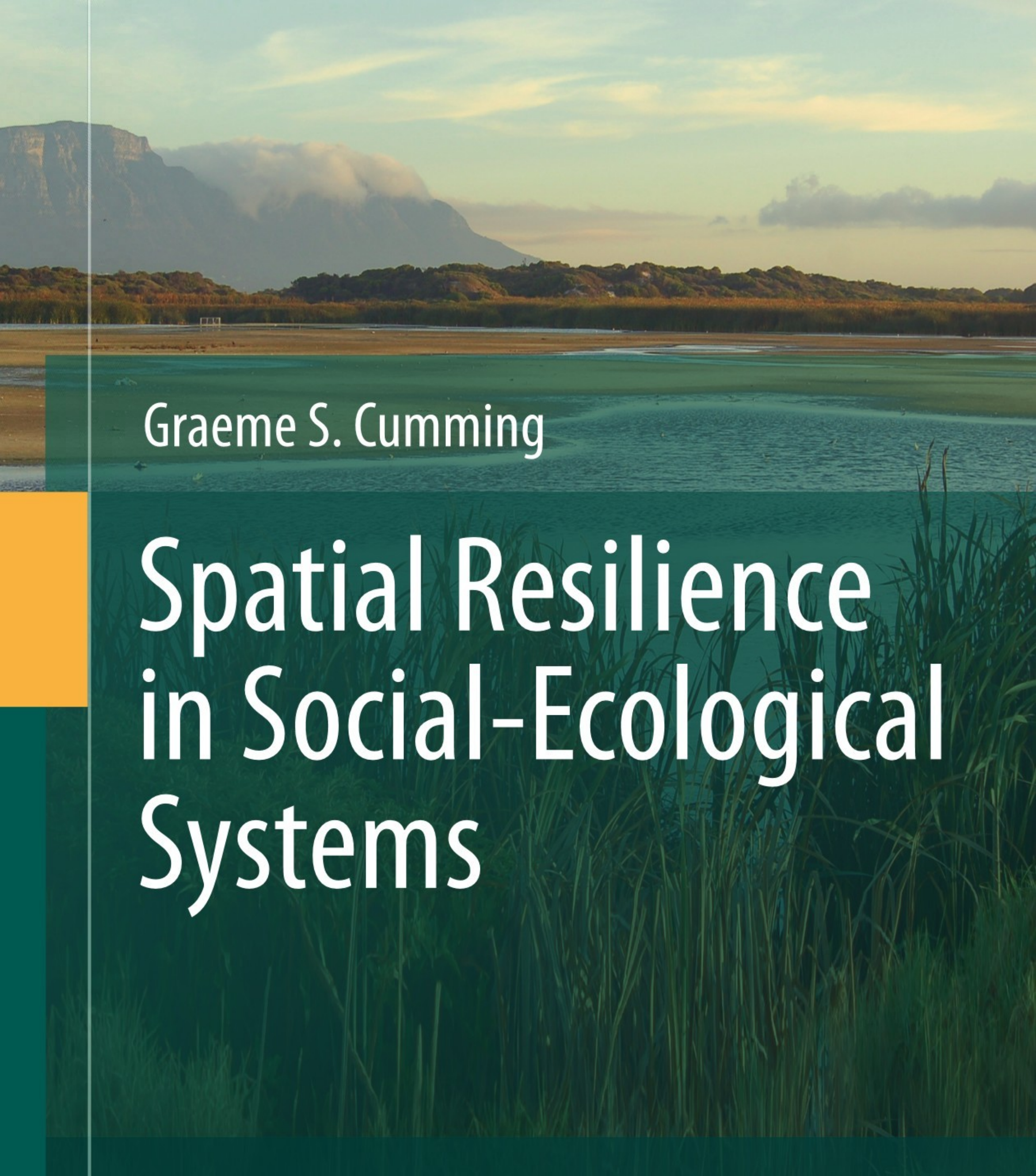

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Spatial Resilience in Social-Ecological Systems

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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