Chapter 3
System Dynamics as a Framework for Understanding Human—Environment Dynamics

Krystyna Stave and Birgit Kopainsky

Abstract Understanding the dynamics of human—environment systems, and developing policies that promote their sustainability, requires a holistic, integrated approach. Although many frameworks have been developed that include social and environmental components, managing social and ecological systems as integrated systems has been difficult in practice. The analytical and practical challenge is to identify the interactions that underlie resource management problems, find leverage points where management or policy changes can effectively move the system in a more sustainable direction, and build cooperation among system stakeholders to implement change. This chapter gives an overview of existing frameworks for examining social—ecological interactions, then presents system dynamics as both a theoretical perspective and a practical method for integrating across disciplines. The system dynamics approach makes feedback relationships in the system explicit, and provides a platform to foster collaboration and coordination among stakeholders in the system. This chapter offers a systems framework for considering the connections among the individual chapters to follow. This approach was used for a collaborative mapping workshop on sustainability issues in the Lake Tana basin held in November 2014 as a first step toward integrating disparate research disciplines and stakeholders. Chapter 34 describes the workshop.

Keywords Social–ecological systems · SES · Analytic framework · Participatory modelling · System dynamics · System integration · Integrated system analysis

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3.1 Introduction

The Lake Tana region faces a number of challenges that arise from interactions between people and the environment. As Chaps. 1 and 2 described, environmental conditions such as soil and water quality and species diversity are deteriorating. Environmental degradation, in turn, threatens the quality of human life and shapes the types of natural resource use possible. This region is one of many in the world in which human activity and environmental conditions are closely interwoven. Though the details of each place are unique, the general relationships are similar. The influence diagram in Fig. 3.1 shows key relationships and feedback mechanisms linking human activity and environmental characteristics. Human activities are mediated by the environmental and social context in which they take place. Local environmental characteristics—the quantities and quality of environmental resources—constrain and provide opportunities for individual and community use of natural resources and ecosystem services. For example, the types of crops that

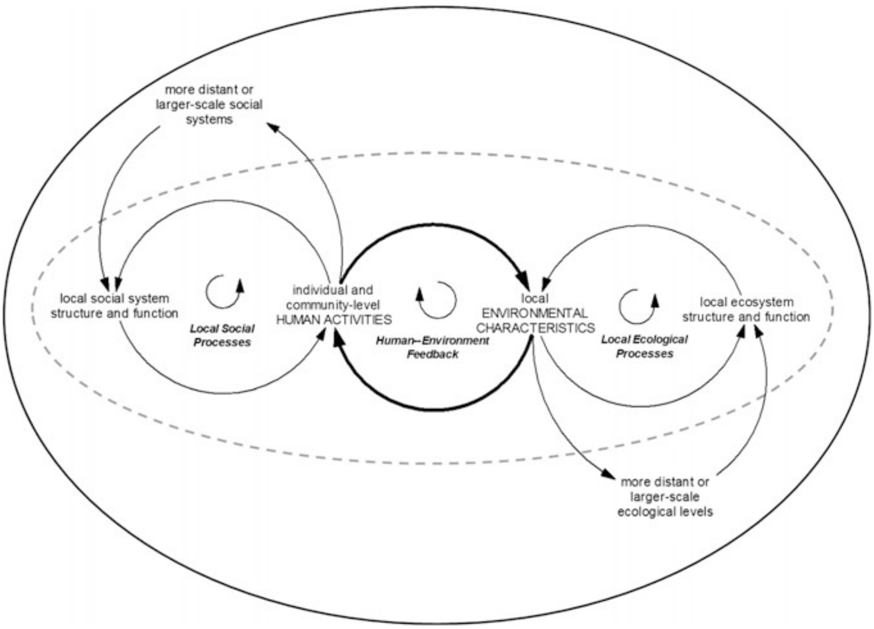

Fig. 3.1 A high-level view of feedback relationships in social–ecological systems. *Arrows* show the direction of cause-and-effect. Human activities lead to changes in environmental characteristics (quantity and quality of environmental components), which, in turn, constrain or provide opportunities for further human activities. Human activities also affect and are affected by social system characteristics. Changes in environmental characteristics in response to disturbances from human activities are shaped by and further shape ecosystem structure and ecological processes. These causal influences underlie the dynamic behavior of all parts of the system, including the central human—environment connection

can be grown or minerals that can be mined are a function of the resources that exist. Construction practices are influenced by climate and other factors such as bedrock geology and seismic activity. Human uses of environmental resources are further mediated by local social system structure and function. Social system factors including cultural norms, markets, institutional regulations, and governance structures shape decisions such as the types of crops farmers choose to grow, labor availability, farming practices, and land use patterns.

Human activities lead to further changes in environmental and social conditions. Farming practices such as land clearing or open grazing transform the landscape, changing forest habitats to open land, causing soil erosion in places and building up soil nutrients in others. Increasing rural population and decreasing land availability lead to agricultural intensification and pressure to convert marginal lands such as wetlands to farmland. Decreased wetland area leads to changes in vegetation and habitat near the lake shore, affecting the livelihoods of people who harvest papyrus and fish. Land use changes and farming outcomes can alter social relations among farmers. Changes in environmental conditions yield further changes in ecosystem structure and function such as microclimates, local hydrology, species composition and habitat. The direction and magnitude of such changes are further governed by ecological processes and environmental factors such as climate, topography, and geology.

Understanding such human—environment systems, and developing management strategies and policy decisions that promote their sustainability requires a holistic approach. Many conceptual frameworks have been developed that include social and environmental components. Integrating social and ecological systems in practice has been difficult to do, however. The analytical and practical challenge is to identify the interactions among components in such systems that underlie resource management problems, find leverage points where management or policy changes can effectively move the system in a more sustainable direction, and build cooperation among system stakeholders to implement change.

In this chapter we present system dynamics as a theoretical and analytical framework for addressing and formalizing this challenge in the Lake Tana region. System dynamics allows for integration of critical connections across disciplinary lines, highlights feedback relationships that underlie patterns of change in the system, and provides a platform that fosters collaboration and coordination among stakeholders in the system including researchers, policy-makers, and resource users. We first present an overview of existing frameworks for analyzing social—ecological systems and discuss some challenges in applying them. Then we describe what a system dynamics perspective offers for social and ecological system analysis and explain the steps in the approach. This approach was used as the framework for a collaborative mapping workshop on sustainability issues in the Lake Tana basin held in November 2014. Chapter 34 describes the workshop and the initial systems map that was produced.

3.2 Overview of Existing Frameworks, Their Application and Remaining Challenges

3.2.1 Overview of Existing Frameworks for Social and Ecological System Analysis

A number of conceptual and analytic frameworks exist for understanding the interrelationships between humans and nature. They include the three-legged stool or three-pillars model in which environment, economy, and society, often further described as ecological integrity, economic security, and social equity, must be balanced to achieve sustainability. This view is sometimes represented with three equal-sized circles for environment, economy, and society arranged so their edges overlap, with sustainability at the intersection of the three circles. Other versions show different arrangements, depicting unequal relationships among the sectors. Some argue economy and society cannot exist without the environment, so the environment must be the foundation for the stool, represented by a circle fully encompassing both the economy and society (e.g., Dawe and Ryan 2003). Such conceptual models help structure thinking about how people interact with the environment and promote an integrated view.

Other frameworks quantify specific aspects of human—environment interaction. Ecological footprint analysis (Wackernagel and Rees 1996) calculates the amount of land required to provide resources and process waste from human activities. Water footprint analysis (Hoekstra and Mekonnen 2012) determines how much water is used in agricultural or industrial production, how such embodied water flows around the world through international trade, and how water is consumed from sources internal or external to nations. Planetary boundary analysis (Rockström et al. 2009) describes nine dimensions of the environment and identifies a "safe operating space" within which human activity can take place. Comparing the effect of activity to thresholds gives a measure of how much development can take place before serious consequences arise.

These frameworks connect human activity and environmental conditions broadly, account for the resource demands of food and industrial production and the ecosystem services required to process waste, and begin to clarify how close we are to ecological limits. Other frameworks such as coupled human and natural systems (CHANS) (e.g., Liu et al. 2007) examine links among social and ecological system components. The water-energy-food nexus framework (World Economic Forum 2011) is a conceptual model of the links between water, energy, and food security. Biggs et al. (2015) extend the framework to include consideration of livelihoods. Liu et al. (2013) propose the idea of telecoupling, in which human—environment systems that may be spatially distant can be connected by flows of resources and products that have different effects on the sending and receiving systems.

3.2.2 *The Social—Ecological System (SES) Approach*

One approach that is particularly relevant to the resource management issues in the Lake Tana region is social-ecological system analysis (Ostrom 2009; Holling 1973). In this approach, natural resources used by humans are viewed as embedded in social-ecological systems, that is, in systems where cultural, political, social, economic, ecological, technological, and other components interact. A socio-ecological system provides essential services to society such as supply of food, fiber, energy and drinking water (Berkes and Folke 1998). Accordingly, fisheries, forests, pastures, coastal zones, and water bodies are social-ecological systems that are described widely in the SES literature (e.g., Anderies et al. 2006; Berkes et al. 2003; Cifdaloz et al. 2010; Ostrom 2009; Walker et al. 2002, 2006).

Like other types of systems, social-ecological systems consist of many different parts that interact in complex ways (Resilience Alliance 2010). SES subsystems span social, economic, political and environmental dimensions (Ericksen et al. 2009; Thompson and Scoones 2009; Cash et al. 2006) and several hierarchical levels within each dimension (Cash et al. 2006). The ecosystem dimension of an SES, for example, might be considered at five nested levels from micro-habitat to patch, reach, river, and biogeographical region (Dore et al. 2010: 41). In the economic dimension, local economies operate within the provincial, national, regional, and international economy. System activities take place across dimensions and across levels. Individual- and local-level human actions that happen on a daily or weekly basis can have significant implications for sustainable resource management when aggregated at higher spatial or temporal levels.

Through interactions and feedback effects across subsystems and levels in response to internal or external pressures, social-ecological systems can self-organize (i.e., adjust themselves through interactions among their components), novel configurations can emerge, and adaptation is made possible (Berkes et al. 2003). Interactions and feedback effects, however, often lead to the emergence of trade-offs between one set of services, e.g. food production, at the cost of another (often environmental services), e.g. cleaner water (Carpenter et al. 2009, Ericksen 2008, MEA 2005).

3.2.3 *Analyzing Social-Ecological Systems*

Analyzing a social-ecological system requires a systems approach, that is, a holistic approach that does not focus on a detailed understanding of parts, but on how links between key components contribute to the dynamics of the whole system. Integrated social—ecological systems cannot be analyzed with disciplinary approaches alone. Instead, complexity needs to be addressed in an inter- and transdisciplinary way (Carpenter et al. 2009; Ostrom 2009). A variety of methodologies for studying SES have been proposed (Binder et al. 2013). Although they differ with respect to their theoretical foundation and their conceptualization of the ecological and social subsystems and their interrelations, all of these methodologies aim at providing an integrative perspective on social-ecological systems.

The literature describes a variety of steps for analyzing specific SES (e.g., Cumming et al. 2005; Engle et al. 2013; Walker et al. 2002). These can be summarized into four generic stages: (1) defining the system and desired outcomes, (2) identifying drivers of change in the system, (3) identifying interventions to move the system toward desired goals, and (4) evaluating and implementing interventions. Analyzing a social-ecological system involves constructing a model of the system of interest, i.e., a simplification or distillation of the complex system into a conceptual map of the critical features of the place, issues, and people involved. Mapping the system components and flows is a way to *define the system and outcomes* (step 1). The map is used to *identify drivers of change* (step 2). Although some activities and questions address individual system components, these insights are meant to contribute to an understanding of the dynamics of the whole system. Assessing the impact of drivers of change and interventions along with the conceptual model helps to reveal factors that contribute to a sustainable future trajectory (steps 3, *identifying interventions,* and 4, *evaluating and implementing interventions*).

Computer simulation models for SES play an important role in the analysis of SES and consequently, SES modeling is an emerging field (Schlüter et al. 2014). Most existing SES models are largely theoretical, however, (Schlüter et al. 2012) and do not provide solutions to empirically measurable issues (Janssen and Ostrom 2006). Current SES models also have limited representation of feedbacks between the social and ecological systems (Schlüter et al. 2012).

3.2.4 Remaining Challenges and Opportunities for Integrated Social—Ecological System Analysis

While much progress has been made in understanding patterns and drivers of change in coupled human and natural systems, there are still several key challenges. These include: integrating social and ecological components across dimensions and hierarchical levels, accounting for feedback in the system, and coordinating and collaborating with stakeholders across disciplines (e.g., Liu et al. 2015, Hammond and Dubé 2012, Alberti et al. 2011). Interactions and feedback effects between ecological and social subsystems, settings and related ecosystems result in complex and often non-linear dynamics (Liu et al. 2007, Ostrom 2009). Reinforcing feedback loops amplify changes in SES components while balancing feedback loops have a stabilizing effect. Identifying feedback mechanisms and being able to examine the way changes in one part of the system feed through to affect other parts is critical for finding places to intervene with management and policies to reverse undesirable trends and promote sustainable ones.

Engaging and fostering collaboration among stakeholders presents different kinds of challenges. The first involves ensuring that the full range of resource users and other system actors, researchers with expert knowledge, and decision-makers contribute to framing the problems and goals of the analysis, describing the system, and analyzing policy options. Due to the multitude of disciplines involved in the study of an SES, model development in SES research increasingly uses participatory or transdisciplinary modes of operation (Etienne 2011, van de Fliert et al. 2011). Fostering coordination and collaboration among "siloed" researchers is difficult (Alberti et al. 2011; Hammond and Dubé 2012). Transdisciplinary work requires developing a common language across disciplines and between researchers and decision-makers. When the analysis is done, a further challenge is to translate findings into implementable policy recommendations (Liu et al. 2015).

In sum, the challenges are not necessarily to develop better models or measures of the human or environmental components, but, rather, to find better ways to understand and represent the connections between them, create tools that allow policy analysis, and integrate stakeholders into the process.

3.3 System Dynamics and SES Integration for Sustainability

System dynamics is a computer-aided approach for policy analysis and design in complex, dynamic systems. It applies to problems that can be framed as undesirable trends over time arising in systems characterized by interdependence, mutual interaction, information feedback, and circular causality (Richardson 1991). It is well suited for formalizing social-ecological systems analyses, because it provides a method for operationalizing the SES framework in Fig. 3.1, and includes well-developed techniques for addressing the challenges of system integration and stakeholder engagement.

The central principle of system dynamics is that a system's structure generates its behavior, where the structure of the system consists of variables describing system characteristics and the material and information flows among them that form feedback loops and cause the system to change. Operating over time, the structure generates dynamic behavior such as exponential growth or decline, s-shaped growth or decline, collapse or oscillations (Saysel et al. 2002). The purpose of a system dynamics study can be to explain observed trends, anticipate the system's likely behavior in response to disturbance, or find a solution for a pattern of behavior considered problematic (Stave 2015). A detailed description of the methodology is given in Ford (2010), Forrester (1961), and Sterman (2000).

System dynamics addresses issues of system integration in several ways, including an explicit focus on change over time and an emphasis on modeling a specific problem or set of problems rather than modeling a system. The explicit focus on dynamic behavior necessarily integrates over time. A system's behavior is a function of the interactions of system components over time. System dynamics simulation models keep track of the accumulation and depletion of stocks as the model steps through time. The problem orientation in system dynamics focuses attention on the causal relationships that generate the problematic behavior. The analysis process does not predetermine the disciplinary theories or data needed to understand an issue. Rather, it facilitates the identification of the causal pathways relevant to the particular behavior of interest, regardless of discipline or geography, and thus draws in and integrates the disciplines specific to understanding what is causing the problem at hand (Stave 2015). System dynamics also includes practices for engaging stakeholders in problem solving through participatory or group modeling (e.g., Andersen et al. 1997; Rouwette et al. 2011; Stave 2010).

3.3.1 System Dynamics Modeling Process

The fundamental premise of system dynamics—that a system's dynamic behavior is generated by its structure—drives the modeling and analysis process. Explaining an observed behavior, anticipating behavior after disturbance, or changing a problematic pattern of behavior all begin with a description of the behavior of interest, followed by identification of the components, causal connections and feedback relationships that make up the structure (Stave and Kopainsky 2015). Creating a computer simulation model of the structure involves translating the structure into a set of mathematical equations that represent the relationships between variables. The model is first tested to ensure it can produce the behavior of concern, and revised until it does. Then it is used to probe the system's potential response to planned policy interventions or unplanned disturbances.

The steps in the modeling process are summarized below (see, e.g., Richardson and Pugh 1981; Sterman 2000 for more detail). These steps build on each other, although the modeling process generally involves considerable iteration between steps:

- *Define the behavior of interest*. Identify the trend or set of trends over time that need to be explained, that might be expected in response to a disturbance, or that constitute the problem to be solved. Specify which quantities vary, over what time period, and with what pattern.
- *Develop a conceptual model of the structure underlying the behavior of interest*. System conceptualization is the development of a hypothesis about the structure that generates the dynamic behavior of interest. It is called a *dynamic hypothesis* because it is the structure that is proposed to be causing the behavior. System conceptualization can be qualitative, using diagrams to visually represent different types of variables and the relationships among them, or operational, in which mathematical equations describe relationships among variables. Different types of structural representations are used for different purposes. The process of system conceptualization is to work backward from the identified problematic

variable or variables to determine immediately previous causal connections. A system dynamics analysis traces from the problem behavior outward along chains of cause and effect, rather than from the system boundary inward. This is described as modeling the causes of the problem, rather than modeling the system.

- *Validate the proposed structure*. Model validation takes two main forms, first, testing the logic of the proposed model relationships against what is known in theory, data, or common sense. Second, if the model structure has been converted to an operational computer model, the model can be simulated and the output compared with observed or anticipated system behavior. If the model cannot produce the expected behavior, go back to the previous step and revise the structure.
- *Use the model for analysis*. Use the model to identify points of intervention, either where unplanned shocks or stressors might affect system variables, or where deliberate policy interventions could be targeted. The simulation model allows you to conduct "what-if" analyses to compare the potential effects of alternative policies.

3.3.2 Participatory System Dynamics Modeling

Participatory techniques include diagramming tools such as causal loop diagrams (CLD) or stock and flow diagrams (SFD) that make mental models public so they can be shared. Such visualization tools allow the meaning and importance of system elements to be negotiated. They provide a coherent grammar and syntax, a common language with which participants can communicate with each other about the system (e.g., Black 2013; Hovmand 2014). Engaging stakeholders in problem and system description promotes understanding of the feedbacks and system behavior. Diagramming tools can expand participant ideas about the range of potential solutions by showing system-wide points of intervention (Antunes et al. 2015). Participatory modeling and evaluation of proposed policies on problematic behavior promotes buy-in for implementing policies. A typical participatory systems mapping process consists of the following stages and activities (Antunes et al. 2015):

- Preparation. This stage includes the identification of stakeholders and establishment of a first contact with participants. At this point, guiding questions for initiating the discussion may be developed by the modeling team, as well as preliminary CLDs elaborated from preliminary interviews with the selected stakeholders.
- Workshops. Most of the collaborative construction of CLDs takes place during workshops. One or more workshops may be planned, with one mapping session typically lasting between 1.5–4 hours. The workshop format may include several activities occurring in plenary or small groups, such as identification of variables, establishing causal links, drawing reinforcing and balancing feedback

loops, identifying leverage intervention points, and documenting knowledge gaps.

- Post-production and follow-up. This stage includes tasks such as refinement and digitalization of CLDs, writing of narratives describing the main feedback loops, and use of CLDs as an input for construction of simulation models.

The high-level perspective on feedback relationships shown in Fig. 3.1 offers an analytical framework for considering the connections among the individual chapters to follow. It also lays the ground for the system dynamics-based integration effort that wraps up this book. In November 2014, a workshop was held to begin a process of integrated analysis and collaborative modeling for Lake Tana basin sustainability issues. The workshop used the system dynamics approach to complete a first pass of the first two steps of the system dynamics process and produce an initial causal map. This application of participatory systems dynamics to the Lake Tana SES is described in Chap. 34.

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