, Johnson, & Quay, 2005), a feedback loop that links social networks and ecological fragmentation is created. It has also been suggested that ecological and sociological boundaries and edges may become aligned with one another in some settings (e.g., indigenous rural communities) and that these transitional areas may enhance resilience by acting as mixing zones that foster diversity and adaptation (Turner, Davidson-Hunt, & O'Flaherty, 2003).

While comparisons between ecological and social fragmentation must be treated with care and mechanisms must be carefully distinguished from metaphors, it is clear that many of the general concerns of spatial resilience as laid out in Chapter 3 are relevant to both social and ecological fragmentation. There are at least four fundamental points of overlap that emerge from ideas about fragmentation across different disciplines. The first of these is that fragmentation of any sort almost always has a spatial component. Even though social and economic exclusion are commonly expressed in non-spatial terms, such as differences in relative income or participation in social groupings, most social processes nonetheless have a spatial dimension.

Second, the impact of fragmentation on diversity and the role of diversity in fostering resilience to fragmentation events have similarities and differences in social and ecological systems. For example, thinking about the Lago Guri case study discussed in Box 8.1 of Chapter 8, it is more likely that a rapidly isolated forest fragment will contain a full range of functional groups (including vertebrate predators) in a more diverse ecosystem. In similar fashion, social exclusion (which can be viewed as an outcome of a lack of resilience to spatial fragmentation) may be less likely in a more diverse community in which people from different backgrounds are used to interacting with one another across cultural and economic boundaries on a regular basis. However, it is equally important to keep in mind that the response of diversity to fragmentation events differs; over time scales that are relevant to people, ecological diversity is usually reduced by fragmentation (Lindenmayer & Fischer, 2006), whereas the homogenising influence of social interactions means that social diversity and inter-group differences can be maintained by isolation and may increase, or become more dominant, following fragmentation (Gell-Mann, 1992; Webersik, 2004). In both cases, intermediate connectivity is perceived as an important component of long-term resilience (Granovetter, 1973; Portes, 1998).

Third, it is apparent that issues of scale and the scaling relationships between different kinds of hierarchy – social, institutional, economic and ecological – can have a large bearing on the overall performance of a social-ecological system. In an economic context, for example, 'sorting effects' resulting from regional policy can induce the highest productivity firms to move to the economic core of the region (i.e., where wealth generation is highest) and the lowest productivity firms to the periphery (Baldwin & Okubo, 2005). Scale mismatches, in which misalignment between scales of governance or management and scales of ecological or sociological problems occur, can cripple social-ecological systems and reduce their resilience (Cumming et al., 2006).

Fourth, it should be emphasized that graph theory, and particularly the relatively new set of approaches (discussed in Chapter 6) that have been developed for the detailed analysis of networks, can capture important elements of social, economic and ecological connectivity in a common form. By expressing connections as simple graphical relationships, it becomes possible to map out parallel networks of different kinds and analyse their points of overlap. As Cumming, Bodin, Ernstson, and Emlqvist (2010) have argued, understanding the degree and the nature of the overlap between social and ecological networks is enormously relevant to the effective management of social-ecological systems.

As a spatially explicit process, fragmentation in social-ecological systems thus has much to teach us about spatial resilience. It is in many ways the single area of current research that brings us closest to a more general science of spatial resilience. However, if the study of resilience is to profit more effectively from the many excellent but more discipline-specific studies of fragmentation, we will need to introduce a more explicitly theory-oriented perspective into our deliberations on the nature of fragmentation in SESs and to gradually build a better understanding of feedbacks between the biophysical environment, human decision making and anthropogenic impacts.

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Chapter 10
Spatial Resilience in Case Studies of SESs

Introduction

One of the ultimate tests of the value of ideas about spatial resilience is whether or not they can be applied usefully to understanding and interpreting real-world case studies. In the introduction to this book I made the claim that the widespread tendency amongst empirical complex systems researchers to disregard spatial aspects of resilience, or at least to leave them out of core analyses and models, is one of the reasons why case studies of resilience in qualitatively different systems have yielded so few of the generalities that give science its predictive power.

The preceding chapters have presented numerous specific examples of how spatial relationships to other social-ecological systems can be important and how spatial influences (such as rescue effects, transfers of information through networks, and cross-scale subsidies) may explain some of the dynamics that can confound comparative analyses of resilience in social-ecological system resilience. What this synthesis still lacks, however, is clarification of how the framework presented in Chapter 3 and the ideas and methods in Chapters 4, 5, 6, 7, 8 and 9 can be applied to and enriched by real-world case studies.

Applications of the spatial resilience framework in Chapter 3 to case studies of social-ecological systems may occur in two complementary ways, which can be categorised as case-driven and theory-driven respectively. Case-driven analyses take a set of existing case studies and attempt to derive common patterns and generalities from them. A good example of case-driven analysis is provided by a special feature in the journal *Ecology and Society* (see editorial by Walker, Anderies, Kinzig, & Ryan, 2006), in which participants looked for common threads and shared outcomes across 15 different social-ecological case studies. One of the outcomes of the exercise was a valuable contribution to theory, in the form of a list of general propositions for further testing.

Theory-driven analyses, by contrast, focus on explicit empirical tests of hypotheses; they usually require careful a priori identification of research questions and the application of methods (e.g., data collection protocols that pay attention to sample sizes, controls, and confounding factors) that are designed to yield clear results. Good examples of theory-driven approaches are provided by many of the landscape experiments discussed in Chapter 8 (a good review is provided in Debinski & Holt, 2000).

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Although theory-driven approaches generally offer a more rigorous and effective way of doing science than case-driven approaches, a variety of factors (such as time, costs, the need for ongoing stakeholder engagement, and variation in the occurrences of 'windows of opportunity' for understanding change in social-ecological systems) can make theory-driven projects in social-ecological systems impractical. Case-driven and theory-driven approaches have both made valuable contributions to our current understanding of resilience in SESs. I will structure my discussion of case study applications according to these two categories, starting with case-driven analyses but focusing on detailed empirical analysis in the theory-driven section.

Moving from Case Studies to Theory

A typical motivating question for a case-driven analysis is, 'What can we learn from comparing these case studies?'. The nature of interdisciplinary collaboration and the scientific process is such that this question is often posed well into a case study, and usually at a point along a research trajectory where substantial investments have already been made in collecting particular data sets using a particular protocol. The analytical challenge thus becomes one of finding a way to accommodate several different kinds of data under a single umbrella.

Different kinds of data, collected from different places in different ways, are difficult to compare rigorously to one another. Out of the set of 15 case studies mentioned earlier (Walker et al., 2006), for example, the greatest number of studies used in addressing any single question was five (Olsson, Gunderson, Carpenter, Ryan, & Lebel, 2006) and despite the many useful qualitative insights that the exercise produced, none of the cross-case analyses in the special feature included a fully quantitative comparison between different case studies.

As discussed in Chapter 3, a recipe for cross-case comparisons includes the following steps: (1) describe each case study as an SES, using the basic groupings of structural, temporal and spatial variables; (2) from these descriptions, identify generic elements and interactions that occur in and are of fundamental importance in some or all case studies (Cumming et al., 2005b; RA, 2007), as well as one or more common perturbations (e.g., climate change or market collapse) against which resilience is to be assessed; (3) develop a generic systems model that incorporates variables of interest as well as key system drivers, and use it to focus the analysis (i.e., answering the question of resilience *of* what *to* what (Carpenter, Walker, Anderies, & Abel, 2001) while also thinking about interactions, non-linearities, and thresholds); (4) formulate one or more general hypotheses relating to spatial resilience that can be tested across different cases; and (5) obtain comparable quantitative data sets from different cases and test the hypotheses as rigorously as possible.

The fourth and fifth steps of this outline correspond to equivalent steps in theory-driven analyses; the primary difference is that in the case-driven situation, the data from different case studies are usually incompatible in various ways and hence the kinds of empirical analysis that can be undertaken (and the power of the conclusions) are limited by practicalities. I will deal with steps 4 and 5, hypothesis formulation and quantitative analysis, in the next section (theory-driven case studies).

I applied the first three steps of this outline to a comparison of the resilience of nine large river basins, using data from a set of case studies developed as part of the CGIAR Challenge programme on water and food (Harrington et al., 2008). The basins included the Andes, the Indus-Ganges, the Karkeh, the Limpopo, the Mekong, the Niger, the Nile, the Volta, and the Yellow River. Although each basin has its own problems, one of the key concerns in nearly every basin is that water production may not be sufficiently resilient to climate change and the expansion of irrigated agriculture (Cumming, 2011).

Chapter 3 and the components of identity that were described by Cumming et al. (2005b) suggested a set of generic elements that should be present in any large river basin (Table 10.1). From an identity perspective, the key elements that are common to all large river basins include water; long-term residents of the catchment; commercial, large-scale players who contribute to national food security and economic growth; unique ecosystems, such as mangroves and wetlands; the institutions that govern water management and use; and a range of ecosystem services that are integral to the wellbeing of people living in the basin (Cumming, 2011). From a spatially explicit perspective, river systems are strongly influenced by asymmetries (Vannote, Minshall, Cummins, Sedell, & Cushing, 1980; Fig. 10.1), questions of connectivity (Wiens, 2002), and other forms of biophysical variation (Dent, Cumming, & Carpenter, 2002).

Table 10.1 Generic system elements in a large river basin. Modified from Cumming (2011). This list offers examples but is not intended to be exhaustive

System attribute	Generic elements
1. Structural axis	
SES	
Components	Actors: farmers, fishers, household users, management agencies, local and international NGOs, researchers, different ethnic or racial groups, mining companies, civil society groups, hydroelectric power producers, bridging groups or fora that connect different stakeholders Biophysical components: water, vegetation, crops, livestock, fish Built components: impoundments, roads, canals, cities Institutions: laws, policies, regulations
Interactions	Implementation of land tenure and water rights; negotiations over water withdrawals; upstream-downstream user interactions; transboundary politics; social networks
Continuity and memory	Provided by long-term policies, laws, and conventions; long-standing management agencies; historical precedents; and knowledgeable individuals
Information processing	Refers to information availability, decision making, and response capacity. Although research is typically undertaken by universities and NGOs, information processing is often undertaken by individuals (e.g., farmers may respond to predictions of drought by storing excess water) and by organizations

Table 10.1 (continued)

System attribute	Generic elements
Adaptation	Related to research and local innovations; may also occur through the action of selection on diversity, although high social diversity may inhibit collective action
Environment	
Inputs and outputs to SES	External drivers, such as rainfall and global market demands for local produce; international and national influences such as resettlement schemes, economic incentives, flood compensation, etc Outputs include water, food, and information
Perturbations	Floods, droughts, climate change, economic shocks, politics (e.g., governmental changes)
Asymmetries	Gradients exist along each case study from headwaters to foothills. These include biophysical gradients (elevation, river size, water quality, etc.) and socioeconomic gradients in household income and production systems as one moves from highlands to lowlands
2. Spatial axis	
Connectivity	Human communities in big river basins are connected by the water that flows through them and by networks of roads and waterways. Downstream ecosystems depend on upstream water production. Social networks and shared institutions provide an additional form of spatial connectivity
Subsidies	Many large downstream towns are to some extent subsidised by the opportunity costs incurred by upstream communities. Food may be locally produced or imported; dependence on external sources can alter system resilience
3. Temporal axis	
Slow variables	Groundwater extraction, soil fertility, human population increase, changes in attitudes of local community
Evolution/selection	As the system changes through time, elements (such as farming systems or organizations) are lost and gained
Path dependence	In some case studies the role of history is an important determinant of current patterns in such things as tenure, land use, soil fertility, and equity. Historical precedents may also determine later outcomes
Phase of adaptive cycle	Is the system increasing in one or more capitals, reaching a ceiling, in a state of collapse, and/or just emerging from a collapse?

Consideration of primary elements, together with the case study descriptions for each basin suggested a simple representation of a generic river basin (Fig. 10.2). In this preliminary model, spatial dynamics are represented by an upstream-downstream divide. Water connects different parts of the basin as it moves downstream, often with a delay created by one or more large impoundments. Bridging organizations, such as the Nile Basin Initiative, connect actors across different zones. In each zone, local actors and production systems use and are influenced by water, and a variety of important interactions and feedbacks occur within both of these boxes. Climate in the form of local rainfall and temperature (e.g., via temperature-linked processes such as snowmelt, convection, and evaporation) determines water quantity, while also influencing land cover; and feedbacks

Fig. 10.1 Asymmetries in stream ecosystems. (**a**) A typical mountain stream with cold, clear water and a rocky substratum. This picture was taken near Thendele camp in the Drakensburg Mountains of Kwazulu-Natal, South Africa. (**b**) The Zambezi River, mid-way along its length, as seen from an aeroplane on the flight from Harare to Lusaka. Note the low-sided, sandy, braided channel and the extensively cultivated floodplain. This morphology is typical of a large, mature river. Photographs by Graeme S. Cumming

from land cover (e.g., vegetation via evapotranspiration, urban heat islands, or other albedo-altering effects as discussed in Chapter 7) can in turn influence local rainfall. Production systems include the full range of different sectors (e.g., agriculture, mining, power generation, household users) and may directly influence land cover, for example through the clearing of native vegetation for irrigated cropping systems or

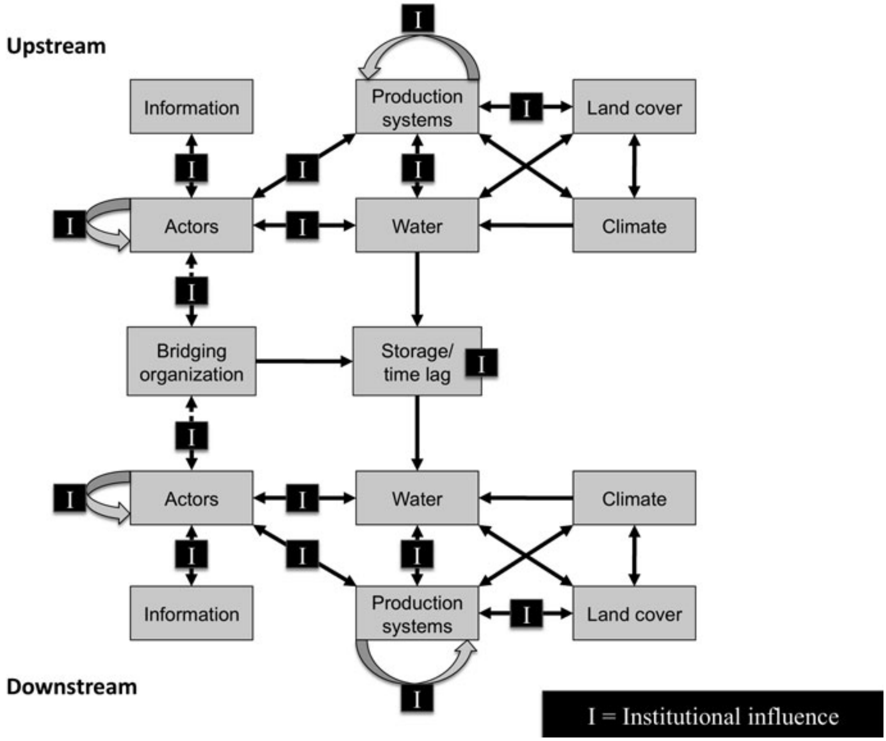

Fig. 10.2 Generic representation of a large river basin. 'I' in this diagram indicates potential institutional intervention points. Further explanation in text. After Cumming (2011)

the planting of commercial pine forests. Production systems respond to water quantity and quality while also influencing water quality and quantity by such activities as extraction, alterations to runoff, and pollution. Land cover influences infiltration and runoff rates, with effects on water quantity and quality. Actors generate information, which may influence human actions and interactions that have relevance to water use. Lastly, institutional interventions or guidelines, denoted in this diagram by 'I', have the ability to influence some but not all interactions within the system.

This simple representation of a river basin SES suggested that one of the most important tipping points occurs when a river basin crosses a threshold in water quantity from water sufficiency to water scarcity (Cumming, 2011). Before this point is reached, water is not considered a limiting factor and actors do not need to make major concessions in their use of water (although some tradeoffs between different uses of water, such as hydroelectric power versus waste removal, may still need to be confronted; Rodriguez et al., 2006). If water becomes limiting, the SES crosses a threshold and the creation of a water economy – with attendant legal and livelihood concerns – is set in motion (Cumming, 2011). At this point a number of initially dormant or potential interactions between actors, production systems and land cover start to become increasingly realised and defined. The state of the system at the point where the water scarcity threshold is crossed is thus a hugely important determinant of the subsequent resilience of the basin. For example, if social capital is low and existing institutions are weak, water scarcity may cause conflict (Rajasekaram, Simonovic, & Nandalal, 2003), particularly if it is accompanied by other biophysical changes. River basin SESs can exhibit many other non-linear feedbacks (Gordon, Peterson, & Bennett, 2008) and it is easy to envisage instances in which multiple thresholds are crossed simultaneously (e.g., water scarcity and eutrophication together could result in dramatic shifts in both water quantity and water quality).

Note that this breakdown uses the concept of spatial resilience to help guide and focus empirical investigation. Thinking spatially raises awareness of the importance of processes such as land cover change and upstream-downstream interactions. Viewing the entire system as an integrated social-ecological system, and thinking about its resilience, helps further in developing a perspective that is both holistic and suitably focused. With a clear focus, the more formal analysis of spatial resilience becomes a lot easier. Using the framework in Chapter 3, *spatial* aspects of the resilience of river basins to decreases in water quantity can readily be rephrased as generic questions that have relevance across different case studies (Table 10.2).

Table 10.2 Important spatial issues and generic questions about spatial resilience that have relevance across multiple large river basins

Element of spatial resilience	What to think about in a large river basin	Example questions
Internal		
Internal arrangement of components	Gradients from headwaters to delta; upstream-downstream interactions; relative locations of different actors, locations where different ecosystem services are produced, and proximity of irrigated agriculture and mining activities to the river	How does the length and steepness of the watercourse influence water management systems along tributaries? Does this basic biophysical variation drive the structure of informal water management institutions?
System morphology (size, shape, P/A ratio, etc.)	Size of catchment area relative to anthropogenic water demand; relative sizes of different system components (e.g., water producing, water storing, water using); floodplain morphology; influence of catchment shape (e.g., branching pattern) on key processes or interactions, such as eutrophication and species invasions	How does floodplain morphology influence the prductivity of farming systems and their access to markets?

Table 10.2 (continued)

Element of spatial resilience	What to think about in a large river basin	Example questions
Number and nature of boundaries	Location of catchment boundaries relative to administrative units, such as national and provincial boundaries; degree to which catchment boundaries are protected; scale of boundaries relative to size of basin and effective scales of legislative action	Are rivers with catchments that fall across multiple boundaries (e.g., the Nile and the Zambezi) more or less likely to have water quality and quantity problems than those that occur in a single country (e.g., the Karkeh and the Yellow)?
Spatial variation in phase	Different resource users may have time-structured demands for water that create water shortages at certain times of year. Similarly, the location of highest demand may shift around a catchment, from upstream to downstream and back	What institutions exist for regulating water use at different times of the year, do they differ predictably along a catchment, and how do they affect food production?
Properties of location	Location appears to be an important factor in determining whether river basins will receive more or less rain as the climate changes. In the social system, location-linked cultural norms may influence the outcomes of attempts to co-manage water resources	Given that latitude influences species richness, and that more speciose ecosystems are expected to be more resilient, does latitude also influence the resilience of water quality to nutrient additions?
External		
Context (area influencing system) and system footprint (area influenced by system)	National and international context, especially institutional environment; influence of global economy on cropping and mining systems and household livelihoods; number and location of people living outside basin boundaries who are dependent on water in basin	How does the amount of local food production that is used locally, relative to the amount that is exported outside the catchment, relate to social capital within the river basin? And how does the resulting social capital influence household-level resilience to crop failures?
Connectivity	Ecological connections within the system (e.g., presence of barriers, such as impoundments or dry reaches, to movements of aquatic organisms); role of interbasin transfers, if any; social links to broader management, policy or learning-oriented networks	How do changes in connectivity (e.g., construction of impoundments) influence resilience-related properties of social-ecological systems (e.g., diversity, capital, production of ecosystem services)?

Table 10.2 (continued)

Element of spatial resilience	What to think about in a large river basin	Example questions
Spatial feedbacks	Are there positive or negative feedbacks between spatial processes; to what extent does system alter its external environment	Theory predicts that the area of invasive alien vegetation in ecologically sensitive areas ill expand faster as it gets larger. Given that alien trees can alter stream hydrology (Richardson, 1998; Scott & Lesch, 1997), do thresholds exist beyond which species invasions will affect livelihoods?
Spatial subsidies	Upstream communities may subsidise downstream communities if upstream water use is limited by downstream demands. Fertilisers are often imported into large basins and may cause eutrophication and declining water quality downstream. Water extraction by distant cities may effectively remove water from the system. Subsidies can be negative: in the Mississippi Basin and hundreds of others, upstream nitrogen inputs for agriculture have created extensive offshore hypoxic dead zones (Diaz & Rosenberg, 2008)	How do nutrient subsidies influence water quality and quantity, and is there a general relationship between catchment size, nutrient inputs, and eutrophication? If so, can this relationship be used to guide agricultural policy? How do intensive and extensive systems differ in the way that they set up these tradeoffs and in the total food production that can be achieved before the environment is negatively impacted?
Spatially relevant aspects of resilience		
Adaptation and learning	Is learning occurring; if so, it is active or passive and what mechanisms reinforce it; does adaptation occur proactively (through deliberate management towards a goal) or passively (i.e., as a result of the action of selective processes on diversity)	Do social learning programmes (e.g., European HarmoniCOP [Harmonizing Collaborative Planning] project (Pahl-Wostl et al., 2007)) enhance river basin SES resilience?
Memory	Does the system have some form of memory and where is memory located; is memory internal or external to the system	Are river basins with more detailed historical data also better managed and more resilient, and if not, why?

Table 10.2 (continued)

Element of spatial resilience	What to think about in a large river basin	Example questions
Thresholds	Does the system have the potential for alternate stable states? And if so, what drives state change and where are the thresholds for change located?	How frequent are regime shifts in big river basins and do they occur more frequently in basins that exhibit a particular form of spatial pattern (e.g., clustered versus dispersed food production)?

Table 10.2 completes point 3 in the series of steps that I outlined at the beginning of this section. In the next section I will first discuss theory-driven analyses and then present some ideas about how to (4) formulate a range of general hypotheses relating to spatial resilience that could be tested across different cases and (5) use quantitative data to test specific hypotheses.

Theory to Case Studies: General to Specific

Projects that have the luxury of being able to start with theory and specific hypotheses, and subsequently decide on study design and approach, have some notable strengths. In addition to being able to determine exactly which kinds of data are collected, and according to which protocol, researchers who are focused on a particular question from the start of a project can exploit spatial differences and similarities to contrast competing hypotheses. For example, in the project discussed by Cumming et al. (2005b), we were able to contrast the different impacts of three different political systems (those of Brazil, Bolivia, and Peru) on different areas within the same biophysical system, Amazonian rainforest.

Deciding on a suitable focus is one of the most difficult and most critical steps in any theory-driven investigation of an SES. Most empirical studies of SESs have a host of practical questions that they must address. In addition, the study of SESs has not primarily been a theory-driven exercise; and as discussed in Chapters 2 and 3, most of the overarching concepts in the study of resilience require translation before they can be operationalized (i.e., applied to solving specific problems in empirical studies).

The framework in Chapter 3 and the hypotheses discussed in Chapters 4, 5, 6, 7, 8 and 9 suggest many potential starting points for theory-driven investigation. Another approach that I have found useful as a way of generating interesting hypotheses is to contrast the descriptive framework from Chapter 3 with the different categories of complex adaptive systems phenomena presented by Norberg and Cumming (2008); asymmetries, networks, and information processing. A detailed example, with numerous general hypotheses, has already been presented in Table 3.3 of Chapter 3.

Once an analysis has been suitably focused, and once the researcher is armed with one or more interesting hypotheses and focal questions, the next steps in the analysis of spatial resilience are to design the study, obtain or simulate data from different cases, and test the hypotheses. The finer details of study design are outside the scope of this book, but it is important that good standard practice is observed in the collection of all data sets, including careful consideration from an early stage of practicality and the statistical requirements of the kinds of analysis that will be performed on the data.

Decisions must be made at an early stage on exactly how resilience and spatial resilience are to be analysed. These decisions also involve deciding on the role of broader participation (e.g., stakeholder involvement) in the scientific process. In Chapter 3, I outlined five possible approaches to analysing spatial resilience. To briefly summarize, they including the following:

Approach 1: Winnow down. Focus on a small number of spatially explicit variables that seem truly important as the basis for empirical data collection and/or a mechanistic modelling exercise (Carpenter et al., 2001).

Approach 2: Identity and threshold focus. Develop a set of identity criteria, as layed out in Cumming et al. (2005b). Use these criteria to determine critical thresholds in the system. Assess spatial influences for their potential to push the system over a threshold.

Approach 3: Add space to a simple systems model. Develop a simple systems model and then attempt to factor spatial influences more directly in to it, adding complexity from a simple starting point, as discussed in Bennett, Cumming, and Peterson (2005).

Approach 4: Use scale and scaling as unifying themes. Select three to five focal variables acting at different speeds and different extents and use them to develop spatially explicit models of fundamental, non-linear dynamics across scales (Holling, 2001).

Approach 5: Use of narratives. Develop four or five scenarios (Peterson, Cumming, & Carpenter, 2003) that pay particular attention to spatial aspects of resilience, focusing on key uncertainties in the role of spatial resilience in the system, and then quantify relevant variables and test particular hypotheses suggested by the storylines.

These five approaches are each data-heavy, in different ways, and it is beyond the scope of this book to work through all of them at the level of detail that a full analysis of spatial resilience would demand. What I will do instead is to draw on my own research to provide three examples of spatially explicit analyses that demonstrate how some of the concepts and methods discussed in this book can be used to think about specific aspects of spatial resilience. Since these three examples are also intended to convince you that spatial resilience is a useful concept for researchers working on social-ecological systems, it will be useful to read the next three sections with a few criteria for 'useful' in mind. Specifically, I expect that (1) spatial resilience will offer better explanations for complex phenomena that have been difficult to understand with a non-spatial approach; (2) spatial resilience will contribute significantly to our understanding of overall resilience; and (3) cross-case syntheses (i.e., attempts to derive general theoretical principles from analysis of the commonalities between different case studies) will be considerably more successful if they adopt a spatially explicit approach.

Example 1: Spatial Influences on Fish Biodiversity

Although the management of freshwater systems is influenced by a wide range of social, economic and ecological variables, ecological resilience is intricately related to biodiversity. If good spatially explicit biodiversity data exist, they offer a convenient entry point from which to understand at least some of the ecological aspects of the problem. This first example focuses on the distributions of fish in the state of Wisconsin, USA (Cumming, 2004). I was fortunate to be given access to a large database of fish collection records that had been assembled by the Wisconsin Department of Natural Resources (WiDNR) over the preceding 20 years. The data characterized fish communities by reach and were obtained by netting and electroshocking. About 13,600 locations were sampled and over 180,000 individual fish were identified to species. With additional help from The Nature Conservancy, I was able to obtain and work with a set of files (the Environmental Protection Agency's Reach Files Database version 3, now incorporated into the National Hydrography Database) which allowed me to complete many of the more technical aspects of characterising spatial pattern in rivers. Leaving aside for the moment the gaps in our understanding of exactly how biodiversity translates into ecological resilience, one starting point for thinking about the ecological aspects of spatial resilience in the Wisconsin SES was thus to ask how spatial influences affect fish biodiversity.

Many of the central issues of freshwater conservation and management in Wisconsin have a strong spatial component (Fig. 10.3). Wisconsin contains three major catchments; two of these drain into the Great Lakes (Lake Michigan and Lake Superior), while the third and largest catchment drains into the Mississippi, which forms the western boundary of the state. Downstream connection to a lake or a large river affects the species that are likely to be found in these catchments, with some species – such as sturgeon and paddlefish – being primarily inhabitants of large rivers.

There is also a strong historical influence on Wisconsin. European colonisation of Wisconsin, and subsequent alterations to waterways in and around the state, have left their mark on regional social-ecological systems (Box 10.1). Brook trout and various invasive species, such as the rusty crayfish *Orconectes rusticus*, have been introduced to many catchments. Another kind of historical imprint, from much further back in time, can still be seen in the spatial configuration of Wisconsin streams. The extent of glaciation during the last ice age was such that much of Wisconsin was ground down into a series of low, rolling hills and relatively simple watercourses. In the part of the state that locals call the driftless area, however, glaciers were

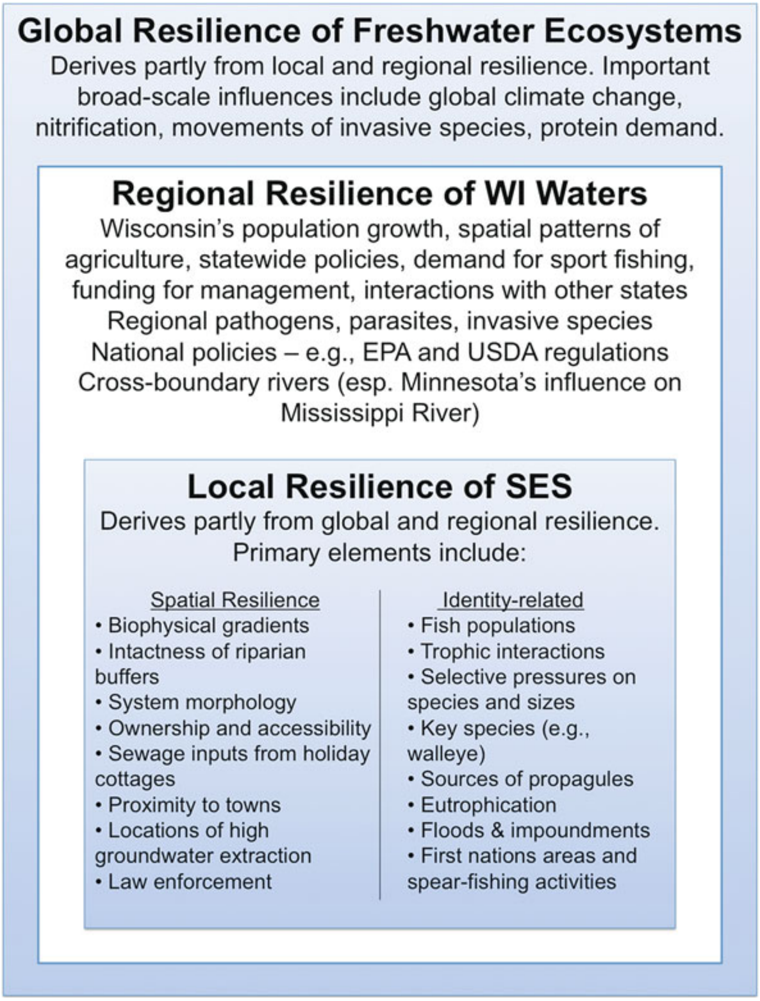

Fig. 10.3 Examples of important variables for spatial resilience in Wisconsin fish communities at three different scales. This figure offers some explicit examples of the more general variables suggested in Fig. 3.3 of Chapter 3. Further details of individual variables are discussed in the text

not present and the watercourses have maintained a greater degree of branching (Fig. 10.4).

Asymmetries in a number of relevant variables (such as rainfall, climate, elevation, and human settlement density) exist within Wisconsin. Rainfall, for example, follows both a standard latitudinal gradient from north to south and a more localised gradient, influenced by the biophysical effects of Lake Michigan, that runs from east to west. Human settlements are clustered in the southern portion of the state where the growing season for crops is longer. First Nations communities, such as the Menominee (west of Green Bay), tend to live further north. As a consequence

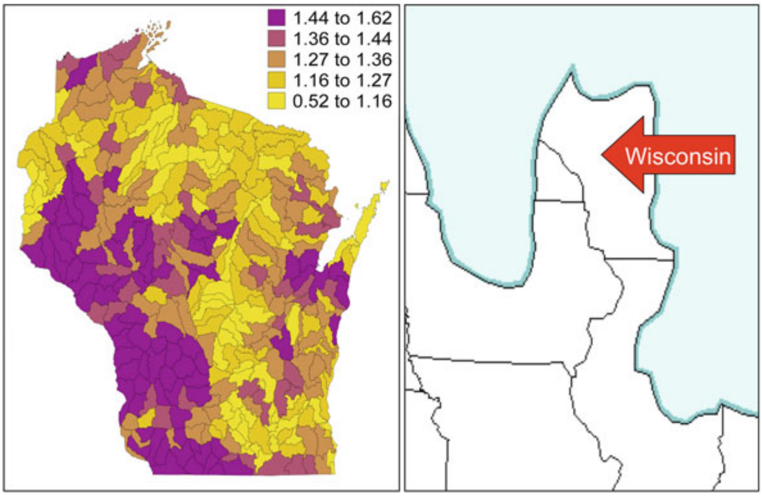

Fig. 10.4 Wisconsin's glacial hangover. This figure shows the fractal dimensions of Wisconsin streams by catchment (at *left*; the range of values corresponding to each *shade* is given at the *upper right*) and the extent of glaciation 18,000 years ago, as documented by the Illinois State Museum on their web-site http://www.museum.state.il.us/exhibits/larson/content.html. Note how the driftless area of Wisconsin, to the south-west of the state, has more convoluted catchments

Box 10.1 Connectivity and Canals in Wisconsin Waterways

The human geography of Wisconsin still relates to the colonisation of North America by Europeans. Prior to the construction of railroads, navigable waterways drove the development of western infrastructure and settlement patterns. Connection of the Mississippi Basin to the Great Lakes occurred in several places via man-made shipping canals at the towns of Chicago and Portage. Portage derives its name from being the place where canoes were carried (*le portage*, in French) from one water body to the next; it is situated where the Fox River (which drains into Lake Michigan) and the Wisconsin River (which drains into the Mississippi) are only 3.2 km apart. This spatial proximity made the Fox and Wisconsin Rivers central to the European exploration and colonisation of Wisconsin and influenced patterns of settlement within the state, at least until railroads took over the role of waterbodies for the transport of goods and people. According to the Portage Canal Society's web site, the Portage canal was functional from about 1876–1951, when the locks on the Wisconsin River were welded shut; the locks on the lower Fox River were closed in 1983 to limit the spread of sea lamprey. The Illinois and Michigan canal ran 155 km from the town of Chicago and connected Lake Michigan to the Illinois River, which is also part of the Mississippi system. The canal was operational from roughly 1848–1933, when it was replaced by the 45 km Chicago Sanitary and Ship canal, which remains open today.

In addition to the immediate ecological impacts of each of these canals, some of which required extensive re-engineering of entire river systems (e.g., reversing the flow of the Chicago River), they had lasting ecological consequences by opening the upper end of the Mississippi system to external (spatial) influences from the Great Lakes, including invasions by species such as sea lamprey and alewife. The United States Geological Survey (USGS; see http://www.glsc.usgs.gov) states that sea lamprey first entered Lake Ontario around 1830 and proceeded to expand their range over the next century, being recorded in Lake Erie by 1921 and Lake Michigan by 1936. Lamprey cause a relatively large number of fatalities of their hosts and were responsible for the near extinction of lake trout in Lakes Ontario, Erie, and Michigan as well as crashes in the populations of whitefish and chub, with attendant consequences for local livelihoods, in the 1940s and 1950s.

Movements of invasive species in the other direction (i.e., from the Mississippi system into the Great Lakes) have also been a major concern. The relevance of the Chicago Sanitary and Ship Canal for social-ecological resilience continues into the present time, with Michigan State Attorney General Mike Cox recently filing a lawsuit with the U.S. Supreme Court seeking the immediate closure of the Chicago Sanitary and Ship Canal to keep Asian carp out of Lake Michigan (Nelson, 2010). An interesting item of information to emerge from this debate is that the commercial value of the Great Lakes fishery is currently estimated at over US$7 billion per year, making the potential impacts of invasive species a huge economic concern. In February 2010, the Obama administration committed to spending around US$78.5 Million a year to keep Asian carp out of the Great Lakes; legal actions continue, and the canal will doubtless remain at the heart of this controversy for some time to come.

of the treaty rights that were granted during the colonisation of the mid-West, many first nations communities have their own natural resource management systems and tenure rights, adding further diversity to management practices (Westley, Carpenter, Brock, Holling, & Gunderson, 2002).

The aquatic environment of the state of Wisconsin is further characterised by its large number of impoundments (Fig. 10.5). Although some of these impoundments have high dam walls, many are low-head dams (i.e., head height < 15 m, often 2–3 m; Poff and Hart (2002)). Low-head dams in Wisconsin were originally constructed for a variety of reasons, including boating, fishing, production of hydroelectric power, and to increase water capacity for logging. The iconic Wisconsin River, which cuts across the middle of the state, has no fewer than 26 impoundments along its 692 km length. Many of the low-head dams across the state are now ageing, and are in the process of coming up for relicensing; and the question of whether

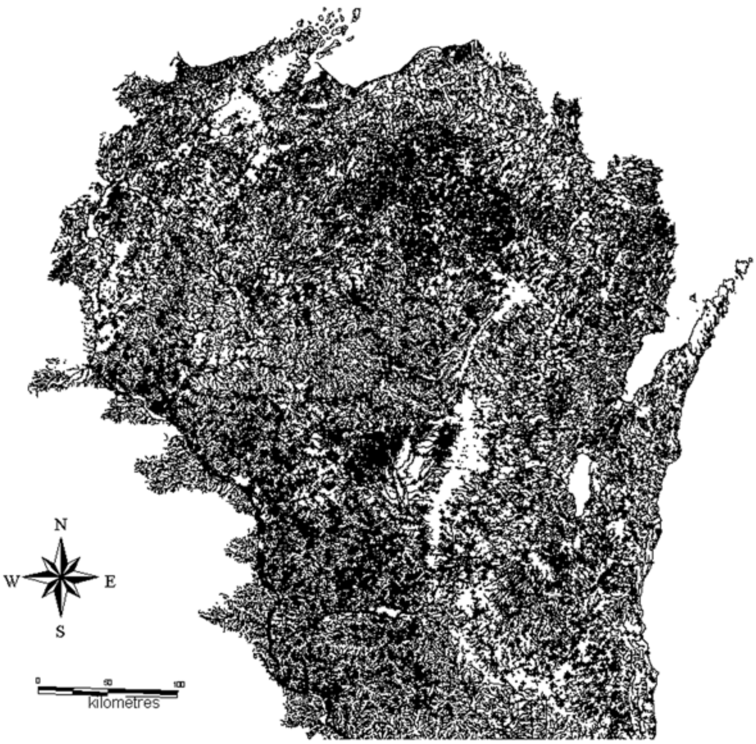

Fig. 10.5 River channels and locations of impoundments in the state of Wisconsin. After Cumming (2004)

to relicense dams or remove them entirely is an important conservation concern (see discussion and references in Stanley & Doyle, 2003). In theory, re-establishing regional connectivity is likely to build ecological resilience because dispersal of aquatic organisms through the stream network will allow the recolonisation of areas in which local extinctions have occurred. However, resident biodiversity has in some cases adapted to the presence of dams. In particular, freshwater mussels occur in Wisconsin in high diversity and some rare species need submerged rocky habitats, such as those created by dams, in which to live. Since little is known about the timing and effectiveness of colonisation of new sites by mussels (mussel larvae are dispersed by fish), extirpation of breeding populations of mussels through dam removal is a very real concern. Dams may also play a positive role in fostering aquatic biodiversity by serving as barriers to invasive species such as sea lamprey, alewife, and Asian carp.

Connectivity thus emerges as a key ingredient in understanding human impacts on fish biodiversity in Wisconsin. River systems form networks in which spatial proximity is not always a good indicator of effective distance. Although riverbeds on different sides of a ridge may appear close to a human observer, the distance that a fish would have to swim to get from one to the other may be many miles. In addition, streams are linear and directional. One of the central problems in understanding spatial patterns in fish biodiversity is that of working out how to deal with a revised concept of space.

Using the reach files database, and with assistance from Tom FitzHugh of the Nature Conservancy, I was able to gradually assemble a set of metrics that captured potentially important measures of spatial aspects of river systems. These included the arbolate sum (the total length of the upstream river system); the link number (the number of first-order tributaries upstream); stream order (when two first order rivers meet, they become a second-order stream; when two second-order streams meet, they become a third-order stream; and so on); fractal dimension; and the distance of each reach from the mainstem, which in this case constituted either the main channel of the Mississippi or one of the Great Lakes. Importantly, each of these metrics could be quantified in a GIS environment for each stream reach in the state. Connecting spatially explicit measures with more standard biophysical data and the fish collection localities ultimately allowed me to explore the influences of spatial location and connectivity on fish species richness.

The data showed some interesting trends. The most confusing of these was that many important asymmetries within the system mirrored one another. Fish species richness decreased as the number of dams downstream of a sampling point increased, but this trend could be explained by any of five different variables that were correlated with dam numbers: downstream link number, latitude, elevation, the number of dams downstream of a sampling location, and proximity to the nearest town. Analysis of the data using traditional multiple regression approaches suggested only a bewildering lack of consistency in terms of which variables appeared to be more important. I was eventually able to obtain a sensible conclusion using structural equation models (Shipley, 2002), which allowed me to at last obtain some useful biological insights into the nature of spatial resilience of the fish community (Fig. 10.6).

In a nutshell, the structural equation model showed that the primary influence on fish species richness is, as one might expect from terrestrial species-area relationships, the total amount of water in the stream. Water temperature also appears to be a major influence on fish species richness in Wisconsin, where warm- and cold-water communities are demonstrably different (Lyons, 1996). Correcting for these influences with the structural equation model suggested that the effect size of other variables, such as elevation, is relatively small. Interestingly, however, the model did demonstrate a small but significant impact of low-head dams on fish species richness.

From a management perspective, this study deals with only one small part of the broader problem of how to build resilience in Wisconsin's aquatic systems (e.g., see Wang, Lyons, Kanehi, Bannerman, & Emmons, 2007). It does, however, provide a useful microcosm of some of the more important spatial considerations relating to resilience. Water quantity emerged as the single most important variable influencing fish species richness. Removal of low-head dams to increase aquatic connectivity appears to be a worthwhile conservation goal; but the more important effects of dams may well be their downstream impacts on water temperature and water quantity. The analysis also provides some useful insights into asymmetries and gradients with the social-ecological system, raising further questions about why

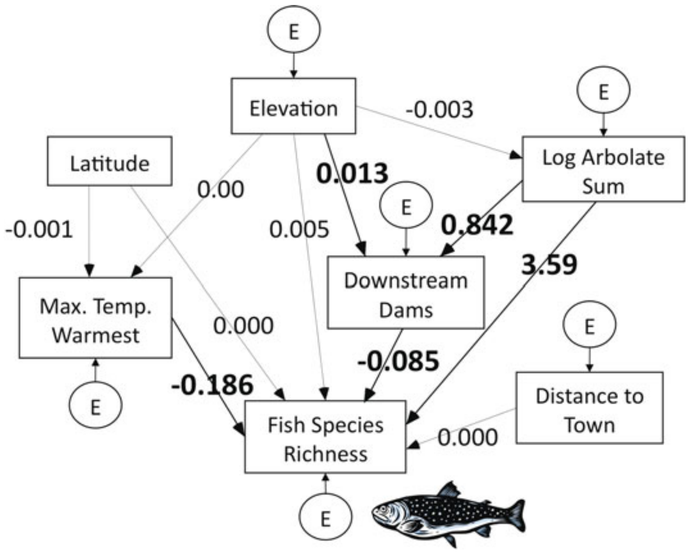

Fig. 10.6 Structural equation model showing the relationships between some of the different variables considered in this study. As explained in the text, the model tells a complicated but interpretable story about multivariate spatial interactions. The arbolate sum is the total length of the river channel upstream from a sampling point. Redrawn from Cumming (2004)

and whether dams are built in non-random locations (unpublished analyses suggest that they are strongly tied to gradient and stream order) and the relevance of regional management policies on dam construction and removal.

From a methodological perspective, referring back to my criteria for usefulness, viewing aquatic resilience in Wisconsin as a spatial problem leads to a vastly better explanation of fish community composition than a non-spatial explanation. It facilitates quantification of the relative strengths of the interactions between water quantity, water temperature, and connectivity, with high relevance for dam removals and other efforts to manage for resilience; and it allows for an integrated analysis of data from numerous different places (i.e., the fish sampling locations) to achieve a regional understanding of influences on fish biodiversity. Statistical correction for the local and contextual differences between sites, in terms of both immediate influences on sites and their location along different gradients, would be virtually impossible with a non-spatial data set.

Example 2: Understanding the Impacts of Catchment Morphology on Fish Population Dynamics

The first example illustrates the use of GIS and species distribution information to explore spatial relationships in the upper end of a large river basin. These analyses raised some new and interesting questions. In thinking through the spatial properties of stream networks, I started to wonder whether the nature of the branching pattern in a stream network – and particularly the degree to which subcatchments are compartmentalised (i.e., composed of catchments nested within other catchments) – has an influence on biological processes.

Unlike the first example, suitable empirical data for addressing this question were not available. I thus explored it using two of the spatial approaches discussed in Chapter 4, cellular automata and reaction-diffusion models, to simulate a spatial process – population expansion by an invading or recolonising species – in different habitats (Cumming, 2002). The population was introduced to a hypothetical stream network at one location and I tracked the time that it took for the simulated population to completely colonise the stream network and attain a local equilibrium. The lengths of each network remained the same, but the shape of the network varied, including a straight line, a line with simple branches off it, and a truly nested topology (i.e., looking structurally like a phylogeny or family tree).

The results showed quite clearly that the more nested stream network was colonised (invaded) faster than the more linear stream network, because the potential for colonisation was higher in the nested system where populations were effectively closer to one another. A second interesting and somewhat unexpected result was that the equilibrium population density in the more nested network was higher, primarily because vacant cells (i.e., those left empty following mortality events) were recolonised faster.

This analysis was relatively quick and easy to run (and to publish, as it turned out, appearing in print 2 years before the preceding study) but it provided some useful insights into the nature of spatial pattern and population resilience. I later did some exploratory analysis with Karen Wilson, now based at the University of Southern Maine, to see if we could use the same models to simulate the invasion of Trout Lake (in northern Wisconsin) by the rusty crayfish *Orconectes rusticus*. Rusty crayfish were introduced near a boat slip at one end of Trout Lake, but they took a surprisingly long period – more than 16 years – to completely colonise the lake's 30 km shoreline, dispersing at an annual rate of only 0.68 m/day despite being capable of movement rates of over 100 m/day (Byron & Wilson, 2001). Even assuming that the crayfish moved only in a narrow strip of shallow water close to the shore, and that they were active for only for 3 months a year, we were unable to find reasonable population and dispersal parameters that would result in anything approaching such a slow colonisation rate. Some factor other than dispersal ability was clearly limiting population spread. In this case, the most likely contenders were habitat-dependent predation and the possible existence of one or more invisible 'death zones' (or other ecological boundaries) for crayfish somewhere along the edge of the lake. Although the riddle of the crayfish remains unsolved, it is worth noting that even though the assumptions on which the population models were based did not fit this particular species, they did serve as a very solid way of establishing what would constitute a reasonable assumption. In other words, the model may not have solved the problem, but it did tell us that we could safely assume that 'something else' besides business as usual was going on.

Evaluating the usefulness of spatial resilience concepts once again, spatial models in this example shed additional light on the relationship between catchment morphology and ecological processes. They also show that spatial structure may explain some of the variation in colonisation rates (and other processes that may be dispersal-limited) in networks. Although the crayfish problem was not 'solved' by the model, the results and observations together suggest that the slow spread of crayfish in Trout Lake was not simply a case of 'crayfish don't move'. This insight suggests a possible mechanism for limitation of the colonization rate, narrowing the range of plausible explanations and offering more depth than a non-spatial analysis. Given that a manager would probably want to reduce rather than enhance the resilience of the crayfish population, a spatial resilience perspective here suggests further empirical studies (e.g., littoral zone manipulation of rocks, or altering predation pressure by stocking fish) that might suggest practical ways in which crayfish spread could be further slowed or even reversed. Although this was not a typical cross-case analysis, but rather a targeted comparison of theoretical extremes, the model also suggests some general principles that might be applicable to a variety of different case studies. In particular, the idea that recolonization or invasion time is slower in a more linear system may have important implications for understanding the overall resilience to species invasions and local extinctions of individual protected areas in reserve networks.

Example 3: Spatial Variation in the Resilience of Ecosystem Function

The first two examples deal with community and population-level trends respectively. This example focuses on ecosystem function. In simple terms, one of the primary reasons why biodiversity matters to people is that we are part of a community of interdependent organisms. Other organisms and the biophysical environment collectively provide us with a life-support system. The many benefits that we get from this system – such as clean air, clean water, food, fuel, and pest regulation – are called ecosystem services (e.g., see Ehrlich & Mooney, 1983; Loring, Chapin, & Gerlach, 2008; MA, 2005; Postel & Carpenter, 1997).

One way to develop a quantitative link between social and ecological systems is to map out and measure the feedback loop that runs from communities of species through functional groups, ecosystem function, ecosystem services, human use of ecosystem services, and the impacts of human use of ecosystem services (including, for example, social processes and structures like governance, institutions, and decision making) on communities of species (Cumming, 2007; Cumming et al., 2005a). As discussed in Chapter 5, greater biodiversity means in theory that there are more species that can perform a given function; since each species is adapted to its environment in a slightly different way, communities with more species are more likely to consistently provide ecosystem services through times of change

(Loreau et al., 2001; Yachi & Loreau, 1999). Human communities and production systems that depend on more diverse ecosystems should thus have greater resilience to perturbations that remove species, such as climate change, altered fire regimes, or overgrazing (Kinzig, Pacala, & Tilman, 2001; Walker, Kinzig, & Langridge, 1999).

Animal and plant communities exist in space, and functional group occurrences may further depend on interactions (like herbivory and competition) that exhibit a spatial structure. Spatial variation also occurs in anthropogenic impacts and human dependencies on ecosystem services. Consideration of patterns in functional group composition and in the number of species per functional group thus takes us a step closer to understanding patterns of spatial resilience in social-ecological systems.

Somewhat surprisingly to many people, birds perform a wide range of ecological functions (Sekercioglu, 2006; Sekercioglu, Daily, & Ehrlich, 2004). Their distributions in South Africa are also relatively well mapped (Harrison et al., 1997). To explore some of the linkages between biodiversity and ecosystem services, I worked with my then student Matt Child to determine how functional groups of South African birds were distributed in space and how the distribution of functional groups and the number of species per functional group related to patterns in the number of species. Interestingly, although species number was correlated with both the number of functional groups and the number of species per functional group, the relationship between species and functional measures was non-linear; and there was a high level of variance in the relationship (Cumming & Child, 2009). In other words, a species-rich location might be function-poor or function-rich; and two locations with the same number of species might exhibit different levels of resilience of ecosystem services (and dependent social-ecological systems) to species loss.

We then posed a more explicitly social-ecological question, that of how land use affected the composition of functional groups. We tested for differences between bird communities in pairs of well-sampled bird atlas cells that were dominated by protected areas and agricultural areas respectively. Each ‘protected’ cell was paired with a nearby ‘agricultural’ cell in the same biophysical environment, and we tested for a wide range of potentially confounding biophysical variables to ensure that we had a valid comparison.

The analysis suggested that outside protected areas a differential loss of two upper trophic level functional groups, raptors and scavengers, was occurring (Child, Cumming, & Amano, 2009). Our results supported the earlier proposal by Dobson et al. (2006) that the ecosystem functions provided by groups at different trophic levels should be lost at different rates during ecosystem collapse. Our work also provided a clear-cut indication that protected areas in South Africa are contributing to social-ecological resilience by acting as reservoirs for important functional groups.

In this example, thinking about the spatial resilience of ecosystem services led us first to adopt a functional approach and then to take the novel step of exploring functional variation in space. The analysis does not directly explain a complex phenomenon, but it demonstrates quite strongly that adding a spatial component to functional approaches can yield valuable insights. If functional group diversity and response diversity are indeed important for ecosystem resilience, then the demonstration that protected areas make a regional contribution to conserving functional diversity is an important step towards understanding the overall resilience of avian ecological functions in South Africa. It would not have been possible to undertake a valid comparison of data from different protected area-farmland pairs without first undertaking corrections for other spatial influences, which explain a substantial proportion of the variance in the bird community. In non-spatial case study comparisons that explore resilience, such confounding spatial influences are generally wrapped up with the variables of interest and create additional (and often non-random) variance in the data, making it difficult for the analyst to tease out general causal relationships. This example thus demonstrates both the ways in which the spatial resilience framework can guide the formulation of useful and interesting questions and the ways in which the inclusion of space into resilience-related analyses can clarify important regional trends by explicitly removing the signatures of 'irrelevant' (i.e., for the question being posed) spatial variation.

Concluding Comments

As these examples have demonstrated, the concept of spatial resilience can be usefully applied across a range of different scales and at different levels of quantitative detail. It is interesting to note that although the practical analysis of spatial resilience in a typical case study is a feasible proposition if, and only if, the properties of the system that are selected for analysis can be related to the broader framework of resilience theory, it is also true that the exact link between the system property and overall system resilience need not be precisely known for the analysis to yield useful and interpretable outcomes. For example, we know that diversity will often enhance the ability of a social-ecological system to cope with change, because more options are available in a more diverse system (Norberg, Wilson, Walker, & Ostrom, 2008). Similarly, although we do not know which perturbations a given case study will experience, we can be relatively confident that on average, ecosystem function is more likely to be retained in a system that has more species (see discussions by Loreau et al., 2001; Naeem, 1998). Spatial influences on biodiversity and functional group composition thus offer a tractable entry point for thinking about the spatial resilience of ecosystems.

With theory as our guide, we can start to more confidently make the connections between fine-scale studies of pieces of the system and the more general resilience of the social-ecological system. Case studies will need to be approached from both holistic and reductionist perspectives, possibly using comparisons of pattern-process relationships across different scales as a way of cross-validating models and assumptions and gradually following different lines of evidence towards an improved understanding of causality (Cumming, 2007; Plowright, Sokolow, Gorman, Daszak, & Foley, 2008). The process of scientific enquiry in SESs is discussed in more detail in Chapter 11.

One of the major challenges in applying theories of social-ecological systems to cross-case comparisons is to select problems that can in principle be approached and solved with acceptable levels of academic rigour across a variety of systems. In many instances, detailed studies of subsets of the problem make a vastly more useful contribution if they are embedded in relevant theory and framed in such a way that their broader relevance is clear. I am optimistic that if greater attention is paid to the interaction between SES theory and empirical research, and to the development of standardised and comparable case study methodologies, we will soon start to see rapid progress in the analysis of spatial resilience.

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Chapter 11
Synthesis and Conclusions

Introduction

In this book I have attempted to provide the first comprehensive synthesis of a set of interrelated ideas that together create a foundation for an emerging field, the study of spatial resilience in social-ecological systems. Three key points about spatial resilience should by now be clear. First, although the explicit study of spatial resilience in social-ecological systems is a relatively new development, the concepts from which it developed have a long and illustrious history, with roots stretching back over 200 years (von Humboldt & Bonpland, 1807 (reprint 2010)). Spatial resilience offers a new way of looking at spatial phenomena in social-ecological systems, but it does not require overthrowing or disregarding the progress that many disciplines have made in our understanding of the importance of spatial variation for complex systems.

Second, spatial resilience offers a framework for integrating the analysis of different kinds of spatial effects (as studied in different disciplines, often using different methods and data sets) under a single umbrella, and for exploring commonalities in the spatial dynamics of different elements of social-ecological systems. In the interdisciplinary arena, the concept of spatial resilience should contribute to novel insights in the same way that the study of resilience (and its congeners, such as vulnerability and robustness) has led to a wide variety of new insights into the workings of systems of people and nature.

Third, spatial resilience is intertwined with the study of resilience itself. Resilience is an emerging concept and the study of resilience is still at a relatively early stage. Spatial resilience had its first formal mention in the literature in 2001 (Nystrom & Folke, 2001) and this book, written in 2010, is the first attempt to define the field and synthesize the relevant literature into a single volume. Some of the weaknesses of this book, and of the framework that I have presented, derive from the stage at which the field finds itself. The contributions of resilience theory to the study of spatial resilience in social-ecological systems are self-evident; but it is perhaps too early to say exactly how spatial resilience should contribute to the study of resilience. As discussed in Chapter 10, however, I would nonetheless expect to find that spatial resilience will offer explanations for complex phenomena that have been difficult to understand with a non-spatial approach; that spatial

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resilience will contribute significantly to our understanding of overall resilience; and that cross-case syntheses (i.e., attempts to derive general theoretical principles from analysis of the commonalities between different case studies) will be considerably more successful if they adopt a spatially explicit approach.

In this concluding chapter I first summarize the generalities that have emerged during the writing of this book. I then discuss some deep-rooted themes and problems in the study of spatial resilience, before looking forward to highlight what I perceive as some of the central challenges that lie ahead.

Where from?

To briefly run through the progression of ideas followed in this book, I started in Chapter 2 by laying out a set of foundational concepts and defining spatial resilience. This definition was new and somewhat broader than that used by previous studies, and hence required detailed explanation and clarification. In Chapter 3 I presented a framework for the analysis of spatial resilience and discussed how the concept of spatial resilience could be made operational. Chapter 3 also contrasted the different elements of spatial resilience with the theoretical framework used by Norberg and Cumming (2008), which addressed SESs from the three inter-related perspectives of asymmetries, networks, and information processing. By the end of Chapter 3 I had defined spatial resilience, explained how the concept of spatial resilience relates to the broader body of theory around Social-Ecological Systems, and discussed how spatial resilience concepts can be useful for both the further development of theory (e.g., by generating novel hypotheses) and for organizing inquiry in particular case studies and problems that have a spatial component.

Having laid the conceptual groundwork for spatial resilience, I took a brief diversion (Chapter 4) to summarize relevant approaches to spatial modelling. Although Chapter 4 has a strong focus on ecological models, and in all likelihood ignores some relevant economic and sociological models, the range of approaches that are used in ecology offers a good representative sample of the modelling approaches that are most useful for exploring spatial resilience in SESs. The modelling theme of Chapter 4 was continued into Chapter 5.

The material covered in Chapter 5 suggested at least eight basic principles of spatial resilience. Although these derive primarily from ecological models, their relevance transcends ecology in the sense that they are generally applicable to social-ecological systems. To briefly summarize, they included the observations that (1) spatial effects and interactions are distance-dependent; (2) the probability of extinction, or localised component loss, correlates with habitat and population size (larger usually being more resilient); (3) the decay of spatial effects along gradients is non-linear, and hence spatial variation introduces the potential for thresholds and other complex behaviours; (4) spatial processes can produce spatial patterns, even in the absence of environmental variation; (5) spatial variation in the environment is created by feedbacks between pattern and process, both creating the potential for self-organization and necessitating balanced sampling designs to distinguish between spatial and temporal drivers; (6) spatial variation often, but not always, stabilises system dynamics; (7) localised interactions and uneven mixing help to maintain diversity in the nature of interactions, contributing to spatial resilience at a system level; and (8) since the tradeoffs that exist between dispersal and stationarity are environmentally contingent, resilient long-term strategies will often include varying and/or flexible dispersal behaviours.

Chapter 6 introduced a different perspective to the analysis and understanding of spatial resilience, that of networks and network analysis. Most published network analyses are mid-way between models and fully empirical studies; they abstract many elements of the problem while also incorporating real-world data. Network analysis has been used as a useful tool for understanding a range of case study systems, but it is difficult at present to pinpoint any generalities that network analysis provides about spatial resilience, aside perhaps from the importance of intermediate connectivity and the possibility for an 'intermediate resilience hypothesis'. Progress in this field is rapid, however, and depicting and visualising SESs as networks clearly has a high potential to address big-picture spatial and relational questions, such as that of how network architecture relates to network function.

Another approach that currently falls mid-way between theory and method is that of Land Use and Land Cover Change (LULCC) research. Chapter 7 argued that landscapes can be considered as complex adaptive systems and drew parallels between ecosystems and the pattern-process relationships that drive changes in landcover types. Landscape analyses have a high potential to offer useful insights into spatial resilience; but land cover change research needs to become more 'upward-looking' (i.e., more interested in theory and generality, and in particular in using models to test concrete hypotheses) before this potential can be realised.

The methods that were reviewed in Chapters 4, 5, 6 and 7 have been applied widely in several different contexts. One of the most interesting of these contexts is that of understanding the causes and consequences of fragmentation. Chapters 8 and 9 brought together many of the themes from previous chapters, as well as introducing a role for experiments, by looking first at landscape experiments and then at social fragmentation. Chapter 8 yielded some additional principles and expectations for understanding spatial resilience. In particular: (1) different system components will respond to changes in spatial patterns and processes differentially, and hence spatial resilience at a community level is influenced by the nature of local components; (2) as fragments and communities become smaller, the idiosyncracies of the local community become more important and the consequences of fragmentation become harder to predict; (3) patch surroundings (local context, matrix) influence within-patch outcomes; and (4) apparently fragmented landscapes may not be fragmented for all system components. These conclusions appear to be equally valid for ecological, social, and economic systems.

Chapter 9 explored spatial fragmentation in social systems through consideration of urban geography and planning, social capital and social exclusion, and conflict. This analysis identified a number of generalities about spatial pattern and spatial resilience in social systems, including the ideas that (1) spatial fragmentation may drive both market failures (including failures of economic solutions due to violations of assumptions) and political failures; (2) in situations where local and regional benefits may be in conflict, there is a tradeoff in the degree to which institutions and management are decentralised (local government may be more responsive, but regional governance may be better placed to ensure equity and sustainability); (3) social exclusion and marginalization typically have a strong spatial component, and spatial patterns of exclusion can in turn interact with social processes to create feedbacks that may further entrench inequities; (4) social exclusion can increase the likelihood of conflict, thus providing an example in which spatially-structured social fragmentation makes the system less resilient; (5) resilience to conflict appears to reside primarily in institutions, such as treaties, that govern spatial interactions; (6) system resilience may be enhanced by the formation of spatially structured social networks that build social capital across several different scales; and (7) the impacts of social fragmentation on spatial resilience may be either positive or negative, depending on the relative importance of coordinated societal responses on the one hand and maintaining a diversity of perspectives and views, and hence of possible solutions, on the other.

In an interdisciplinary context, Chapter 9 suggested that (1) fragmentation, exclusion, or division of any sort (ecological, social, or economic) almost always has a spatial component; (2) the impacts of fragmentation on diversity, and the role of diversity in fostering resilience to fragmentation events, have similarities in both social and ecological systems but also some differences, particularly in relation to their short-term impacts on regional diversity; (3) issues of scale and the scaling relationships and mismatches between different kinds of hierarchy – social, institutional, economic, and ecological – can have a large influence on the overall performance of a social-ecological system; and (4) the commonalities and differences between social and ecological networks, seen through the lenses of social capital and ecological connectivity respectively, can be analysed together using graph theory in ways that should be highly relevant to the management of social-ecological systems.

Chapter 9 concluded my attempt to provide a broad-brush and somewhat selective overview of the big-picture research agendas and methods that I consider to have the highest relevance to understanding and analysing spatial resilience. Chapter 10 responsed to the anticipated demand for more examples by showing how to use the framework from Chapter 3, and some of the methods discussed in other chapters, to gradually home in on key issues in a given case study (or set of case studies). Chapter 10 considered case study analyses from two perspectives, bottom up (case-driven) and top–down (theory-driven). It started with a general discussion of the spatial resilience of large river basins and then focused more narrowly on quantitative analyses of three particular problems: (1) understanding the broad-scale drivers of fish biodiversity; (2) understanding the relevance of habitat structure for dispersal and population-level processes; and (3) understanding the relevance of functional variation in bird communities for system resilience.

This summary brings us to the present chapter. Having largely completed our tour of spatial resilience, it still remains for me to discuss some overarching themes and then to look forward to the future development of this exciting field of research.

Overarching Themes

The themes that I have outlined in this book show some promising signs of coming together into a single, cohesive body of knowledge about spatial variation and resilience. I am optimistic that further attempts to develop and elaborate on the framework that I have presented will yield a series of fruitful case studies, cross-case comparisons, and additional theoretical development. Many interesting hypotheses relating to spatial resilience have arisen during the writing of this book, and many of these hypotheses are presented for your consideration within the text; at a minimum, refining and testing these hypotheses across a range of social-ecological systems will provide stronger foundations for the science of spatial resilience.

As a counterpoint to this optimism, however, I have become increasingly aware of a set of important tensions that exist within what we think of as science. Some of these tensions may need to be resolved, or at least confronted head-on, before we can progress to a generally accepted body of knowledge about social-ecological systems. In particular, there is a strong divergence of views within the scientific community on what constitutes science and how scientific enquiry should be pursued. The current dominance of traditional disciplinary viewpoints dictates academic career success by determining the availability of funding and the acceptance of papers by top journals. Philosophy provides an overarching point of reference for different disciplines, but practising scientists are often content to ignore philosophical analyses and stick to the relatively safe guidelines of their current disciplinary norms. Philosophical research on the history of science shows quite clearly that the scientific learning system, of which universities and other research organizations are components, has changed greatly over the past 200 years and can be expected to continue to change and adapt. History implies that many of the perspectives that each of us carries out of our school and university training can be expected to become outdated within our own lifetimes. Paradigm shifts may not be common, but they exist. In trying to unite the social, ecological and biophysical sciences to think about social-ecological resilience, we enter a new paradigm and are forced to confront a situation in which an incommensurability of paradigms (Kuhn, 1962) is glaringly obvious. The majority of 'hard' scientists do not trust analyses that are based on attitudes or opinions; although interestingly, many of the same scientists are comfortable with applying frequentist statistical approaches and linear models to project environmental trends, such as deforestation and species loss, that are primarily driven by people. Conversely, many sociologists are uncomfortable with attempts to make statistical generalisations about social behaviour, particularly if the details of intentionality and social and institutional influences on individual freedoms are poorly understood. When we attempt to unify ecology and sociology, or ecology and economics, resistance is encountered on all sides; ecologists find the human elements of the study difficult or too vague to incorporate within an ecological model of how research should be done, and social scientists are often unhappy with the coarseness of statistical averaging, either for or against assumptions of consistent and rational behaviour, and concerned about the downplaying of the relevance of values and attitudes (and other things that are hard to measure) that social-ecological studies frequently seem to demand.

This conflict in social-ecological analysis raises some profound questions: how should we do science if we wish to include perspectives from a number of different disciplines, each with their own norms and standards? And more specifically, should ecologists, economists, and social scientists do science differently if they are dealing with social-ecological systems? I do not think that there are easy answers to these questions, and there should certainly be no suggestion of lowering standards or accepting dubious assumptions simply because research is interdisciplinary. As I worked my way through some of the material in this book, however, it became more and more apparent that most 'hard' scientists view themselves as working in an arena in which the *process* of research (as opposed to the methods) is in many ways irrelevant to the results that are obtained. Science is perceived as being primarily a goal-oriented activity. By contrast, social scientists have had to think a great deal about how they collect data and how they interact with their study communities. As Adger and Jordan explain in their recent book, in social systems it matters a great deal *how* a particular outcome is reached (Adger & Jordan, 2009); the same endpoint can be attained in different ways, but its viability thereafter is strongly conditional on the nature of the preceding and subsequent social and political processes (see also Cronon, 2000). If we want the science that we do to influence social-ecological systems and solve real-world problems, social-ecological scientists will have to start paying more attention to the research process and to finding ways to link science and social processes without compromising on scientific rigour and quality.

Writing this book has also made me think more deeply about theory and its role in the scientific process of discovery. There is an inherent tension within many disciplines between theory and application. I think of this in a simplistic way as the difference between being upward-looking and downward-looking. If I constantly scan the horizon, I am better equipped to see where I am going and to respond well in advance to potential problem situations. I am also more likely to lose my footing, to miss important details on the ground, and to fail to see things that are in front of my nose. By contrast, if I spend most of my time looking down, I am well equipped to deal with my immediate environment but far more likely to get lost. To make good progress, I need to spend time on both activities: looking at the horizon and thinking big-picture thoughts about where I am going, why, and how I will get there; and watching where I put my feet, learning from signs along the way, and accumulating relevant knowledge.

The tension between theory and application emerges quite clearly throughout this book. Although a balance between upward- and downward-looking approaches is ideal, most subdisciplines (and inded, most practitioners) tend more towards one or the other approach. In some cases, such as network analysis and land cover change analysis, subdisciplines have arisen out of an interest in taking and applying a particular method or approach in the context of social-ecological systems. The challenge in these situations is to ensure that the problems that are opened up by the method become the focus of analysis, rather than merely applying the same methods to different data sets to show, over and over again, what the method can do.

In other cases, such as game theory, the primary focus has been on theoretical questions and empirical tests have followed later (or not at all, as the case may be). The chapters of this book that focus on method-based approaches generally have less to say than the theory-based chapters about general principles for spatial resilience, although in the examples discussed here, the potential for further contributions out of fast-developing method-based fields is very clear. I suspect that in many cases the required shift in focus may be as simple as noticing that specific models can be used to test theoretical generalities. In the hubbub of developing a recommendation for a water management agency, for example, tests of theory may be as simple as finding the time to explore what the model says about alternative stable states if some of its key feedback mechanisms or drivers (e.g., ground water contributions or evapotranspiration rates) are altered outside the range of what is currently considered normal. Such activities do of course depend on having a prepared mind and the necessary background to know which overarching questions can be analysed with the model in question, as well as which having the time to think about which questions would be interesting and novel to explore further.

Where to?

Assuming that the study of spatial resilience can resolve the quandries raised by paradigm incommensurability and achieve a suitable balance between upward- and downward-looking perspectives, what constitute the major challenges and directions for future research in this area? Future challenges for the study of spatial resilience can be summarized under three main headings: (1) theoretical development, (2) methodological development, and (3) translational development.

Theoretical Development

The central challenge for the theoretical development of spatial resilience is the formulation of better, more insightful frameworks that connect different pieces of theory together to provide insights into the roles of space and spatial variation in social-ecological resilience. Although the framework presented in this book offers a starting point from which to build, it is deficient in any number of ways, the most obvious being its focus on description rather than on mechanism.

The study of spatial resilience is intricately linked to the study of resilience in general. These areas of study should ideally develop in a two-way partnership, with analyses of resilience paying greater attention to the role of space and the analysis of spatial resilience translating theoretical developments in the study of resilience into more concrete, spatially explicit terms. Ultimately, spatial resilience may be able to do for the study of resilience what island biogeography did for community ecology, in the sense that it should provide clear and testable explanations of important patterns in SESs (such as the diversity of different elements) against which alternative hypotheses can be usefully contrasted.

Spatial resilience also has the potential to act as a unifying theme for different areas of spatial research. For example, it should be possible to use the concept of spatial resilience to unify perspectives from network theory, metacommunity theory, evolutionary biology, fragmentation analyses, and land use and land cover change studies. Some of these connections are spelled out in this book, but many remain to be further explored and developed.

There are many specific areas of spatial resilience theory that are strongly in need of further development. I have touched on a number of these, to varying degrees of detail, through this book. For example, spatial aspects of evolutionary and adaptive processes are underexplored in analyses of SESs (although some intriguing approaches to adaptive dynamics are under development; (see Dieckmann, 1997; Egas, Sabelis, & Dieckmann, 2005)); we lack the theory that would enable us to deal conceptually with the simultaneous analysis of multiple feedbacks and thresholds; we lack a theory of scale and scaling in SESs; and many of the relationships between structure and function in complex systems are still unclear. In each of these cases, theoretical development will need to occur gradually and carefully through a classical process of hypothesis formulation and rigorous empirical testing.

Methodological Development

Progress in the analysis of spatial resilience will also depend on further methodological advances. Methodology encompasses both the specific approaches that we adopt for doing science (e.g., statistical and modelling tools) and the more general question of how the analysis of social-ecological systems should be undertaken.

Although we have many useful tools already in hand, the fundamental complexity and non-linearity of social-ecological systems makes many 'standard' analytical methods useless. Some of the most important methodological advances come more from the development of new ways of organizing the process of enquiry than from the creation of specific statistical or model-oriented approaches (Checkland, 2009). I particularly like the concepts of 'triangulation', as explained by Plowright, Sokolow, Gorman, Daszak, and Foley (2008), and cross-scale comparisons (Cumming, 2007). These approaches suggest that to achieve a consistent perspective on a complex, multi-scale system, it is necessary to pursue several different lines of exploration at several different scales. For example, in trying to understand the movement patterns of nomadic southern African waterfowl, we have been trying to piece together evidence from genetics, ringing (banding) recoveries, bird counts, satellite telemetry, atlasing efforts, stable isotope analysis, and simulation models. Each of these different approaches to understanding waterfowl biology offers different and complementary insights. Ultimately, as in reconstructing a crime scene, they should tell a single, consistent story.

Many studies of SESs use participatory approaches to identify, characterize, and solve management-related problems (e.g., Chambers, 1994; Mahanty & Russell, 2002; Tabara & Pahl-Wostl, 2007; Walker et al., 2002). Although most participatory approaches have an internal set of rules for how they should be applied, the application of a participatory approach is broader than the method itself. The decision about which method to use – scenario planning, for example – represents an active choice on the part of the problem solver and leads on to a further range of choices about who should be invited to participate and how the problem-solving process should be structured. Potential participants will in turn decide to opt in or out of the problem-solving process at different stages. All of these decisions may be critical to the outcome of the process, but they are seldom discussed or quantified in any comparable way (but see Pahl-Wostl et al., 2007). If a science (or a better sociology) of participatory management were to be developed, it could in theory offer better ways of both designing the process and quantifying and comparing successes and failures.

Another area in which methodological development is needed is that of the incorporation of case studies into a resilience framework. In ecology, quantitative meta-analysis of experiments and data sets collected by different researchers has a high potential to yield new and general insights (e.g., Houlahan et al., 2007). Unfortunately, the lack of standardisation and disciplinary norms in many areas of social-ecological research means that the majority of case study data sets can not be quantitatively compared. Spatial analysis has the potential to provide an integrative framework, given a consistent set of sampling procedures; but in my own experience, even getting researchers in other disciplines to agree to collect spatially explicit data (e.g., recording coordinates of interview locations or markets) at a comparable grain and extent to that of ecological data can be challenging. Similarly, comparisons between different land-use and land cover data sets can be made far harder than they need to be through the use of novel classification criteria and a failure to follow standard protocols (e.g., corrections for haze and vegetation greenness) for processing and comparing satellite images. Considerably more thought thus needs to be given within the study of spatial resilience to developing, maintaining, and sharing high quality data sets that offer genuine cross-case comparability between and within disciplines.

Given that many of the more tangible results of social-ecological analyses appear to be contingent on the analytical process and the values of the people who undertake the analysis, we also need better ways of assessing data collection protocols and the successes and failures of particular processes. For instance, scenario planning exercises may be published (and presented to policy makers) as participatory outcomes when in reality, they have been captured by a small minority of participants and do not reflect a majority consensus. Similarly, assessment tools for the quantification of the use of ecosystem services by a local community require more stringent standards and common protocols if they are to be genuinely comparable. Without clearly defining the criteria for success, it is difficult for these methods to be improved.

In the domain of modelling there is an obvious need for researchers to spend more time developing analytical tools that reflect the potential of a complex system to change its internal rules. Some of the more promising approaches in this area come from the emerging fields of genetic programming and genetic algorithms (Holland, 1992; Mitchell, 1996) as well as multi-agent models (Bousquet et al., 2007; Janssen, 2002). Genetic algorithms at present are mostly used to find optimal solutions to clearly specified problems. However, the fact that they simulate the mechanisms by which most complex systems adapt (i.e., iteratively selecting the best solution from a set of possible solutions) suggests that they should also be useful for exploring fundamental questions about complexity. For example, training a genetic algorithm over multiple iterations using a dynamic test data set (i.e., one that changes with each successive iteration) can result in selection for a robust or resilient solution, rather than one that is optimal under a steady-state set of conditions. Resilience theory in general has been slow to take on questions of evolution and adaptation, which have the distinction of being both vitally important and heavily under-studied.

Lastly, the development of monitoring protocols that deal with social as well as ecological systems remains an important need in the study of spatial resilience. Monitoring provides a feedback mechanism that is essential for learning. As Peter Checkland pointed out many years ago (Checkland, 1981), one of the most important perspectives in working with systems that have a substantial human component – as SESs do – is to see one's goal as being to develop a learning system, rather than a single unique solution. For the study of spatial resilience, monitoring means not only tracking spatiotemporal variation in relevant social and ecological patterns and processes, but also developing ways to monitor and respond to emergent aspects of the system, such as its adaptive capacity or its ability to provide ecosystem services at the locations where those services are needed.

Translational Development

Translational development is a term that I have coined for this summary. As explained by Pickett, Jones, and Kolasa (2007), translation modes 'are required to relate the abstractions made by laws, generalizations, and conceptual or quantitative models to the field or to experimental systems relevant to the theory'. A lack of translational development has been an important limiting factor in the study of resilience. For instance, I have seen many students become excited by resilience-related concepts, such as the adaptive cycle, and then encounter a series of frustrating difficulties in trying to apply them to real-world study systems. Workshop-based attempts to apply resilience theory can be equally frustrating, with participants struggling to apply theoretical constructs to their own systems.

We currently lack objective ways to learn from and about attempts to apply theories in different contexts and in different ways. Many of the broader concepts involved in thinking about spatial resilience are conceptually difficult, lack specificity, and can be interpreted in a number of different ways. These problems can make them difficult to use in a participatory problem-solving context. Theoretical ideas such as thresholds and feedbacks require translational modes that allow people across a wide spectrum of ability to work with them and apply them correctly in particular situations. For example, the development of simple models in a problem situation can offer people one way of converting abstract ideas into tangible outcomes (Box 11.1).

Box 11.1 Translation: Taking a Model from Theory to Measurement

Attempts to apply resilience theory to specific case studies often share common elements. In some cases, getting to the core of a problem can be as simple as placing the situation in a well-studied context and identifying the similarities and differences that are present in the focal system. For example, many readers will be familiar with the idea of a 'tragedy of the commons' dynamic, in which a shared resource (such as a pasture used for grazing by several different livestock owners) is gradually depleted because the distribution of short-term gains is uneven and long-term gains are unlikely to be realised if one individual choses to overexploit the resource. Identifying the problem in a given case study, such as a fishery, as a 'tragedy of the commons' case immediately provides a background literature and a set of solutions that have been tried and tested in other cases.

The tragedy of the commons is just one of a number of archetypal management syndromes. Peter Senge lists another eight, with such evocative titles as 'success to the successful' and 'shifting the burden' (Senge, 1990). These archetypes can offer a useful way of bridging the gaps between theory and practice. For example, during a class exercise on management, one of my then students (Ivan Diaz) gave an example in which people in Chile were felling rainforest for short-term gains while gradually eroding the ecosystem on which they depended (Fig. 11.1). This example fits Senge's 'Fixes that fail' model.

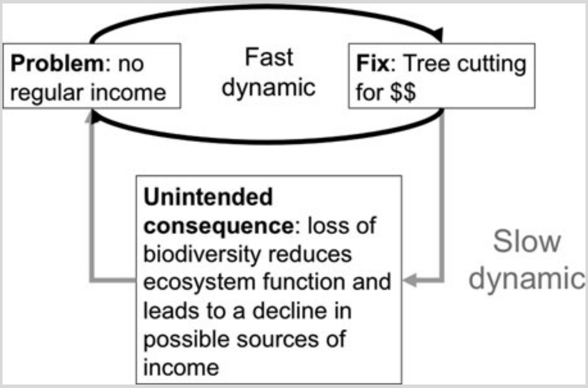

Fig. 11.1 Schematic diagram summarising 'fixes that fail' model as implemented for forestry example

To work with Fig. 11.1, we must first think about the ingredients of the system. Its components include people, trees, and money, as well as something a little more vague that we term 'ecosystem function'. The system has two fundamental speeds: a set of fast variables, driven by people cutting trees to generate income; and a set of slow variables, including tree growth and a decline in ecosystem function.

To model this dynamic, we need to be specific about elements and relationships. We start by assuming that the number of people in the community is constant at the time scales that matter – so, 'people' can be captured by a single integer with a magnitude around 50. The number of trees ('Trees') gradually declines over time, and relates to the number of people. If each person on average cuts a tree every 10 days, we have a simple linear function describing the decline of trees over time. Next, we need to think about ecosystem function. Again for the sake of this model, we assume that ecosystem function (Eco_function) depends on the number of trees according to a species area-like relationship, defined by the function $y = cT^z$ where T is the number of trees and z, c are constants between 0 and 1.

We then need to include an estimate of the quality of life of a person living in the community. Suppose that the return from cutting a tree increases average life quality because more income is available; while a decline in ecosystem services (wood, water, fibre) decreases life quality. As a starting point, let's relate mean quality of life for our 50 people directly to the total number of trees cut, by saying life_quality = 1,000-trees; and then add in the component of quality of life that depends on ecosystem services by saying that life_quality = 500*Eco_function.

This leaves us with the following model parameters:

Constants: people = 50; Start_trees = 1,000; Values of *c* and *z* between 0 and 1

Variables: T = time (current time in simulation); Trees = 1,000–1/10*50*t = 1,000–5t; Eco_function = 0.5*Trees^0.3; life_quality = 1,000-trees + 500*Eco_function.

The results from each of these equations can easily be calculated for increasing values of T, giving rise to the curve below (Fig. 11.2).

As this curve shows, the model parameters (which of course, have been sneakily selected by me to achieve this effect) produce a situation in which quality of life initially rises with tree cutting but then undergoes a dramatic decline – a 'surprise' – as the slow variable takes command of the system.

This model is obviously not directly representative of reality. Further research and real data would produce more realistic equations that better describe the different dynamics here, and the addition of greater realism might change the outcome considerably. However, despite its simplicity, the value of this kind of model as a translation mode for resilience theory should not be

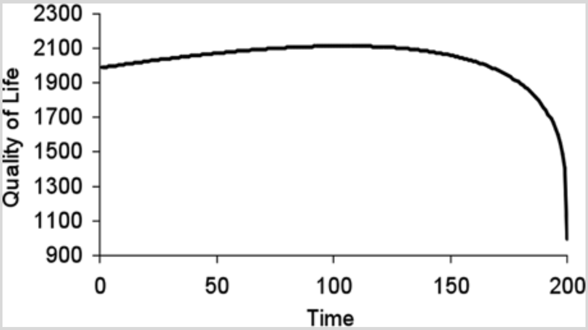

Fig. 11.2 Plot of quality of life against time, as produced using the parameters outlined in the text. Note the 'surprise' crash around iteration 150

underestimated. It provides an accessible demonstration of how short-term resource depletion can lead to unexpected ecological collapse, and it can be encoded in an Excel spreadsheet in which the consequences of changing different parameters (e.g., increasing harvest rates or numbers of people) can easily be explored. In a workshop situation, a simple model may be all that is needed to explain to participants the fundamental nature of a resource management problem.

Concluding Comments

Spatial resilience is a young and fast-growing area of research. It is an important element of an equally fast-growing interest in complexity and resilience. We are currently witnessing an explosion of new ideas and approaches to studying and understanding systems of people and nature. In the midst of this excitement, and with the growing awareness of a paradigm shift in how we understand the world, it is easy to become distracted by the intricacies of case studies and the minor distinctions between different terms and concepts. However, what the study of social-ecological resilience needs most, and more than ever, is the gradual development of generalities: hypotheses, laws, and principles that will allow knowledge gained from one case study to be connected to the broader body of resilience theory and applied in other case studies without the need for continual rediscovery and reinvention.

The study of spatial resilience already has a rich history and background on which to draw. Spatial relationships are being increasingly studied in many disciplines, and those which have largely ignored space are slowly beginning to realise its relevance to the fundamental processes that underpin social-ecological systems. In this book I have outlined a framework for thinking about the spatial aspects of resilience and its relationship to the more general topic of resilience. To further advance the discipline, however, will require research that explicitly targets the further theoretical development of this framework (or a better one!) and fleshes it out while also ensuring that it is grounded in rigorous, critical tests of models and hypotheses and based on solid, real-world data.

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