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Chapter 6
Principle 4 - Foster Complex Adaptive Systems Thinking

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Summary
The social-ecological systems that provide ecosystem services to society can be viewed as complex adaptive systems (CAS), characterised by a high level of interconnectedness, potential for non-linear change, and inherent uncertainty and surprise. This chapter focuses on whether resilience of ecosystem services is enhanced by management based on what we refer to as "CAS thinking," meaning a mental model for interpreting the world that recognises these CAS properties. We present evidence that CAS thinking has contributed to change in management approaches in the Kruger National Park, Great Barrier Reef, Tisza River Basin, and Chile among other places. However, attempts to introduce CAS thinking may compromise resilience when complexity is not effectively communicated, when uncomfortable institutional change is required, or when CAS thinking is not able to evolve with changing contexts or is not equitably shared. We suggest that CAS thinking can be fostered by adopting a systems framework; tolerating and embracing uncertainty; investigating critical thresholds and non-linearities; acknowledging epistemological pluralism; matching institutions to CAS processes; and recognising barriers to cognitive change. Key questions for future research on this principle relate to communicating CAS thinking, the role of power, importance of organisational level of CAS thinking, and institutional barriers.

6.1 Introduction
The social-ecological systems (SES) that provide ecosystem services (ES) to society can be viewed as complex adaptive systems (CAS) (Walker *et al*. 2002; Levin *et al*. 2013). As discussed in Chapter 1, CAS are made up of many interacting components that are individually and collectively adaptive to change, enabling them to self-organise and evolve, and often yielding emergent properties at different scales (Norberg & Cumming 2009). Furthermore, CAS may shift between alternative regimes, often abruptly and irreversibly (Scheffer *et al*. 2001; Scheffer & Carpenter 2003), resulting in a system that looks, behaves

and delivers ES in an entirely different way than before (P3–Slow variables & Feedbacks). These features make aspects of CAS highly uncertain, and therefore challenging to predict and control. Yet understanding and managing CAS is not inherently beyond our capabilities, and long traditions of research and practical experimentation have helped to reduce some important aspects of uncertainty (Lee 1993). However, to understand CAS is to accept that some facets of their uncertainty are irreducible due to unpredictability, incomplete knowledge, or multiple knowledge frames (Levin 2003; Brugnach *et al*. 2008), and that this demands adaptive management approaches (Walters & Holling 1990; Lee 1993; P5-Learning) that can account for these uncertainties.

The resilience of an SES is partly driven by decisions taken by actors – the resources users, managers and policy makers – within the system. To understand SES therefore requires understanding how actors within the SES think (Jones *et al.* 2011). One way of understanding this is through the lens of mental models, or cognitive frameworks used to interpret and understand the world and decide on appropriate actions (Bower & Morrow 1990). Like worldviews, which describe a collection of ideas and theorems that allow one to construct a composite image of the world and understand one's experience and how one should act (Aaerts *et al*. 2007; Vidal 2012; Gratani *et al*. 2014), mental models are not only individually held but are also shared. This concept of shared or collective mental models (Abel *et al*. 1998) acknowledges the social aspects of individual cognition and decision making (Jones *et al.* 2011). Furthermore, collective mental models and worldviews are culturally constructed, and function as schema (Quinn 2005) that describe and make meaning of understanding and experience among particular groups. They may be tacitly held as well as formalised and expressed through paradigms and discourses, or negotiated ways through which a society apprehends the world (Dryzek 2005) through language, metaphors and power structures.

Mental models have been the subject of cognitive science and psychology research for more than 70 years (Craik 1943), but the application of mental models concepts in an SES context is relatively recent (Jones *et al*. 2011). While mental models are variously defined (Doyle & Ford 1998) there is general agreement about some key features:

- Mental models are the cognitive structures upon which reasoning, decision making, and behaviour are based. They are internal representations of external reality (Jones *et al*. 2011).
- As 'models' they describe relationships between system parts or phenomena, which distinguishes mental models from perceptions and attitudes, the focus of much behavioural research relevant to SES.
- Mental models can be thought of as 'habits of mind' (Rogers *et al*. 2013) that represent a pattern or cluster of cognitive behaviour that leads to action.
- Mental models are 'working models' and are always partial and limited views of the world. They are dynamic and context-dependent, and therefore often evolve over time. Thus, someone with a CAS mental model can have a more or less complex understanding of, and approaches to, problems in an SES which can change in response to different prompts.

Understanding the different mental models that people have can help to delineate different conceptualisations of how a system works: the interactions between factors or components, the critical issues, and the causal links (Lynam & Brown 2011). Importantly, current mental models theory and approaches extend beyond simplistic 'information-deficit' models that assume knowledge influences awareness which in turn influences behaviour (Kollmuss & Agyeman 2002). Mental models thinking aligns with more sophisticated conceptualisations

that posit multi-dimensional relationships between cognition (what we know), affect (what we feel) and behaviour (what we do) (e.g. Lorenzoni *et al*. 2007). Thus, a mental models approach offers insight not only into how managers understand an SES but also how a manager might act and how he or she perceives the responsiveness of the SES to such management actions.

6.2 What do we mean by fostering CAS thinking?

This chapter is about how people, individually and collectively, *think about* and *make sense of* SES dynamics, and how this sense-making influences SES management in ways that enable society to benefit from a range of ES without undermining the SES that provide them. This way in which individual people and collective societies make sense of SES can be seen as a mental model or worldview. In particular, this chapter focuses on whether resilience of ES is enhanced by management of SES based on CAS thinking. Management that views SES as CAS is thought to enhance the resilience of ES by emphasising holistic (rather than reductionist) approaches, the management of multiple ES and trade-offs in an integrated way, the importance of managing at multiple temporal and spatial scales, and the existence of lags and feedbacks in SES dynamics (P3–Slow variables and feedbacks) (Holling & Meffe 1996; Pahl-Wostl 2009; Levin *et al*. 2013). A CAS approach also emphasises the substantial uncertainties surrounding SES and, therefore, the need to continually learn and experiment (P5-Learning) and adaptively manage uncertainty, disturbance, and surprise rather than attempt to eliminate it (Gunderson *et al*. 2002; Chapin *et al*. 2009). Fostering CAS thinking therefore does not directly influence the resilience of ES but changes and adapts the cognitive foundations and paradigms that underpin management processes and decisions. That is, acknowledging that SES are based on a complex and unpredictable web of connections and interdependencies is the first step towards management actions that can foster resilience.

The characteristics of CAS thinking are perhaps easiest to grasp when they are contrasted with other mental models. Prevailing mental models of how ecosystems function have shifted over time (Table 6.1), in line with advances in education, science, technology and socio-cultural change. Religion, classical economics, politics and industrialisation have each provided the intellectual foundations that through much of history have underpinned a quest to analyse, understand and control nature (van Doren 1992; Wallace *et al*. 1996). By controlling nature, it was believed that uncertainty could be reduced and outcomes predicted, establishing a basis for agricultural, industrial, and social development (Holling *et al*. 2002). Mental models focused on linearity, determinism and the primacy of humans over nature remain deeply entrenched in the norms of business, academia and policy (Ludwig 2001) and are the foundation of highly mechanised resource management systems such as plantation forestry, monoculture farming, and large-scale commercial fisheries (Holling & Meffe 1996). Until relatively recently, ecologists advocated an equilibrium worldview (Holling *et al*. 2002) which guided resource management agencies and broader society's thinking about SES. With time it became evident that the view of nature 'in balance' and management through stabilisation often led to decline in ES over the longer term.

In this chapter, we define CAS thinking as a mental model or worldview that views SES as CAS and appreciates the resulting implications for management. Key CAS properties in this regard include a high level of interconnectedness; potential for non-linear change; inherent, and to some extent irreducible, uncertainty (which can lead to surprise); and a multiplicity of perspectives within SES. Rather than attempt to reduce uncertainty and surprise, CAS thinking embraces these as opportunities for positive motivational change (Janssen 2002; Cilliers *et al*. 2013). Other fields, such as the health care industry, have recognised this

positive impact of CAS thinking, whereby "the attitude toward surprises can become one of approach and exploration rather than avoidance and defense" (McDaniel *et al*. 2003: 267). A CAS worldview acknowledges that attempts to smooth the variable rhythms of SES to achieve management objectives often result in unintended consequences. Today, SES management increasingly recognises that one of the key challenges facing policy makers, scholars and practitioners is to understand and anticipate the dynamic behaviour of a CAS that result in 'wicked problems' with neither a definitive formulation nor clear solutions (Ludwig 2001).

CAS thinking is not new. Aspects of CAS understanding and approaches are evident in some of the longstanding practices of small-scale farmers (Ishizawa 2006), traditional resource users (Moller *et al*. 2004), and nomadic herders (Fernandez-Gimez 2000). They are integral to traditional ecological knowledge systems (Berkes *et al*. 2000) and holistic frameworks to describe and support relationships between people and the environment (Salmón 2000; Turner *et al*. 2000; Walsh *et al*. 2013). CAS mental models are also present in some 'mainstream' natural resource management that adopts adaptive management and co-management approaches. In these contexts, the process of development of the collective CAS mental model is important, as it may be critical for building mutual understanding amongst stakeholders (Abel *et al*. 1998; Biggs *et al*. 2011a; Jones *et al*. 2011) (P5–Learning; P6-Participation).

6.3 How does CAS thinking enhance the resilience of ecosystem services?

Much of what we assume about how CAS thinking can enhance resilience comes from cases where conventional resource management – lacking an appreciation of how CAS function – has resulted in a loss of SES resilience. A litany of examples suggest that management practices that optimise provision of a narrow set of ES on the basis of linear, reductionist worldviews of ecosystems inadvertently undermine the ability of these systems to continue producing ES in the face of disturbance and change. The pervasiveness of ecosystem modification in the U.S. for many decades led Holling & Meffe (1996) to describe a 'pathology of resource management' entailing practices such as river stabilisation, fire suppression and monocultural farming to the point of system collapse. Such a pathology also characterises the Gariep basin in South Africa (Bohensky & Lynam 2005), the Western Australia wheat belt (Allison & Hobbes 2004), and the Goulburn Broken catchment (Walker & Salt 2006). Each SES was narrowly managed to maximise agriculture-based economic production in the short term but this management approach ignored the underlying capacity of the system to produce ES. As a consequence groundwater tables were drawn down, land was degraded, rivers were transformed and polluted. Agriculture, as the backbone of these regional economies, contributed to well-being and underpinned social development, but because it was unsustainable, was ultimately at great ecological and social expense. Similarly, widespread mismanagement of fisheries (Mahon *et al*. 2008) and forests (Agrawal 2005) is partly attributed to forms of management based on technical, reductionist, and one-size-fits-all approaches. This management style was not limited to production systems; protected areas too were managed as 'islands' with narrow functions of strict wildlife preservation or recreation, without considering a broader range of beneficiaries or landscape connectivity within and beyond park borders (Cundill & Rodela 2012). These cases suggest that an alternative management style based on a worldview that recognises CAS properties may result in more resilient ES in the long term, because it considers consequences at a system level, across time, space and actors.

Though generally less visible than these management 'failures', cases exist where CAS thinking has contributed to improved social-ecological outcomes through resilient ES. Examples of transformations in ecosystem management suggest that changes in underlying mental models that acknowledge the characteristics of SES as CAS can lead to improvements in the resilience of ES. One example is the large-scale rezoning of Australia's Great Barrier Reef (Box 6.1), driven by increased recognition of the importance of connectivity, nonlinear change, and multiscale interactions in coral reef systems (Olsson *et al*. 2008). The aim of the rezoning was to enact spatial restrictions on fishing and other uses to enhance the resilience of ecosystem functions to a range of perturbations including temperature anomalies and cyclones. This approach addressed CAS properties in two ways: by maintaining connectivity within the reef system and increasing the system's capacity to absorb large disturbance, and importantly, by recognising the values and perspectives of different reef users. Ecological monitoring and experimentation indicated that the reef's marine ecosystems were more resilient to climate change impacts where herbivorous fish assemblages are intact, thus improving the reef's ability to provide a diversity of ES (McCook *et al*. 2010). More recently, management is taking a more expansive view of the roles of humans in the reef system, for example, by supporting a long-term monitoring program that considers human drivers (Marshall *et al*. 2013). Despite this, CAS thinking within the primary management agency may be insufficient to address some of the external pressures that originate outside the marine park's boundaries, such as climate change and industrial coastal development (Bohensky *et al*. 2011). Thus, while CAS thinking has influenced policy in the Great Barrier Reef, the problem domain has become increasingly complex, as drivers become more multi-scale in nature and stakeholder views more factious (Brodie & Waterhouse 2012; Brodie 2014).

In South Africa's Kruger National Park, increased emphasis on the value of variation in maintaining biodiversity has led its managers, South African National Park (SANParks), to move away from objectives that aim to keep ecosystem conditions, such as elephant populations and fire frequencies, fixed at optimal levels (Biggs *et al*. 2011b; Cundill & Rodela 2012). Instead, elephant numbers and fires are now allowed to fluctuate between specified boundaries (Biggs & Rogers 2003). Thresholds of Potential Concern are developed to identify and monitor triggers of change and anticipate regime shifts, functioning as 'amber lights' that signal to managers that a component of the system (e.g. elephant numbers) is approaching a critical point. Thresholds of Potential Concern and strategic adaptive management are credited with making Kruger a functional adaptive management site that supports a range of ES including greater variation in faunal diversity, fire regimes, vegetation and river flows (Biggs & Rogers 2003). This shift has reduced the human investment needed to manage ecosystems and has increased the variety of ecosystem and habitat types, as well as the opportunities for specialist species that support particular ES. SANParks has also recognised the need to incorporate human preferences, behaviour and institutional responses more explicitly into the Thresholds of Potential Concern concept (Biggs *et al*. 2011b). However, as in the Great Barrier Reef case, SANParks' approach is unable to entirely mitigate impacts on biodiversity that originate beyond its borders, such as extraction from rivers upstream.

In Europe, water management is embracing CAS thinking. Projects such as NeWater (New methods for adaptive Water management under uncertainty) sought to improve the scientific foundations of adaptive and integrated water resource management and support transitions from historical management regimes (Pahl-Wostl *et al*. 2009). For example, in Hungary, NeWater studied how a shadow network of scientists and local activists in the internationally-shared Tisza River Basin evolved over several decades around a set of dialogues about

alternative river management in response to extreme flooding, water quality decline and lost productivity (Sendzimir *et al*. 2008). Using participatory system dynamics modelling tools in its dialogues to develop a CAS understanding and incorporate multiple views into river management practices, the shadow network sought to understand what factors have obstructed or enabled transformation of the current river management regime from one focused on transport and flood mitigation to one able to maintain biodiversity and land management practices. In this way, a participatory forum (P6–Participation) was key to the development of a shared CAS worldview. These dialogues also learned from the experiences of Germany and the Netherlands, where a CAS approach initiated a new governance paradigm termed 'living with the river', which encourages the reallocation of land for floodplains, to allow water to ebb and flow across space and time (Sendzimir *et al*. 2008).

Despite the above examples that demonstrate that CAS thinking contributes to ES resilience, there is scant evidence that enhanced resilience can be directly attributed to CAS mental models. This owes in part to the indirect influence of CAS thinking on management and subsequently changes in resilience. That is, it must be demonstrated first that CAS thinking exists among the relevant actors, and secondly that it influences current management practices and subsequently effects a positive change in resilience. Much of the science underpinning contemporary CAS thinking only emerged in the late 1970s, and began guiding management even more recently. In many cases it is too early to assess the extent to which CAS thinking is guiding management or catalysing change. Some evidence shows that CAS thinking can trigger a change in management approaches but has not yet had demonstrable effects on the resilience of ES, or only limited change in some ES. Such an outcome seems to apply in the Great Barrier Reef and Kruger cases, where broader-scale drivers are beyond the influence of the key agency. In other cases a CAS approach is helping to build shared understanding and, by incorporating multiple perspectives, is creating social capital, such as in the Tisza River Basin through the shadow network dialogues, but is yet to lead to management changes (Sendzimir *et al*. 2008).

6.4 Under what conditions may resilience of ecosystem services be compromised?

While CAS thinking in itself may not compromise resilience, *attempts to foster* CAS thinking may compromise resilience in SES. For scientists and managers, communicating and applying the concepts of CAS in ways that do not create a sense of bewilderment and paralysis remains a key challenge in practical ecosystem management settings (Cilliers *et al*. 2013). Managers may be motivated by political expediency, and tried and tested 'simple' approaches may appear less risky than those that are unfamiliar, run against the grain of agency practice, and threaten the status quo (Gunderson *et al*. 2002). Moreover, 'complexity' can be interpreted in ways which do not reflect an appreciation of the fundamental properties of CAS. For example, complexity sometimes implies all dimensions of a system that are not yet understood (Holling 2001). When combined with reductionist views about the need to eliminate uncertainty before taking action, such interpretations may lead managers to invest heavily in monitoring and data collection for variables and relationships thought to be important, rather than encourage the use of adaptive approaches that allow for experimentation and the probing of boundaries as a mechanism to address uncertainty (Walters & Holling 1990). In these situations, management styles and problems that erode resilience may persist, sometimes amid the belief that complexity is being addressed.

Secondly, attempts to foster CAS thinking may also compromise resilience because a CAS framework implies a more integrated approach that is difficult to address across governance units that are often separate (e.g. departments of water and land). Successful integration

seems to require significant investment in multi-agency coordination and sometimes new institutional arrangements that enable CAS thinking and practice to thrive (Bohensky & Lynam 2005). In addition, a CAS approach often implies a change in management paradigm from a focus on causality and control within short time frames, to a focus on coping with change and uncertainty over longer time scales. Such a management shift may be difficult to operationalise in contexts that focus on accountability and meeting targets (Pahl-Wostl 2009). Such changes may threaten the incentive structures agents have learned to navigate, creating new uncertainty and anxiety. These challenges may be long enduring (e.g. inequitable distribution of costs and benefits across society) and ultimately detrimental to ES resilience. Transitions to new management paradigms may also involve temporary, albeit uncomfortable, "excursions into lowered resilience to cross to another…stability domain" (Sendzimir *et al*. 2007: 602). For instance, Sendzimir *et al*. (2007) describe how the transition from intensive to organic agriculture in the Tisza River Basin involved a seven-year lag before financial benefits were realised.

Thirdly, attempts to foster CAS thinking can compromise resilience when a CAS mental model is deliberately or inadvertently treated as static, intended to assist transition to a new management paradigm which is seen as the end point. The implications of this are that continued knowledge-building, experimentation, and adaptation are not pursued. Gelcich *et al*. (2010) observed such a situation in Chile following transition to a national benthic fisheries policy, the Management and Exploitation Areas for Benthic Resources (MEABR). Though the new policy – by redefining rights to fish for the socially and economically important artisanal fishing sector – was lauded as 'transformative', avenues for continued experimentation and social learning were not maintained, thereby limiting the potential for future adaptations or transformations. A CAS worldview did not continue to evolve alongside the ever-changing SES, highlighting the importance of a supportive institutional environment for fostering CAS thinking. The Chilean case is not unique; such an outcome has also been reported in the Tisza River Basin (Sendzimir *et al*. 2010).

Lastly, ineffective attempts to introduce CAS thinking can erode the resilience of particular agents or groups within the system if CAS mental models are not widely shared, and fail to promote distributive justice; that is, CAS thinking may result in the same trade-offs and inequities as those experienced under more conventional management systems, or even create new trade-offs and inequities, all while being hailed as a CAS approach. These issues are discussed more in Chapter 2.

6.5 How can CAS thinking be operationalised and applied?

CAS thinking can represent system complexity, and be developed, fostered and applied in different ways (Table 6.2). As highlighted earlier in the chapter, CAS worldviews have been present in many traditional societies who are highly dependent on ES for their livelihoods. They have also been purposefully fostered in some contemporary governance approaches. In both cases it appears that the context and process of learning matter (P5-Learning). Among some traditional societies, variability in environmental conditions and supplies of ES, and the long-term perspectives captured in knowledge systems passed from generation to generation have fostered CAS thinking (Berkes *et al*. 2000). In contemporary cases, the alternative paradigms of linked SES, resilience, and complexity thinking have converged in response to evidence that linear mental models were not adequately explaining system dynamics or securing sustainable production of ES (Berkes & Folke 1998). These paradigms suggest that fostering CAS thinking requires long time-frames, a multi-scale approach, and explicit attention to the key properties of CAS including a high level of interconnectedness; potential

for non-linear change; uncertainty; and a multiplicity of perspectives within a system (Resilience Alliance 2010).

The examples and analysis above highlight some general guidelines for operationalising and applying CAS thinking and approaches, primarily at the collective level:

- *Develop an uncertainty-tolerant culture:* CAS thinking embodies a broad acceptance of uncertainty, variability and change, which conventional resource management paradigms avoid. Scenario planning has been remarkably effective as an approach to illuminate and embrace uncertainty in SES and develop robust responses, all while fostering CAS thinking (Biggs *et al.* 2010). Scenario planning is a structured process of exploring and evaluating future complexity and uncertainty by identifying alternative development pathways, assessing unintended consequences of decisions, and even recognising opportunities. It has proven powerful in a wide range of SES settings, including tropical forest communities, lakeshore management in the United States, and to navigate political change in South Africa (Wollenberg *et al.* 2000; Peterson *et al*. 2003; Tompkins *et al.* 2008). Accepting change and uncertainty in SES dynamics is also part of adaptive management and monitoring approaches (Lindenmayer & Likens 2009). Case studies suggest that a change in the cultural attitude toward uncertainty that enables CAS thinking often evolves from long-term monitoring and experimentation articulated through both scientific and local knowledge systems (Olsson *et al*. 2008; Gelcich *et al*. 2010)

- *Start with a systems framework:* A framework can help people to articulate and organise their thinking about interconnected concepts and relationships; many traditional societies have used systems-based frameworks over generations, and continue to do so where traditional practice remains strong (Holmes & Janpijinpa 2013). Cilliers *et al*. (2013) argue that it is only possible to have knowledge of a CAS in terms of a certain framework. Frameworks based on elements of CAS thinking include the Millennium Ecosystem Assessment (MA 2005) with its emphasis on multiple scales and knowledge systems, the SES Diagnosis Framework (Ostrom 2007) to foster widespread understanding of resource use systems as coupled and dynamic SES, and the Management Transition Framework (Sendzimir *et al*. 2010) used to analyse regime change; while the Resilience Workbooks (Resilience Alliance 2010) offer guidance on how to apply these frameworks in practice. In some cases, those wishing to collaboratively build CAS thinking might prefer to build a systems model or mind map from the ground up**.**

- *Acknowledge epistemological pluralism as a source of complexity:* As we noted at the beginning of this chapter, some facets of uncertainty in SES arise from multiple knowledge frames: individuals represent diverse epistemologies or knowledge systems, social values and preferences. Reflecting our discussion in section 6.4 and the issues of power and representation (Chapter 2), CAS thinking must acknowledge the knowledge traditions of diverse stakeholders if the aim is to build resilient ES in the long term. Therefore, fostering CAS thinking generally needs to be grounded in a collaborative knowledge-building process, involving managers, scientists and resource users, such as the participatory methods noted above (Fig 6.2) and described in more detail in other chapters (P5–Learning; P6–Participation). However, while collective CAS thinking often emerges in social learning and stakeholder engagement processes, it is often not the

primary goal, and how these processes contribute to developing CAS thinking needs to be better understood.

- *Investigate critical thresholds and non-linearities:* Not all change processes in SES are characterised by discontinuities or thresholds. However, where non-linear change does occur it has important implications for managers and resource users because of the high social and ecological costs of surprise events and the prospect of hysteresis – effective irreversibility. Central to fostering CAS thinking is therefore to at least consider and explore system boundaries and thresholds. The Thresholds of Potential Concern approach, for example, is used by managers in the Kruger National Park to build a CAS understanding to manage fire regimes and elephant populations within a variable range that accounts for 'natural' uncertainty (Biggs & Rogers 2003; Van Wilgen & Biggs 2010; Biggs *et al*. 2011b). Similarly, fishers and managers in the Pacific and West Africa have trialled participatory threshold dashboards that account for ecological and social thresholds, producing stakeholder-defined and socially-relevant metrics to learn about, monitor and manage their small-scale fisheries (Béné *et al*. 2011; Schwarz *et al*. 2011).

- *Match institutions to CAS processes:* In practice it appears that institutional change at some level may be needed to foster, and sustain the evolution of, CAS thinking at appropriate scales. Though opportunities to revamp existing institutions only arise periodically, CAS thinking can be fostered through the design of research and governance approaches such as spatial management (e.g. the Kruger National Park, Great Barrier Reef and Chilean benthic fisheries) and the 'living with the river' floodplain management paradigm in Europe. Catchment management agencies are another example of integrated governance capable of dealing with system processes across multiple interconnected ES, as opposed to historical management on a resource-by-resource basis, and thus may be more amenable to CAS thinking. It must also be remembered that CAS often resist being clearly bounded (Cilliers *et al*. 2013), and external drivers of change need to be explicitly accounted for, for example, by framing coastal SES as having 'porous' system boundaries at the land-sea interface. In some situations institutional change will be beyond the agency of actors in the system, but cross-scale networks can help to foster CAS thinking about processes 'outside' the SES (P7–Polycentricity).

- *Recognise the many barriers to cognitive change:* Human understanding is dynamic, changing over time through experience and learning (Jones *et al*. 2011). Research in psychology suggests that deliberately changing mental models, as distinct from updating or adding to them, is transformative in that it implies the unknown – unknown risks and requirements for time, energy, skills and knowledge (Costa & Kallick 1995). As such, individuals or groups invested in a particular *modus operandi* may believe they can improve outcomes by simply doing things better, rather than doing things differently. Those benefiting from existing regimes of ecosystem management may, therefore, resist adopting CAS thinking and accepting its implications for the status quo.

6.6 Key research and application gaps

We have presented some empirical evidence to suggest that fostering CAS thinking can facilitate the management of SES to enhance the resilient provision of ES, mainly through the choice of management approaches that recognise interconnectedness, non-linear change, uncertainty, and multiple perspectives. Much of this evidence comes from examples in which a lack of CAS thinking has eroded the resilience of ES. It remains unclear to what extent CAS thinking can be credited for the adoption of management approaches to enhance

resilience of ES. Two problems help explain this: i) CAS thinking can take many forms, and it is not always clear–for those not involved in the management–what constitutes CAS thinking; ii) CAS thinking is only one of many interacting components, types and scales of decision-making in an SES, making its contribution to resilience difficult to clarify.

The above evidence points to the following gaps in our current appreciation of how fostering CAS thinking is likely to enhance the resilience of ES, and how it can be applied in practice in a range of different contexts:

- How do we communicate complexity so that CAS thinking can be fostered and mobilised into action? To avoid bewilderment and gridlock that may stem from a perception of overwhelming complexity, participatory processes such as scenario planning have shown themselves to be helpful tools. Yet a key research gap lies in understanding how such processes can be most effective (P6–Participation) in communicating complex concepts so that understanding and mental models can be shifted (Etienne *et al*. 2008; Bohensky *et al*. 2011; Cundill *et al*. 2012) and not simply lead to 'endless learning' (Fabricius & Cundill 2014). Further research can help identify which participatory processes best strengthen CAS thinking among managers, noting that many managers already have a long-evolved understanding of systems as CAS but expressed more often through the language of practice.

- How does power influence the use of a CAS approach? Whose understanding of CAS matters and how can conflicting views be reconciled? These questions underscore that decision-making about how to apply CAS thinking (i.e. the direction and intent of institutional change and which ES should be made resilient to which disturbance events) is a political rather than purely academic exercise (see Chapter 2), and raises questions sometimes seen as absent from the resilience literature (Nadasdy 2007).

- There is a need to understand the relative importance of fostering CAS thinking at individual as opposed to collective (social and organisational) levels. Research has shown the importance of influential individuals in catalysing SES change (Olsson *et al*. 2006), but is CAS thinking among their constituents at the coalface equally if not more critical? We suggest there is a role for research on how a CAS framework might be extended to incorporate normative issues related to the distribution of power within an SES. In this context, and following from questions 1) and 2), are there participatory and decision-making processes for the co-construction of a CAS understanding that are more likely to lead to CAS-informed decisions than others (e.g. Barnaud *et al*. 2008; Barnaud *et al*. 2010)?

- How can institutional barriers to CAS thinking and path dependency be overcome? Institutional design, including legal structures and accounting and auditing systems, stem from a worldview based on reductionist thinking, and a command-and-control approach to management (Ebbesson 2010). Even when mental models shift, the artefacts of previous administration systems sometimes linger as historical legacies. Thus, this problem pervades even those organisations that are considered world-leaders in the institutionalisation of CAS thinking in management such as SANParks (Biggs *et al*. 2011a). A key research gap is therefore to understand which aspects of CAS thinking can be institutionalised and implemented within the current legal and auditing structures (Ebbesson 2010).

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Box 6.1 Complex enough? CAS thinking and the Great Barrier Reef

Changes in the way the Great Barrier Reef has been managed during the past several decades illustrate the evolution of CAS thinking, and its varied success in bringing about management change. One of the seven natural wonders of the world, the reef has long been an icon of conservation concern, and as concern grew over pressures on the reef so did the recognition that the cognitive basis of management needed to change. In 1975 the reef's designation as a marine park was a first step towards implementing precautionary and adaptive management: it prohibited mining on the reef and established a network of no-entry, no-take and multi-use zones (Fig 6.1a). Nevertheless, pressures on the reef continued to increase and in 1994, the Great Barrier Reef Marine Park Authority initiated a strategic process of organisational and institutional change for the region to 'Keep it Great' (GBRMPA 1994: 1). The Authority was re-structured around core strategic goals including resilient ecosystems (Fig 6.1b).

In 1999 a systematic conservation planning approach called the Representative Areas Program (RAP) was initiated (Day 2002). This process involved developing a deep, adaptive understanding of the reef SES as a CAS. For instance, by the mid 1990s scientists had observed catastrophic phase shifts in coral reef systems in other parts of the world (Hughes 1994). This was followed by two notable disturbance events on the Great Barrier Reef: Tropical Cyclone Justin in March 1997 (Tobin *et al*. 2010) and extensive bleaching of corals in the 1997-1998 El Niño Oscillation (Wilkinson 2004). These occurrences emphasised the vulnerability of the reef—previously viewed as a pristine habitat—due to high interconnectedness and nonlinear change. To investigate further, scientists and managers undertook a large-scale experiment to analyse the effectiveness of the current zoning plan (Hughes *et al*. 2007; Mapstone *et al*. 2004). This involved testing opening and closure regimes on the reef, and examining the role of herbivores in preventing and reversing phase shifts from coral to algal dominance. By the late 1990s there was broad scientific and management consensus around the need to increase the extent of no-take zones on the reef to ensure resilient provision of diverse ES. In order to legitimately implement a new zoning plan the Authority then undertook an extensive process of stakeholder engagement and broader public awareness (Olsson *et al*. 2008). The new plan came into effect in 2004. It emphasises representation of key bioregions, connectivity between habitats and species populations, and uncertainty through the use of spatial management. Consistent monitoring and research has supported the scientific argument for increasing the area of no-take zones from 4% to 33% to improve biodiversity and resilience of the reef (McCook *et al*. 2010).

CAS thinking is also evident in the management approach to water quality pollution from farming in the catchment, but as this originates outside the Marine Park boundaries and has diffuse sources, it has involved another set of institutions to manage, which has achieved considerable reduction in agricultural runoff (Brodie & Waterhouse 2012; Brodie 2014). Again, reef managers recognised that interactions between threats could lead to irreversible change, and implied engagement with multiple stakeholder groups. Scenario planning has been used to support such engagement around CAS thinking, particularly to explore how different climate change trajectories might play out for the reef (Bohensky *et al.*, 2011; Evans et al. 2013; Fig. 6.1b). However, by some estimations the greatest threat to the reef is currently posed by major port expansions being planned for the export of coal and coal seam gas (Brodie 2014). As the problem domain for the reef's managers expands to involve increasingly intractable, cross-scale issues with a set of stakeholders much removed from the impacts on the reef, it appears that CAS thinking is not expanding accordingly or being applied quickly enough (Brodie & Waterhouse 2012). The current situation raises the critical

question of whether CAS thinking among the agencies responsible for the reef is sufficiently complex, able to evolve and address the broader-scale drivers affecting the system. It raises the question of whether, as a consequence, the CAS thinking that has guided past management can enhance resilience of all ES provided by the system, or whether trade-offs will inevitably be required in the multi-use, multi-stakeholder, multi-scale context in which the reef is situated, for instance between catchment ES and coastal ES, and ultimately between ES and economic growth. Does this point to the need for a CAS understanding at the broader political decision-making scales that influence outcomes for the reef, essentially redefining the boundaries of the CAS in question?

Fig 6.1 (a). The management of the Great Barrier Reef illustrates how aspects of CAS thinking have shaped the evolution of this iconic SES, but also highlights challenges encountered by managers attempting to operationalise this principle in a multi-scale, multi-stakeholder context. **Fig 6.2 (b).** Resilient ecosystems are a core strategic goal around which the reef's primary management agency, the Great Barrier Reef Marine Park Authority, is structured. Photo credits: (a) Erin Bohensky, CSIRO. (b) Matt Curnock, CSIRO.

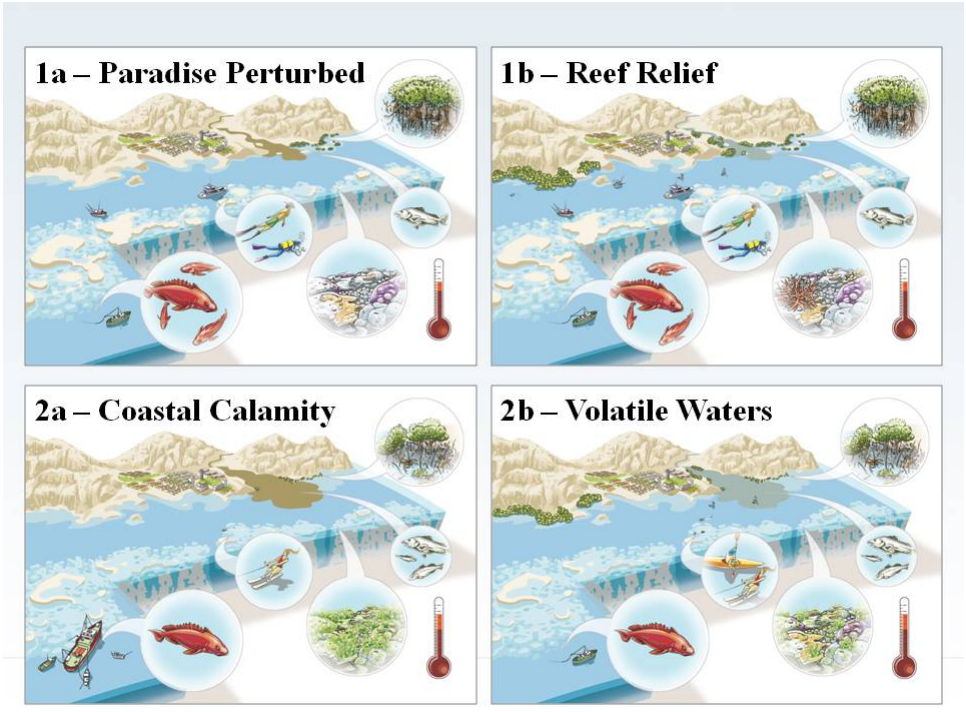

Fig 6.3b. Alternative future scenarios for the Great Barrier Reef (Evans *et al*. 2013). Scenario planning is an approach based on CAS thinking, in which participants identify key uncertainties, thresholds and non-linearities in the system.

Fig 6.4 Engaging multiple stakeholders and knowledge systems is a key component of fostering CAS thinking in practice. **a)** Participatory mapping of cultural ecosystem services in Milne Bay, Papua New Guinea (Bohensky *et al*. 2009). **b)** Discussing drivers of change as part of a scenario planning workshop on Erub Island in the Torres Strait, Australia. Photo credits: Erin Bohensky, Matt Curnock, CSIRO.

Fig 6.5a

Fig 6.6b


VINTAGE

Table 6.1: Views of ecosystems have shifted over time towards recognition of CAS properties (based on Schlüter *et al*. 2012).

Conventional view of ecosystems	**SES as CAS**
System dynamics are linear and monotonic	System dynamics exhibit thresholds, hysteresis
Uncertainty is largely ignored: probability distributions for key drivers and decision variable are treated as known	Complexity and uncertainty of SESs are explicitly considered: probability distributions for key drivers and decision variables are highly uncertain, as are outcomes; some uncertainties are irreducible
Individual elements can be treated in isolation	Complex systems of interacting entities at microscale from which macroscale patterns emerge
Focus on impact of human behaviour on resource	Incorporate reflexive response of humans to forecasts and interventions
Actors are rational and have full information and computational capacity	Actors have imperfect knowledge, are boundedly rational or follow more complex decision patterns
Management objectives are based on simple reference points	Management involves complex trade-offs
Managed by a command-and-control approach, management of resource stocks and condition, not wider ecosystem	Managed for resilience and adaptive capacity, management of stabilising and amplifying feedbacks within a broader context

Table 6.2: Applications of CAS thinking discussed in this chapter.

Case	Problem description and approach	Further reading
Great Barrier Reef (Australia)	Management of the GBR has evolved from focus on species to broader ecosystem-based management, and encompasses ideas of building resilience to multiple perturbations and adaptive management. Scenario planning involving stakeholders has highlighted multi-scale nature of drivers of change and responses.	Olsson *et al*. 2008; McCook *et al*. 2010; Bohensky *et al*. 2011; Evans *et al*. 2013
Kruger National Park (South Africa)	Thresholds of Potential Concern (TPC)s linked to clear, nested objectives to define measurable variables, to allow for system variability in fire, elephant populations, vegetation and river flows, for example. More recent thinking includes incorporating social values and preferences and how changes in these can be incorporated into Kruger's strategic adaptive management system.	Biggs & Rogers 2003; Biggs *et al*. 2011b; Van Wilgen & Biggs 2010
Tisza River Basin (Hungary)	In parallel with political change, a "shadow network" of government agents, local activists, and scientists engaged in dialogue to explore how to transition from conventional to more adaptive river management based on a paradigm of "living with the river" and ensuring the river basin supports a range of ecosystem services on which biodiversity and agriculture rely. System dynamics modeling tools were used to explore barriers and bridges to transformation of the river management regime and build capacity for participatory science and learning.	Sendzimir *et al*. 2007; 2008; 2010
Benthic Fisheries Management (Chile)	Fisheries management in Chile has undergone a transformation following stock depletion, and now emphasise scientific knowledge of the ecology and resilience of targeted species and their role in ecosystem dynamics. Demonstration-scale experimental trials have identified new management pathways, improved cooperation among scientists and fishers, integrating knowledge and establishing trust. Political turbulence and resource stock collapse provided a window of opportunity that triggered the transformation, supported by new enabling legislation marine tenure that allocates user rights and responsibilities to fisher collectives. However, current discussion in Chile criticises the rigidity of the new legislation, which may poise it to fail because it undermines adaptation to ongoing change.	Gelcich *et al*. 2010