Chapter 1
Complex Adaptive Systems and a Sustainability Framework

Abstract This chapter describes the key features of complex adaptive systems (CAS) and presents a framework for analyzing sustainability of coupled human-environment systems (CHES). The framework uses two concepts to characterize and quantify sustainability: well-being and resilience. Well-being describes the state of a CHES at a given point in time, and resilience describes the state change of the system. The framework suggests some quantitative measures for well-being in the context of climate change and variability. It also includes specific analyses that are intended to undertsand the complex processes in a CHES and to provide scientific support for policy to promote sustainable development. The chapter closes with an overview of the study of rural development in the Poyang Lake Region of China.

Keywords Complex adaptive systems • Coupled human-environment systems • Well-being • Resilience • Sustainability • Policy analysis

1.1 The Science of Complexity and Sustainability of Human-Environment Systems

Complex adaptive systems (CAS) consist of networks of heterogeneous agents that interact with one another and with the environment, giving rise to system-level patterns or properties (Gell-Mann 1994; Holland 1995, 1998, 2012; Kauffman 1995; Arthur et al. 1997; Axelrod and Cohen 2000). Markets, economies, organizations, societies, and ecosystems are all examples of complex adaptive systems.

In a complex adaptive system, the agents learn and adapt through interactions with other agents, leading to *adaptability* of the system. Because agent behaviors are linked in a co-evolutionary way, complex adaptive systems often show "perpetual novelty," and it is difficult to predict novel system-level patterns simply by knowing the properties and actions of individual agents. In other words, the behavior of the whole system cannot be obtained by summing the behaviors of the agents in a linear way; these systems thus exhibit *non-linearity*. The *adaptive interactions* of agents that possess distinctive characteristics and experiences are the keys to understand the processes and dynamics of CAS. Such adaptive interactions also lead to other general features of complex adaptive systems.

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A complex adaptive system usually has a large state space; it may exhibit *non-equilibrium* or *multiple equilibriums*, with *tipping points* that propel it into a sudden phase transition. Complex adaptive systems can have *lever points* at which a small intervention produces large changes in system-level outcomes. One example of a lever point is a vaccine, which causes important, long-term changes in an immune system. The evolution of a CAS is also *path-dependent*, i.e., dependent upon its initial conditions and previous states. As a result, a system can experience "lock-in" on an undesirable, long-term path.

Complex adaptive systems tend to *self-organize*, often without a central control; although coherent behaviors can and often do emerge from individual agent actions and interactions, the system can fall into a state of chaos. These systems often have "*fat-tailed*" behaviors, i.e., rare events—market crashes, for example, can occur more often than a normal distribution would predict. Additionally, these systems tend to have *hierarchical structures*, with components at lower levels forming the building blocks of components at higher levels. The global economy, for example, comprises many country-level economies, which are themselves complex systems made up of yet smaller systems.

In systems dynamics, an earlier paradigm of complexity science, researchers used multiple system-level variables to describe the state of a complex system and examine the interconnected changes of these variables to explain the system's behavior and dynamics (Luenberger 1979). The newer CAS paradigm advances our understanding of complex systems by looking deeper at the role of individual agents' actions and interactions on the macro dynamics.

Coupled human-environment systems (CHES) are complex adaptive systems, in which social and natural components interact with one another (Levin 1999; Gunderson and Holling 2002; Turner et al. 2003, 2007; Clark 2007; Liu et al. 2007; Ostrom 2009; Levin and Clark 2010; Moran 2010; Cioffi-Revilla 2016). In a human-environment system, many human agents, all situated within social, economic, and institutional contexts, make decisions and interact both with other agents and with the natural system (Fig. 1.1). The natural system of a CHES also has its own biophysical processes.

When we examine human-environment systems through the lens of CAS, we can understand that *sustainability* is a system-level property emerging from the actions and interactions of human agents, the biophysical processes in the natural system, and the interactions between the social and natural components. Sustainability of a CHES, moreover, can be defined as well-being, including human and environmental well-being, over a long time horizon. Sustainability is essentially about human well-being (Holdren 2008), but we must consider environmental well-being equally because human well-being cannot be sustained in the long run in a degraded natural environment.

In any CHES, multiple issues tend to affect human and environmental well-being, so that sustainability can be characterized across a number of dimensions, including natural resources, biodiversity, pollution, climate, etc. However, for a particular human-environment system, a few dimensions, or perhaps just one, are often more important than the others. We may begin our study with the most important or

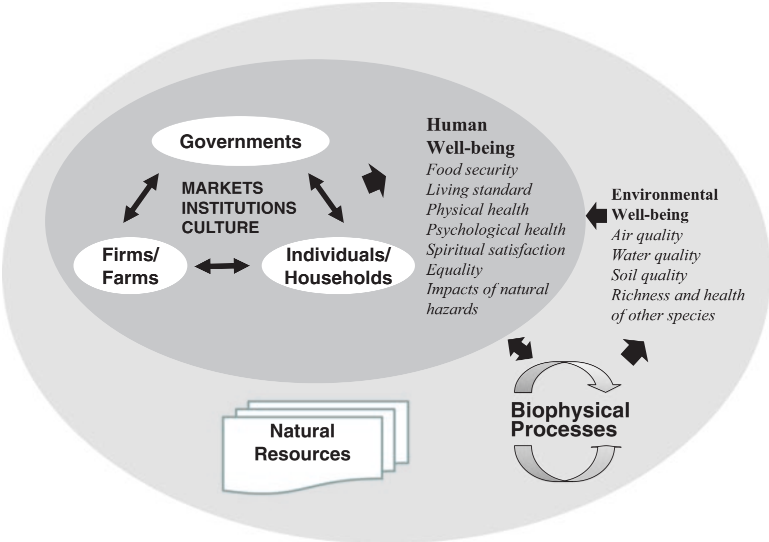

Fig. 1.1 Sustainability of coupled human-environment systems

most relevant dimensions, and later add others to increase our understanding of the system and eventually address all the issues affecting sustainability.

In the next section, I present a sustainability framework for policy analysis, in the context of climate variability (and change), for less developed areas. The framework focuses on the system's social component rather than climate dynamics because humans are the only agents in a CHES that can take deliberate actions to change the system's state. Understanding social dynamics will offer useful insights on how policy may promote positive changes in a human-environment system and direct the system toward a sustainable development path. The framework also focuses on local sustainability, i.e., the sustainability of a CHES in a specific place. I will discuss how to extend this framework to a more general analysis of global sustainability in Chap. 6.

1.2 A Sustainability Framework for Policy Analysis

The framework uses two concepts to characterize and quantify sustainability. The first, as just discussed, is *well-being*, and describes a CHES's state at a given point in time. In the context of climate variability (and change), the well-being of a CHES is defined by: (1) the human system's *exposure* to extreme climate events; (2) the human system's *development level*, which includes various aspects of human development; and (3) the *sensitivity* of human development to extreme climate events.

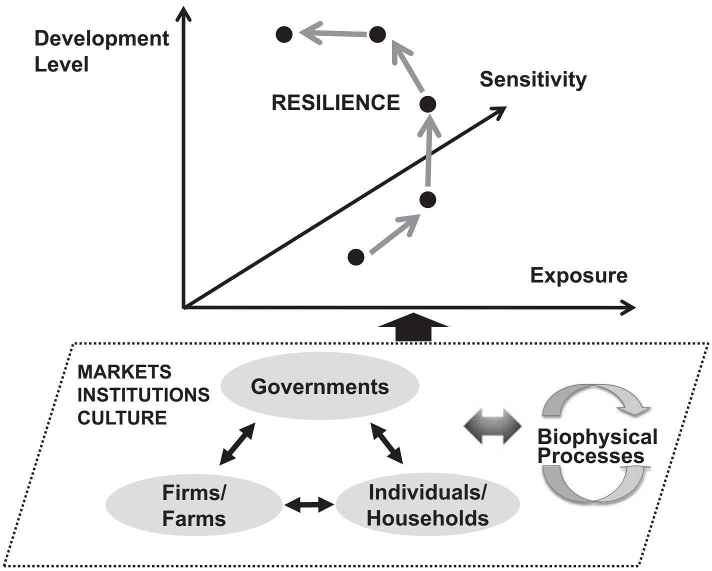

Fig. 1.2 A framework for studying sustainability in less developed areas amid climate variability (and change)

Please note the difference between exposure and sensitivity. *Exposure* characterizes the nature and degree to which the human system is exposed to extreme climate events, and is determined by the natural system. S*ensitivity* reflects the impacts of extreme climate events on human development and results from the interactions between the social and natural systems.

Also note that the definitions of exposure and sensitivity here slightly differ from the IPCC definitions. In the IPCC conceptual framework for vulnerability assessment (Houghton et al. 2001; McCarthy et al. 2001; Fussel and Klein 2006), climate extremes are treated as external to a system, and a system can be any social or natural system.

The second concept is *resilience*, which describes the state change of the system over time. A CHES is said to be resilient if it does not experience a sudden transition from one critical state of well-being to another in the face of social or environmental shocks. A CHES is defined as *sustainable* if human development has reached a certain level that ensures human well-being, and the system is resilient.

The framework is quite simple. Imagine that the state, i.e., the well-being, of a CHES at any given time is a spot in a three-dimensional space of development, exposure, and sensitivity (Fig. 1.2). Human agents in the system act and interact with one another and with the natural environment, within social, economic and institutional contexts, to shape where the spot is at a given time and how it moves in the space from time to time. *Resilience* involves tracing the trajectory of the spot over time.

Higher levels of human development coincident with lower levels of sensitivity are generally desirable. To steer a CHES toward sustainability, it is important to: (1) assess current conditions, i.e., to identify where along that well-being trajectory the system is; (2) understand the causal mechanisms, i.e., how human agents act and interact with one another and their environment to shape the system's state and drive changes in the system's state; and (3) design policies accordingly to steer the system toward more desired states. This is a continuous process of improvements and adjustments, and these three steps must be repeated over time to reflect ongoing social and environmental changes. They can be supported by employing scientific analyses that assess well-being, analyze the complex processes underlying well-being, and explore a system's future paths. I will turn to the implementations of these analyses, following a discussion on the framework's usefulness.

1.3 Potential Usefulness of the Sustainability Framework

The sustainability framework has been influenced by literature from several fields relevant to global environmental change. This section offers a brief introduction to some of the major concepts in the literature, while discussing the framework's potential usefulness. I explain why I chose some concepts over others, and how to integrate the analysis of vulnerability and adaptation into the sustainability framework to provide more useful insights for promoting human well-being in less developed areas that are affected by climate impacts.

The concepts of exposure and sensitivity are important because they reflect the nature and impacts of climate variability (and change). The research in natural hazards has long used these concepts to examine biophysical vulnerability (Burton et al. 1978, 1993). As defined in this framework, exposure and sensitivity offer objective measures of the biophysical environment and the outcome of human-environment interactions with respect to extreme climatic events. As long as the human system is exposed, and human development remains sensitive to climate impacts, people are vulnerable to harm from climate-related natural disasters. Exposure can also serve as a useful reference point to sensitivity, revealing whether human activity is exacerbating or ameliorating natural risk.

Together, measures of exposure, sensitivity, and development provide a meaningful view of human well-being in the context of climate variability (and change), and suggest where adjustments may be made (Table 1.1). Examining sensitivity along with exposure also forces decision-makers to consider specific climate risk and impacts when making development plans. This will help prevent maladaptation or an inappropriate reliance on other means, such as insurance, that may mitigate impacts locally but cause a loss of welfare at the system level.

The concept of social vulnerability, with its roots in political ecology/political economy, is essentially about human well-being. Social vulnerability is often measured by combining socioeconomic variables, such as socioeconomic status, access to resources, age and gender, the degree of urbanization, occupations, infrastructure,

Table 1.1 System states and possible implications

Development	Exposure	Sensitivity	Possible implication
High	Low	Low	Desired state
High	Low	High	Not doing right things—need to locate the sensitive part of development and make appropriate adjustments
High	High	Low	Good—doing things that mitigate natural risk
High	High	High	Serious problem—may need to seek both engineering works and "soft" means to reduce sensitivity
Low	Low	Low	Key issue is development, but need to make sure not to do things that exacerbate natural risk
Low	Low	High	Key issue is development, but need to reduce sensitivity at the same time
Low	High	Low	Key issue is development, but need to pay close attention to sensitivity and may need engineering works to keep sensitivity low
Low	High	High	Might consider migration away as an ultimate solution

education, and social capital (e.g., Cutter et al. 2003; Dwyer et al. 2004; Vincent 2004; Rygel et al. 2006). But exactly how these variables determine vulnerability is not fully understood, and their effects are likely to vary in different contexts. What *is* actually measured in these contexts is human well-being. Researchers—especially those who have worked in less developed countries or with socially and economically disadvantaged groups—have recognized that it is not particularly meaningful to examine vulnerability without looking at development, and that human well-being is the real concern (Ribot et al. 1996; Kates 2000; Adger et al. 2003; Lemos et al. 2007; Wilbanks and Kates 2010; Smith et al. 2011; McCubbin et al. 2015).

The vulnerability analyses that seek to understand how social and political processes affect people's vulnerability (Sen 1981; Hewitt 1983; Dreze and Sen 1990; Swift 1989; Watts and Bohle 1993; Blaikie et al. 1994; Ribot 2009) are important and can be expanded under the new sustainability framework to analyze the complex processes that shape the well-being of CHES. The livelihoods approach (Ellis 1998; Bebbington 1999), often used in development studies to analyze the well-being of a household, is particularly useful and can be applied to analyze the micro- and macro-level processes in CHES. The livelihoods approach can also provide insight about how the livelihoods of households can be affected by climate impacts (Eakin 2005; Paavola 2008; IPCC 2014, Rogers and Xue 2015; Lemos et al. 2016; Tian and Lemos in review).

The concept of resilience generally refers to the ability of a system to maintain its basic function and structure in the face of shocks (Holling 1973; Carpenter et al. 2001; Folke et al. 2002; Berkes et al. 2003; Folke 2006; Walker and Salt 2006). Resilience is a useful concept because it is an important property of a human-environment system and tells us how a system's state changes. However, many human-environment systems are currently in a state of *undesirable* resilience. In these systems, human development levels are low and/or the environments suffer degradation and resource depletion. This is precisely why sustainability is an urgent issue, and why the sustainability framework in this study focuses on how to steer a system toward more desirable states.

The concept of resilience becomes more useful if we can operationalize it. There are multiple lines of resilience thinking in the literature (Walker and Salt 2006). A ball-in-a-basin model is used to illustrate a system's attractors and potential state transitions. The evolution of a system is also thought to have adaptive cycles. My intent here is not to incorporate all the meanings of resilience, but to define the term in a concrete way that is useful for the study of sustainability. Once we quantify well-being using multiple variables, we can use thresholds of these variables to partition the space of well-being into discrete states and begin to define critical states. We can then combine the mathematic tools developed in systems dynamics with new modeling tools for analyzing complex adaptive systems to trace the trajectory of well-being.

When we recognize that climate is one of the factors that affect human well-being, adaptation to climate variability (and change) naturally becomes part of the sustainability agenda. Sensitivity of human development to climate impacts also provides a measure of the outcome of human adaptation: if over time people make development less sensitive to climate impacts, they are adaptive and adapting in the *right* direction.

Adaptive capacity, another central concept in the social science of climate change, is inherently dynamic and difficult to measure directly. But assessing current conditions, understanding causal mechanisms, and making adjustments accordingly are fundamental steps toward progressive adaptation. When we analyze the complex processes underlying the well-being of a human-environment system, we can gain insights into the complex processes that affect adaptive capacity as well. Therefore, these iterative steps toward sustainability are also helpful for enhancing adaptive capacity to climate variability (and change).

1.4 Implementation of the Sustainability Framework

1.4.1 Assessing Well-Being

Assessments of well-being can be carried out for a given time and at different scales. Regional assessments are particularly useful for policy-makers seeking to understand variations in exposure, sensitivity, and development levels across the region and identify problematic "hot spots." They can use the information to design policies that target different problems in different places.

Each of the three dimensions of well-being—development, exposure, and sensitivity—can be represented by multiple variables. The UN Development Programme (1990, 2007, 2008) uses life expectancy, literacy, and income to derive its human development index. These are important basic measures of human development for less developed areas.

Additional variables can be included to provide more comprehensive views of human development or to reflect specific concerns of a place. The World Bank (2009) has listed more than 800 indicators for various aspects of human development. But it is important to note here that more is not necessarily better. Including many *relevant* but *unimportant* variables is likely to mislead or overwhelm policy-makers, and prevent them from seeing the essential parts of the picture. An assessment can actually generate the most insightful information if it captures the system's key elements using the fewest variables possible.

Exposure and sensitivity measures are specific to location and type of climate event. Area extent, speed of onset, spatial distribution, temporal spacing, duration, and frequency are commonly used in natural hazard research to characterize the nature and magnitude of extreme climate events (Burton et al. 1978, 1993). These are appropriate measures for exposure to extreme climate events.

Two types of outcomes are essential to consider in measuring sensitivity: *human lives* and *economic activities*. In different places, major economic activities may differ, but in each place *land-use patterns* are direct manifestations of sensitivity. Especially for rural areas, land-use patterns indicate how climate can affect agricultural production. The distribution of important public facilities and engineering works can also affect sensitivity, and may be considered.

Exposure and sensitivity often vary spatially in a region. To characterize the spatial variations of exposure, we can define and map *risk zones*, using a theoretical approach based on the nature of the risk, or empirically based on historical data on damages suffered from extreme climate events. Land-use patterns can be interpreted from remote sensing images. Land-use maps and other GIS data, such as road networks, crucial facility locations, and population distribution, can then be combined with the risk zones to examine spatial variations of sensitivity.

1.4.2 Analyzing the Complex Processes Underlying Well-Being

Understanding how human agents in a coupled human-environment system interact with one another and with their social and natural environments to shape the well-being of the system can provide important insights into designing policies that gradually but effectively steer the system onto a path of sustainable development. Only if we understand such causal mechanisms, can we effect changes in a system.

Agent decision making is, of course, an essential part of the causal mechanisms at work in complex adaptive systems. Human agents in a CHES are, however, all embedded within large social, economic, institutional, and development contexts, which can affect and constrain individual options and decisions. Policies can play an important role in improving macro-level processes so as to create opportunities for individual agents and facilitate individual agents making better choices.

On the other hand, while individual decisions and actions are major forces driving state change in complex adaptive systems, they do not necessarily result in *optimal* system-level outcomes. The Prisoner's Dilemma and the Tragedy of the Commons are cases in point. If one is to approach policy from a CAS perspective, the goal should not be to impose central control over a system, but to set up "smart" incentives to induce individual decisions and actions that collectively lead to desired system-level outcomes.

It is therefore particularly important to examine how human agents make decisions. If we understand this, we may be able to design effective policies to improve macro-level processes and assist individual agents increase their well-being, or introduce "smart" policies to influence individual behaviors and facilitate changes toward more desired states.

To analyze the interactive processes in human-environment systems, we can combine quantitative and qualitative data and methods. Qualitative approaches, especially, allow us to develop a deeper understanding of processes and to examine social factors that are hard to quantify and therefore often omitted in quantitative analyses. Qualitative approaches, such as interviews, field observations, and participatory methods, are useful for investigating human decision making, and can help us understand how macro-level socioeconomic processes and environmental factors affect agent decisions—and, ultimately, the state of a system.

1.4.3 Exploring Future Paths of the System

Agent-based modeling (ABM) is a useful method to explore future paths of a human-environment system. Agent-based models (ABMs) simulate the decisions of heterogeneous agents in complex adaptive systems, and have been used to explain macro-level phenomena in a variety of systems, from economies and markets to social organizations and land use (Epstein and Axtell 1996; Axelrod 1997; Riolo et al. 2001; Bankes 2002; Janssen 2003; Parker et al. 2003; Gilbert 2008; Manson and Evans 2007; Miller and Page 2007; Farmer and Foley 2009; Heppenstall et al. 2012; Railsback and Grimm 2011; Cioffi-Revilla 2014; Walsh and Mena 2016).

The particular strength of agent-based modeling lies in its exploratory capabilities, and these can be tapped for policy analysis. We can use agent-based models to test the potential effects of alternative policies; if we have some idea of how a CHES might respond to a certain policy intervention, we will be more confident about its implementation. We can use ABMs to explore lever points; if we find them, we can introduce large positive changes to a system with few costs. We can use them to explore plausible scenarios of social and environmental changes; this could provide us with insight into the resilience of a CHES and whether human well-being can be sustained. We can also use agent-based models to explore the state space of a CHES; if we can identify dangerous tipping points, or conditions that lead to unsustainability, we will have a better chance to avoid a disastrous future.

1.5 Looking Ahead

The following chapters present a study of rural development, and the application of the sustainability framework, in the Poyang Lake Region (PLR) of China. The PLR is an important agricultural area in Jiangxi Province situated in the middle region of the Yangtze River Basin. Historically, the area has been subjected to flood hazards from Poyang Lake, China's largest freshwater lake. The annual per capita net income of farmers in the region was 5,789 CNY (1 USD equaled about 6.77 CNY) in 2010, below the national average of 5,919 CNY (Yan et al. 2013).

As in other rural areas in China, rural livelihoods in the Poyang Lake Region have been transitioning to an increased dependence on nonfarm work. Based on household surveys across eight villages in the region, on average 65% of rural income was derived from nonfarm sources in 2006 (Tian et al. 2015). Rural development in the PLR, and in China more generally, is facing a number of difficult issues, central to which are low rural income and agricultural decline associated with nonfarm work. In Chap. 2, I provide more details on the broader policy and development context in China, and introduce the dynamic coupled human-environment system around Poyang Lake.

Chapter 3 presents a regional assessment of human well-being carried out for 298 townships (the administrative units below counties and above villages) in the PLR. First, flood hazard zones are mapped, using an innovative geographic approach, based on a digital elevation model, levee location, height and quality, and historical data on lake levels. Measures of exposure and sensitivity at the township level are then derived, combining a land-use map interpreted from remote sensing images and a population distribution map with the flood hazard zones. Socioeconomic variables from the 2000 census are used to represent the three aspects of development in health, literacy, and income defined by UNDP.

The assessment indicates that development in the Poyang Lake Region overall is both highly exposed and sensitive to flooding risk. Sensitivity is closely related to and perhaps bound by exposure, with both levels climbing in proximity to the lake. The development level, however, is more closely associated with the degree of urbanization; higher development levels are also found in townships closer to county capitals (which are economic centers for rural Chinese counties). There are significant variations in different aspects of human well-being among the townships in the PLR. I discuss different sustainable development pathways for several types of townships and the implications for government interventions.

Chapter 4 presents an analysis of rural livelihoods, aiming to understand the complex processes that shape the well-being of rural households in the dynamic process of urbanization. The analysis is based on quantitative surveys and qualitative interviews and field observations in eight villages around Poyang Lake. It examines rural households' livelihoods against China's broad development background, and within their local contexts, which also define their exposure to flood hazards. While urbanization has had a positive effect on reducing the sensitivity of rural livelihoods to flooding, some institutional factors and macro development dynamics can affect and constrain rural households from developing viable livelihoods. I discuss how development programs and policy may simultaneously promote rural development and mitigate flood impacts.

Chapter 5 presents an agent-based model developed to explore the effects of different subsidy policies on rural development and the resilience of rural development in the PLR. The model represents land-use and livelihood decision making of farmer households in three types of villages: those with poor, average, and rich farmland. Households in the model allocate their labor between nonfarm and agricultural work, make rice cropping choices, and exchange farmland in a land rental market. The model tests three policy scenarios: subsidies to rice growers, subsidies to large farms, and subsidies to households that subcontract their farmland to other households for the long term.

The model experiments aid our understanding of the nature and potential effects of these policies across different villages at different stages of development, and how rural development may be affected by economic and environmental shocks. I discuss how policy may need to differentiate across location and adapt in the near future to promote rural development and enhance the resilience of rural development amid social and environmental changes.

Chapter 6 summarizes the findings from the PLR study and discusses the possible implications on sustainable development for other less developed rural areas. I also extend the sustainability framework into a more general framework for analyzing global sustainability.

Chapter 7 includes a reflection on the complex systems approach to policy analysis and a discussion of developing agent-based models to generate useful, convincing insights for policy analysis. The chapter concludes with a conjecture about sustainability of complex adaptive systems in general.

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