8 Sustainability Systems: Seeing the Matrix

Analytical frameworks help researchers from various fields and backgrounds examine and compare the structures and functions of different kinds of systems. Identifying the main components of systems, understanding how these components interact, and assessing how actors can intervene to effect change, are topics of broader interest to analysts who focus on a range of sustainability issues. Findings relating to the components of the mercury systems, their interactions, and past interventions drawn from part II can inform systems-oriented studies related to sustainability. Our analysis shows that important operations and properties of the mercury systems can be examined by applying the human-technical-environmental (HTE) framework and a matrix-based approach to identify and map relationships between human, technical, environmental, institutional, and knowledge components. A similar approach could also yield promising insights for other sustainability issues.

We argued in chapter 1 that advancing understanding of sustainability requires in-depth examination of additional empirical cases to further generate knowledge and test theories. With that purpose in mind, the five topical mercury systems detailed in part II provide a rich set of empirical material covering a long period of human history. People, over centuries and millennia, have interacted with mercury and in the process developed new scientific knowledge, technologies, and products with the goal of improving prosperity and well-being. Human uses and discharges of mercury, however, also modified ecosystems and harmed human health. We used the HTE framework to analyze each of the five mercury systems in part II as an individual system within its own boundaries and with its own interactions among human, technical, environmental, institutional, and knowledge components. Yet the mercury systems are connected to one another, not only by the presence of the element mercury, but also by other common system components, and these components also link to other systems relevant to sustainability.

The HTE framework and the matrix-based approach that we introduced in chapter 2 provide a way for an analyst to “see” system components (as referenced in the title of this chapter) and study their dynamics as part of complex adaptive systems. Examining a system involves determining system boundaries and components for analysis, identifying causal pathways of interactions among system components, and assessing the potential for changing system operations. In this chapter, we draw lessons from across the empirically grounded findings from the mercury systems to answer the first three research questions we posed in chapter 1. First, what are the main components of systems relevant to sustainability? Second, in what ways do components of these systems interact? Third, how can actors intervene in these systems to effect change? We conclude the chapter by discussing the utility of the HTE framework and the matrix approach for analyzing other systems relevant to sustainability.

The Matrix Revisited: System Components, Interactions, and Interventions

The five chapters in part II are intentionally structured in an identical way to follow four consistent steps. The first three steps make up the matrix-based approach: first, the identification and classification of system components; second, the examination of pathways of selected system interactions; and third, the assessment of interventions toward greater sustainability. In this section, we discuss and compare the findings from these three steps and associated research questions. We discuss findings relating to the fourth step, drawing insights from the system analysis, in chapter 9.

System Components

Three findings based on our analysis of the five mercury systems connect to our first research question, about the main components of systems relevant to sustainability. First, the mercury systems can be usefully described as comprising a combination of human, technical, environmental, institutional, and knowledge components. Second, the mercury systems can be analyzed by identifying a relatively small number of each type of component, and different system descriptions require differing levels of specificity for system components. Finally, while some components are unique to a single mercury system, others are common across several mercury systems, and these may also be important to other sustainability-relevant systems.

All of the individual components from the mercury systems are summarized in figure 8.1 (with numbers in parentheses to indicate the chapters they correspond to, 3 through 7). The components are listed in the order in which they appear in those chapters, but they are grouped based on the level of empirical detail with which we have chosen to represent each component. For example, as human components, we treat workers and employers in mercury-using sectors as a single component in the health system and the products and processes system. In other systems, however, we disaggregate human components at a finer level of empirical detail. The artisanal and small-scale gold mining (ASGM) system includes ASGM miners as well as gold processors, whereas the health system involves medical

Human components

- Workers and employers in mercury-related sectors (4,6)
  - Miners (3)
    - ASGM miners (7)
  - Medical professionals (4)
  - Gold processors (7)
- Producers and consumers of energy and (industrial) goods (3,5)
  - Producers and consumers of mercury-added products and other goods made using mercury (6)
    - Medical patients (4)
  - Consumers of food (4)
  - Producers of commercial market food (4)
  - Gold supply chain particpants (7)
  - Mercury supply chain participants (7)
- People living near mercury discharges or contaminated sites (6)
  - Consumers of food (4)
  - Non-commercial harvesters (4)
  - People living near industrial point sources (5)
  - Other ASGM community members (7)
- People living far from mercury discharges (6)
  - Consumers of food (4)
  - Non-commercial harvesters (4)
  - People living far from industrial point sources (5)
  - People living far from ASGM sites (7)

Technical components

- Extracted mercury (3)
  - Mercury in commerce (3,6,7)
  - Mercury in stockpiles and landfills (3,6)
- Extracted geological materials containing mercury (3)
  - Extracted fossil fuels (6)
    - Extracted coal (5)
- Mercury-added products (3,6)
  - Mercury-containing medicines and medical treatments (4)
- Mercury in production processes (3,4,6)
  - Mercury used in ASGM (7)
- Energy and industrial goods (5)
  - Other goods made using mercury (6)
- Industrial point sources of mercury discharges (6)
  - Industrial point sources of mercury emissions (5)
- Air pollution control devices (5)
- Transportation and communciation infrastructure (7)
- Mining and amalgamation equipment (7)
- ASGM mercury capture devices (7)

Environmental components

- Geological reservoirs (3,6)
  - Coal in geological storage (5)
  - Ore at mining sites (7)
- Atmosphere (3,5)
- Land (3)
- Oceans (3)
- Terrestrial and aquatic ecosystems (3)
  - Ecosystems near mercury (emission) sources/uses (4,5,6)
    - Living organisms (3)
      - Fish, shellfish, and marine mammals (4)
    - Rice (4)
    - Ecosystems near ASGM sites (7)
  - Ecosystems far from mercury (emission) sources/uses (4,5,6)
    - Living organisms (3)
      - Fish, shellfish, and marine mammals (4)
    - Ecosystems far from ASGM sites (7)
- Contaminated sites (6)

Institutional components

- Markets for energy and goods (5)
  - Mercury markets (3,6,7)
  - Markets for mercury-added products and goods made using mercury (6)
  - Gold markets (7)
- Regional treaties (3)
  - International air pollution agreements (5)
- Global Mercury Partnership (3,5,6,7)
- Minamata Convention (3,4,5,6,7)
- Trade controls (3)
- National and local laws and regulations (4,5,6,7)
- Dietary recommendations (4)
- Cultural norms (4)
- International certification schemes (7)
- Standards set by international organizations (7)

Knowledge components

- Forms of mercury (3,4)
- Properties of mercury (3,4,6)
- Long-range transport (3,5)
- Mercury concentrations in the environment (3,7)
  - Mercury concentrations in the atmosphere (5)
- Quantities of mercury in stockpiles and trade (3)
- Exposure routes (4)
- Mercury concentrations in people (4)
- Health impacts from mercury exposure (4,6,7)
- Health protection techniques (4,6,7)
- Mercury deposition (5)
- Techniques for air pollution control (5)
- Mercury-based product development and production techniques (6)
- Individual and societal beliefs (6)
- Environmental impacts from mercury discharges (6,7)
- Mercury-free product development and production techniques (6)
- Gold extraction techniques (7)

Figure 8.1

Unique and common components of the mercury systems in part II (chapter numbers in parentheses).

professionals, all of whom are also included in the larger group of workers in mercury-related sectors. Figure 8.1 thus illustrates the relative level of detail for the individual components in each mercury system, and the relationship of these components to each other.

Categories of System Components The system components we chose as the ones most useful for describing the individual mercury systems cover all five categories of components: the material human, technological, and environmental components, and the non-material institutional and knowledge components. Humans are present as workers, employers, producers, consumers, and people living near and far from mercury discharges. Technical components include extracted mercury, mercury-added products, industrial point sources of mercury discharges, and air pollution control devices. Environmental components include the atmosphere, land, oceans, and contaminated sites. Institutional components include markets for energy and goods, the Minamata Convention, and national and local laws and regulations. Knowledge components include information about different forms of mercury, health impacts from mercury exposure, and mercury-free product development and production techniques.

Our decision to classify components among the five predetermined categories undoubtedly influenced our selection and categorization process. Nevertheless, we believe that two findings based on the individual components that we identified are valid and useful. First, we were not able to describe and analyze any of the five mercury systems without including human, technical, environmental, institutional, and knowledge components. This strengthens the assertion at the core of our systems perspective: analyses that only address some of these five sets of components might omit important parts of systems relevant to sustainability. Second, we did not identify any important components that did not fit (or any that fit very imperfectly) into one of the five categories of system components. This suggests that we are not missing an important component category by focusing on these five categories in our analytical framework.

Our categories of system components are similar, but not identical, to those found in other system descriptions such as social-ecological systems, coupled human-natural systems, and socio-technical systems (Liu et al. 2007; Ostrom 2009; de Weck et al. 2011). Several of these systems would capture some of the same individual components that we identify, but sometimes in different categories. For example, what we call technological components would mostly be included in the human category in coupled human-natural systems research (Liu et al. 2007). In our analysis, we find it useful to draw a clearer distinction between technological and human components for the subsequent analysis of interactions and interventions. Some of our components may also be treated as external to systems in other literatures. For example, in engineering systems literature focusing on socio-technical systems, environmental components are often treated as boundary conditions.

In our framework, we differentiate material (human, technical, and environmental) from non-material (institutional and knowledge) components, which helps us connect more explicitly to efforts to model and simulate systems, as discussed below. Our categories of components also overlap with efforts to assess the importance and value of different kinds of capital assets that are viewed as fundamental building blocks of human well-being in sustainability analysis. These capital assets can include human capital, natural capital (most environmental components), manufactured capital (e.g., infrastructure and buildings), social capital (including institutions), and knowledge capital (Polasky et al. 2015). The overlap between our categories and those used in other system descriptions and studies of capital assets suggests that human, technical, environmental, institutional, and knowledge components are indeed important constituents of sustainability.

Number and Specificity of System Components The total number of human, technical, environmental, institutional, and knowledge components that we identify for each component category in the five mercury systems ranges from two to seven. The total number of system components for each of the mercury systems ranges from 20 to 27. The identification of this relatively limited number of individual components nevertheless made it possible to capture the properties and dynamics of each mercury system that we needed for our analysis. It would of course have been possible to identify a larger number of components for each mercury system. This would have given us the ability to describe each mercury system in greater empirical detail. However, we believe that using a greater number of system components would not have had a meaningful positive impact on our analysis of system interactions and interventions; we found that the aggregated descriptions of the selected components captured the necessary degree of detail in each system.

Each system description contains components that vary in specificity and spatial scale. Ecosystems near mercury sources or uses, for example, are included as an environmental component in the health system, atmospheric system, and products and processes system, encompassing a broad range of ecosystems in many regions across the world. Ecosystems near ASGM sites in the ASGM system are a specific sub-category of ecosystems near mercury sources. Similarly, extracted fossil fuels in general are addressed as a technical component in the products and processes system, but extracted coal in particular is identified as an individual component in the atmospheric system. This shows that components need not be described at the same level of detail in system descriptions. With respect to spatial scale, environmental components could be a small contaminated site or as big as the oceans. Technical components can be small and limited to a specific location, such as a mercury capture device that is used in ASGM, or diffused across the world, such as mercury in commerce. Institutions can take the form of locally specific dietary recommendations, or be global in scale like the Minamata Convention.

Clearly identifying the varying levels of specificity and spatial scale needed to describe system components can assist those who model and simulate systems. The modeling community refers to the development of model simulations at differing levels of scale and complexity as a "hierarchy" or "spectrum" of models (Claussen et al. 2002). The term "hierarchy" was initially used to capture the existence of models ranging from simple to more detailed, but could be construed to imply that high-resolution models are better. The term "spectrum" avoids this implication, acknowledging that the scale of modeling should fit its intended purpose. If system descriptions are useful at varying levels of specificity, different models should be developed to answer different questions. The use of mercury models ranging from global biogeochemical cycle models to detailed ecosystem-specific models helps the scientific community to understand interactions occurring on varying scales across time and space (Obrist et al. 2018). The climate modeling community similarly has used a spectrum of models to address interactions between human activities and the climate system at different levels of resolution (Claussen et al. 2002).

Uniqueness of System Components Some of the identified components are unique to one of the five mercury systems. Unique human components include consumers of mercury-added products and other goods made using mercury in the products and processes system, and ASGM miners in the ASGM system. Mercury-containing medicines and air pollution control devices are unique technical components in the health and atmospheric systems, respectively. Contaminated sites are a unique environmental component in the products and processes system, and rice is an environmental component in only the health system. Gold markets and international certification schemes are institutional components only in the ASGM system. Knowledge of technology-based air pollution controls is part of just the atmospheric system, whereas knowledge of mercury-based and mercury-free production techniques is unique to the products and processes system.

Several material components are common across two or more of the mercury systems, and are thus important for examining connections among those systems. Ecosystems far from sources of mercury discharges are affected by mercury emissions and releases from a combination of sources, including industrial point sources, ASGM, mercury-added products, and mercury in production processes. People living far from mercury sources are similarly affected by mercury from all these sources, as some discharged mercury travels long distances in the environment before it is converted into methylmercury. Mercury in commerce links mercury-added products and mercury in production processes to ASGM through supply and demand dynamics.

Common institutional and knowledge components also link several of the mercury systems. The Minamata Convention covers issues that are central to all five mercury systems through its lifecycle focus on mercury management. Other institutions such as the Global Mercury Partnership link societal efforts to control mercury emissions in the atmospheric system, to move to mercury-free alternatives in the products and processes system, and to phase out mercury-based amalgamation methods in the ASGM system. National and local laws and regulations on mercury discharges connect initiatives to protect the environment and human health from several different sources of mercury in the atmospheric, products and processes, and ASGM systems. Scientific knowledge about the properties of mercury influences its use in the products and processes and ASGM systems. Medical knowledge about the human health effects of mercury exposure shapes mercury use in the health, products and processes, and ASGM systems, and also informs the formulation of dietary guidelines targeting particularly vulnerable groups in the health system.

Some of the mercury system components are also relevant to other issues, suggesting that they may be important to sustainability more broadly. Components relevant to other issues fall within all our categories of system components, both material and non-material. For example, workers and consumers are central in the human health, atmospheric, products and processes, and ASGM systems (as miners and supply chain participants). They are also essential components of different types of production and consumption systems as well as energy issues. Extracted fossil fuels are a key technical component for the products and processes system and the atmospheric system (in the form of extracted coal), and are an important component for other air pollution, climate change, and energy issues. Ecosystems far from mercury sources or uses, present in several of the mercury systems, may be areas of particular concern for other environmental issues such as biodiversity. Knowledge of health protection techniques that is important in the health system is also relevant to pesticides and industrial chemicals. In addition, national and local laws and regulations on pollution are key elements in many sustainability-relevant systems. The relevance of components across several domains relates to the concept of nodes in network analysis, which has been applied in studies of social-ecological systems (Janssen et al. 2006). Common system components could be considered as nodes, and interactions considered as links, if the matrix were represented as a network map.

System Interactions

To address our second research question on interactions, we focus on the 14 pathways of interactions that we identified across the five mercury systems. These pathways are summarized in figure 8.2, grouped into four different types based on which material interactions the pathways include. We identify three major findings related to the ways in which the material components interact, in the context of the two non-material components. First, most (but not all) pathways involve interactions among all three categories of material components. Second, pathways that coexist with each other vary with respect to the number of interactions that they include and how interactions are connected to one another. Third, pathways cross

Human and Technical (HT) Pathways

HT1: Occupational exposure and health impacts: Workers in different sectors come into contact with mercury, and different forms of mercury affect their health (Chapter 4, boxes 2-1, 1-1, 1-2: T-H, H-H, H-T)

HT2: Medical use and health impacts: Medical professionals prescribe and patients use mercury-containing medical treatments, which affect patients (Chapter 4, boxes 2-1, 1-2: T-H, H-T)

Human and Environmental (HE) Pathways

HE1: Mercury discharges and global biogeochemical cycling: People discharge mercury, which cycles through ecosystems and converts to methylmercury (Chapter 3, boxes 1-3, 3-3: H-E, E-E)

HE2: Climate and ecosystem changes, mercury cycling, and methylmercury production: People alter ecosystems in ways that lead to changes in mercury cycling and methylmercury production (Chapter 3, boxes 1-3, 3-3: H-E, E-E)

Technical and Environmental (TE) Pathways

TE1: Mercury cycling in society: Mercury in commerce is traded across borders and leads to emissions and releases (Chapter 3, boxes 2-2, 3-2, 2-3: T-T, E-T, T-E)

Human,Technical, and Environmental (HTE) Pathways

HTE1. Dietary exposure to methylmercury: Mercury-contaminated ecosystems provide food for consumers, affecting their health (Chapter 4, boxes 3-1, 2-3, 3-3, 1-3, 1-1: E-H, T-E, E-E, H-E, H-H)

HTE2. Industrial production and air pollution: Production of energy and industrial goods benefits society and leads to emissions of air pollutants, including mercury (Chapter 5, boxes 1-1, 1-2, 2-1, 3-2, 2-3: H-H, H-T, T-H, E-T, T-E)

HTE3. Atmospheric transport of air pollutants: Point sources affect air pollution transport and mercury distribution in ecosystems (Chapter 5, boxes 2-3, 3-3, 3-1: T-E, E-E, E-H)

HTE4. Pollution control and mercury emissions: Air pollution controls reduce mercury emissions, but incur economic costs to producers and consumers (Chapter 5, boxes 2-2, 2-3, 2-1: T-T, T-E, T-H)

HTE5. Commercial mercury benefits and harms: Economic and social conditions and geological reservoirs containing mercury prompt the development of consumer goods that provide human benefits but also cause harms (Chapter 6, boxes 2-1, 3-2, 2-2, 1-1,1-2: T-H, E-T, T-T, H-H, H-T)

HTE6. Commercial mercury and the environment: Commercial mercury enters ecosystems, where it affects human health (Chapter 6, boxes 2-3, 3-3, 3-1, 1-3: T-E, E-E, E-H, H-E)

HTE7. Employment in ASGM: Environmental, technological, and socio-economic factors drive employment and local conditions in the ASGM sector (Chapter 7, boxes 1-1, 3-1, 2-1: H-H, E-H, T-H)

HTE8. Use of mercury in ASGM: ASGM miners, ore types, and mining and amalgamation equipment and techniques affect mercury use in ASGM (Chapter 7, boxes 2-2, 3-2,1-2: T-T, E-T, H-T)

HTE9. Health consequences of ASGM mercury use: Mercury used in ASGM affects ecosystems and human health (Chapter 7, boxes 1-1, 2-1, 1-3, 2-3, 3-3, 3-1: H-H, T-H, H-E, T-E, E-E, E-H)

Figure 8.2

Summary of interaction pathways from chapters in part II, grouped by the types of material component interactions that the pathways include. The underlined box number in each pathway identifies focal interaction.

spatial scales from local to global, and temporal scales from minutes to millennia.

Types of Interaction Pathways None of the 14 pathways that we identified in the mercury systems is composed exclusively of interactions that involve only one type of material component. Some parts of pathways, however, involve interactions among material components of the same type. These parts of pathways involve interactions between human components in the form of producers and consumers in the atmospheric system and the products and processes system, and the cycling of mercury among different environmental components and its conversion to methylmercury in the global cycling system. Separate literatures characterize interactions among one type of component. Economic models document interactions among people in markets. Lifecycle assessment models in industrial ecology simulate the flows of materials in industrial production processes. Ecological models of mercury cycling capture ecosystem interactions such as those between different species in a food web. Because the 14 pathways involve at least two different types of material interactions, they fall into four characteristic types: human and technical (HT); human and environmental (HE); technical and environmental (TE); and human, technical, and environmental (HTE).

Pathways involving human and technical interactions: These types of pathways include interactions between human and technical components that are noted in boxes 1-1, 1-2, 2-1, and 2-2 in the interaction matrices in part II (figures 3.3, 4.2, 5.2, 6.2, and 7.2). We identify two of these human and technical pathways, both in the health system. In the first pathway, workers in different sectors come into contact with mercury, and different forms of mercury affect their health (HT1). In the second pathway, medical professionals prescribed mercury-containing medical treatments to patients for a wide range of illnesses that in turn affect the health of these patients (HT2). The appearance of these two human-technical pathways in the health system is not altogether surprising, as health care systems are increasingly examined as socio-technical systems. Socio-technical perspectives are also common in studies of innovation (Geels 2004). In the case of mercury, however, several other pathways that involve innovation, for example in the products and processes system, include interactions involving environmental components as well (e.g., HTE5 and HTE6).

Pathways involving human and environmental interactions: These types of pathways include interactions that are in boxes 1-1, 1-3, 3-1, and 3-3 in the interaction matrices in part II. Two of these types of pathways are present in our analysis, both in the global cycling system. These pathways are where people discharge mercury that cycles through ecosystems and converts to methylmercury (HE1) and where people alter ecosystems in ways that lead to changes in mercury cycling and methylmercury production (HE2). Methods for analyzing pathways involving human and environmental components can be drawn from the literature on coupled human-natural systems (Liu et al. 2007; Chen 2015). Interactions where environmental components influence human components relate to the concept of ecosystem services in which nature provides functions for society (Daily 1997). The Intergovernmental Platform on Biodiversity and Ecosystem Services use similar concepts to link biodiversity to human well-being (Díaz et al. 2015). We only consider pathways to be human-environmental in character if they do not include interactions with an identified technological component. The highly technological nature of the mercury systems likely explains why we found it useful in most cases to explicitly identify technological components that mediate interactions between human and environmental components. For example, discharges of mercury in ASGM are mediated by amalgamation equipment (HTE8).

Pathways involving technical and environmental interactions: These types of pathways include interactions that are located in boxes 2-2, 2-3, 3-2, and 3-3 in the interaction matrices in part II. One pathway in the global cycling system is of this type. In the identified pathway, mercury in commerce is traded across borders and leads to emissions and releases (TE1). A variety of methods have been developed to track flows of different metals, including mercury, in anthropogenic systems, and most of these methods focus on quantifying flows through technical components (Müller et al. 2014). Emissions inventories track the amount of pollutants entering the environment from technological sources (e.g., Muntean et al. 2018). In the majority of cases that we identify in the mercury systems, however, technical-environmental dynamics were closely coupled with human components. For example, in the ASGM system, pathways that involved interactions between amalgamation equipment and the environment also involved its effects on human health (HTE9).

Pathways involving human, technical, and environmental interactions: Pathways that include interactions that involve all three human, technical, and environmental components are the most common type that we identified across the mercury systems (that is, they include combinations of interactions involving all three material components). These interactions are found in all boxes in the interaction matrices in part II, and 9 out of the 14 pathways fall into this category. These pathways are present in the health, atmospheric, products and processes, and ASGM systems. The predominance of pathways that include human, environmental, and technical interactions suggests that the sustainability-relevant dynamics of most interest—those we chose as focal interactions in each mercury system—often involve influences across all the three material components.

Pathways involving human, technical, and environmental interactions include many different components. In the health system, mercury-contaminated ecosystems provide food for consumers, affecting their health (HTE1). In the atmospheric system, production of energy and industrial goods benefits society and leads to emissions of air pollutants, including mercury (HTE2). Point sources affect air pollution transport and mercury distribution in ecosystems (HTE3). Air pollution controls reduce mercury emissions, but incur economic costs to producers and consumers (HTE4). In the products and processes system, consumer goods that are produced using mercury provide benefits but also cause harms to human health (HTE5). Commercial mercury also enters ecosystems, where it affects human health (HTE6). In the ASGM system, environmental, technological, and socio-economic factors drive employment and local conditions in the ASGM sector (HTE7). ASGM miners, ore types, and mining and amalgamation techniques affect mercury use in ASGM (HTE8). The mercury used in ASGM affects ecosystems and human health (HTE9).

Few previous system analyses have assessed human, technical, and environmental components and their interactions in ways that give each component type equivalent emphasis. Literatures on human-environment systems and socio-technical systems, as noted above, cover subsets of human-technical-environmental pathways. Scientists have developed methods to explore dynamics of environmental and human components, including the environmental cycling of mercury and its effects on wildlife and people. Some engineering approaches explore socio-technical dynamics including human and technical components. For example, the development of emission scenarios for mercury involves projecting economic activity as well as the application of control technologies. The prevalence of pathways in the mercury systems that involve interactions among all three types of material components, however, shows how important it is to integrate perspectives from different disciplines when analyzing interactions among material components of systems related to sustainability.

Some existing studies offer promising ways forward to address system interactions across human, technical, and environmental components in a more integrated and comprehensive manner. For example, one modeling study in China links underlying economic drivers (interactions among producers and consumers in markets) with flows of mercury through technologies and the atmosphere, resulting in the estimate quoted in chapter 5 that 33 percent of China's mercury emissions and releases for 2010 were related to the production of goods for export (Hui et al. 2016). There is, however, a need for more interdisciplinary studies and modeling that focuses on societal and environmental flows of mercury and other hazardous substances. Further combining social science, natural science, and engineering studies toward this end holds much promise for advancing sustainability analyses.

Scope and Complexity of Interaction Pathways Pathways vary with respect to their scope (the number of interactions that they contain), and their complexity (whether they are linear or involve multifactor causality and/or feedbacks). Some pathways involve few linked interactions, such as HT2, which consists of only two linked interactions. In contrast, other pathways consist of a greater number of linked interactions, as illustrated by HTE9, involving seven linked interactions. Some pathways are linear, including in the global cycling system where people discharge mercury into ecosystems, which then cycles through the atmosphere, converts to methylmercury, and then affects living organisms (HE1). Other pathways involve multifactor causality. This is the case in the ASGM system, in which both ecological deterioration and the availability of transportation and communication infrastructure affect the choice of potential miners to enter the ASGM sector (HTE7). Some pathways include feedbacks in the form of reciprocal interactions, such as in the health system where workers use mercury that in turn affects their health (HT1). A larger feedback loop is present in the products and processes system in the pathway involving commercial mercury benefits and harms (HTE5). In this pathway, market interactions between producers and consumers lead to the sale of mercury-added products that provide benefits or harms to consumers, thus influencing their purchasing decisions about mercury-added products.

Pathways of varying numbers of interactions and degrees of complexity coexist and interact with each other. Pathways that include a larger number of interactions caused by multiple factors became more common as a result of the growing use and dispersal of mercury during the industrial era. The global distribution of mercury through the atmosphere—combining mercury from multiple sources—became important once emission levels increased enough to pose risks to faraway ecosystems (HTE3). Some pathways that emerged earlier in history, however, continued to operate alongside the more complex pathways that became more important later on. In the health system, workers in different sectors for centuries came into contact with mercury that affected their health (HT1). The importance of this pathway has declined recently with the reduced commercial use of mercury, but it existed for a long time even as longer pathways emerged from the industrial use of mercury. New knowledge can also reveal the existence of previously unknown pathways. Only recently have scientific studies been able to trace the transport of mercury across environmental components, and identify the importance to environmental levels of previously unrecognized sources such as mercury in commercial products (HTE6).

The high prevalence of non-linear pathways with larger numbers of interactions poses substantial challenges for scientific efforts to document causality and for researchers developing and refining methods to better understand the mercury systems. For example, isotopic analysis makes it possible to identify mercury in an environmental sample that has a specific atomic mass, which can help determine its source (Blum et al. 2014). This holds much promise to account for environmental interactions, but these methods cannot be easily integrated to track causality across human, technical, and environmental components. Environmental monitoring and analysis techniques may at some point be able to distinguish between different sources of historically and recently released mercury in air or water. However, they would not be able to identify whether that mercury was less or more prevalent because of a regulatory policy, the application of a technology, or broader economic forces such as changes in production and trade patterns. This suggests that new interdisciplinary methods are needed to capture the full complexity of interactions in human-technical-environmental systems.

Spatial and Temporal Scale of Interaction Pathways Pathways often comprise interactions that cross multiple spatial scales. The spatial extent of the mercury issue seems global when focusing on global-scale cycling, but environmental and human-driven transport of mercury creates regional and local dynamics as well. In part II, we identified several examples of pathways across local to global levels of spatial scale in the mercury systems. Whale consumers in the Faroe Islands are harmed by mercury released far from their borders (HTE1). But their local culture and dietary habits—the decision to continue the *grindadráp* and to consume whale meat and blubber—mediates their exposure and determines its ultimate impacts on their health. ASGM has many of the hallmarks of a traditional place-based case study of sustainability, but it is fundamentally linked to global-scale forces (HTE7). The international gold market sets the economic conditions for ASGM, and much of the mercury that is used in ASGM is imported (both legally and illegally) from other countries. Multinational mining firms also interact with national authorities and local miners to create complex political situations and socio-economic conditions in the ASGM sector.

All five types of components are involved in interactions crossing spatial scales, from the local to the global. Some people (human components) have moved across countries and even continents to enter the ASGM sector based on conditions in global markets (HTE7). Some mercury in commerce (a technical component) is traded internationally before it is emitted and released (TE1). Mercury that is discharged into ecosystems (environmental components) cycles globally (HE1). The degree to which mercury emissions from industrial point sources travel to affect both local and faraway ecosystems depends on the site-specific application of air pollution controls (HTE4). The application of control technologies involves local technical knowledge as well as institutions such as domestic laws and the global Minamata Convention that mandate technology-based control approaches. Not all interactions, however, occur across spatial scales. Many people who live near contaminated sites that are caused by mercury discharges from local sources are affected by their close proximity to these sites for long periods of time (HTE6). Local exposure to mercury also remains common in ASGM (HTE9).

Interactions involving the five types of components operate at different temporal scales that combine through pathways to determine the timescales of each system. The environmental cycling of mercury continues over centuries and longer (HE1). In contrast, many interactions involving technology and humans involve shorter timescales. Exposure to mercury and related health impacts for workers in mercury mining and other sectors can happen on a timescale of hours to months (HT1). Similarly, interactions involving air pollution controls may occur on timescales of minutes to months, where control devices can be installed and turned on and off and thus affect emissions rapidly (HTE4). Institutions and knowledge play a substantial role in determining the timescales on which interactions occur and change. Although the aspects of exposure in pathway HT1 are short-term, these exposures can persist for much longer because of the influence of institutions and knowledge. For example, while the average life of a miner in Huancavelica was only a few months, colonialism and conscription allowed for mining to continue over centuries. For the pathway HTE4, development of new knowledge such as techniques for pollution controls may take years or longer. The process of changing laws and regulations for pollutant control can further stretch from years to decades, and is influenced by developing scientific understanding of mercury impacts on the environment and human health.

The fact that pathways cross both spatial and temporal scales can separate impacts in space and time from their causes, which challenges efforts to link specific sources to particular observed effects. This can be seen in pathway HTE1 in the health system. Tracing this pathway backward, consumers of commercial market seafood are affected by the concentrations of methylmercury in their entire diet of different species of fish and shellfish, and much commercial seafood is traded across borders. These fish and shellfish spent their various lifetimes (short to long, depending on the age of the harvested seafood) in different freshwater and saltwater basins where they had varying diets, depending on the structure of the ecosystem and their position within the food web. The methylmercury in the fish and shellfish came from a combination of mercury discharges from local and distant sources that was originally discharged during both historic and present times. This methylmercury accumulated in biota over timescales that may have ranged from months to decades depending on ecosystem characteristics.

System Interventions

For the third research question on interventions, we focus on four aspects of how actors can intervene in complex adaptive systems to effect change toward greater sustainability. First, some interveners took actions targeting mercury specifically, while other interventions that affected mercury use and discharges were taken with other goals in mind. Second, interventions addressed both material and non-material components at different leverage points across pathways, and many of the more effective strategies combined different types of interventions. Third, interventions occurred at different spatial and temporal scales, but they often propagated across scales. Fourth, a broad range of actors with varying levels of power and influence was able to prompt system-level changes. Figure 8.3 summarizes the interveners for the five mercury systems, and identifies the material interactions that different interveners targeted.

Goals of Interventions In the mercury systems, the goals of interventions fall into two main categories: those that primarily targeted mercury and those that mainly involved other issues but also affected mercury. Some interventions were taken to protect human health and/or the environment from mercury. Bans of mercury in teething powder and medical applications were introduced to protect small children from acrodynia. Mercury emission controls such as the US Mercury and Air Toxics Standards were set to mitigate human health damages. Bans and restrictions on the use of mercury-containing pesticides such as Panogen in Sweden, the United States, and elsewhere were designed to protect the environment and human health simultaneously. The EU's recent calls to establish a mercury-free economy are motivated by environmental and human health concerns. The elimination of the very small remaining uses in products, such as mercury in button-cell batteries, is related to this goal. In ASGM, phasing out mercury use is a vitally important piece of efforts to reduce environmental discharges and to protect the health of miners, gold processors, and other community members.

Other interventions that reduced or eliminated the use and/or environmental discharges of mercury were largely driven by non-mercury concerns, but had the positive side effect that they also addressed different aspects of the mercury problem. Governments instituted air pollution controls beginning in the 1970s and 1980s that mainly targeted sulfur emissions from industrial point sources, but these controls also helped reduce mercury emissions as an additional benefit. Economic forces and technological innovation, rather than environmental and human health concerns, drove the development of many mercury-free manufacturing processes because

Knowledge

Institutions

	1. Human	2. Technical	3. Environmental
1. Human	MC Article 7 (3); National and local governments (7); International organizations (7); International non-state standard-setting bodies (7)	MC Articles 4–6, 7 (3); Industries (4); National and local governments (4,6,7); Professional organizations (4); International non-state standard-setting bodies (7); Experts (7); International organizations (7)	MC Article 11 (3); National and local governments (4)
2. Technical	MC Article 16 (3); Industries (4); National and local governments (4)	MC Articles 3, 8–9, 10 (3); National and local governments (5,6,7); Industries (5,6); International bodies (5,6); Experts (6,7)	MC Articles 8–9 (3); National and local governments (5,6); International bodies (6)
3. Environmental	MC Article 16 (3); National and local governments (4,5)	MC Article 3 (3); International bodies (5); National and local governments (5); Industries (5)	MC Article 12 (3); National and local governments (6)

Interveners
Minamata Convention parties (3); Minamata Convention bodies (3); Experts (6,7); Global Mercury Partnership participants (3); Industries (4,5,6); National and local governments (4,5,6,7); Professional organizations (4); International bodies (5,6); International organizations (7); International non-state standard-setting bodies (7)

Figure 8.3

Interveners and interventions in the five mercury systems discussed in part II. Minamata Convention (MC) provisions are specified by article, consistent with chapter 3.

they were cheaper and more efficient for producers. The discovery of penicillin, and its effectiveness in treating syphilis, led to the phaseout of this longstanding medical use of mercury before there was a more sustained effort to phase out mercury use in medicine based on health concerns. The higher energy efficiency of LED lighting technology is a central driver of supplanting the minimal use of mercury in compact fluorescent bulbs, which are still allowed under the Minamata Convention.

Some interventions had unintended damaging effects to present and future human well-being as a result of interveners acting with incomplete knowledge of system-level processes and interactions. In some cases, early efforts to communicate mercury-related risks from seafood consumption resulted in pregnant women eating less seafood overall, which was potentially dangerous to fetal development given the nutritional benefits of fish consumption. Switching to cyanide technology is one option for moving away from mercury amalgamation in ASGM, but if done improperly, this can result in even more mercury methylation in local environments (and also creates cyanide management–related problems). Phaseouts of mercury in chlor-alkali production, especially before the US and EU elemental mercury export bans, resulted in the diversion of mercury stocks into ASGM, where much of the mercury was discharged into the environment. Efforts to ban ASGM and related mercury use often result in greater harms to miners and other people who live in mining communities when the activities continue in the informal sector.

Mercury-specific interventions had both positive and negative spillover effects on other sustainability issues. The introduction of mercury emission controls on coal-fired power plants in the United States and Canada, which likely triggered some older plants to close, thus had larger positive effects on abating other types of air pollution and climate change. These effects may not have been completely unintended by those who supported the mercury emission standards, however, given that governments and other public authorities are engaged in broader efforts to improve air quality and reduce carbon dioxide emissions. In contrast, advanced power plants with emission controls can sometimes have a longer lifetime, continuing to emit carbon dioxide. A growing literature aims to better assess links between different interventions and their sustainability-relevant impacts. Many studies focus on connecting actions on climate change to local and regional air pollution, achieving near-term benefits for human health simultaneously with longer-term climate benefits (Nemet et al. 2010; Anenberg et al. 2012). Researchers have also identified the existence of both synergies and tradeoffs among actions to meet targets under the Sustainable Development Goals (Pradhan et al. 2017).

Targets of Interventions Interventions in the mercury systems targeted all nine types of interactions among the material components (as illustrated by figure 8.3, where interventions are present in all nine boxes of the intervention matrix). Different interveners addressed different types of interactions:

this reflects that interveners may have at least partially different goals and capacities when they act to modify specific interactions. National and local governments targeted all nine types of interactions—that is, they appear as interveners in all nine boxes—illustrating the many critical roles that public authorities play in protecting and promoting greater human well-being. The Minamata Convention also addresses all nine types of interactions, consistent with its goal to target the entire lifecycle of mercury. Other interveners targeted more specific types of interactions: for example, industries targeted three of the types of interactions that involve technical components.

Some interventions sought to directly alter interactions among material components, while others instead focused on non-material components in order to change material interactions. Interventions involving material components aimed to reduce discharges of mercury by altering technological components (such as deploying air pollution control devices) and also to physically modify attributes of environmental components (such as by cleaning up contaminated sites). Interventions that modified institutional and knowledge components aimed to alter the rules and parameters for interactions among the material components. National and local governments passed laws to regulate the sale of mercury and mercury-added products and to control mercury emissions and releases. International non-state standard-setting bodies formulated rules about mercury use for certification. These certification schemes and codes shape decisions by ASGM miners on mercury use as well as choices by gold buyers throughout the commodity chain. International bodies collected and diffused knowledge of techniques for air pollution control, affecting implementation of standards through technical components.

Many of the more successful interventions to protect the environment and human health from mercury addressed material and non-material components simultaneously. The deployment of air pollution control devices, a technical intervention, occurred concurrently with efforts to modify institutions to set emission standards at national and international levels. The design and dissemination of mercury capture devices such as retorts in ASGM have been more effective when they are combined with information sharing and education of miners. The role of interventions in influencing material and non-material components relates to ongoing debates on the relative importance that behavioral and technical change has in contributing more broadly to sustainability (Fischer et al. 2012). For example, much debate surrounds the role of individual choices relative to more structural approaches in preventing dangerous climate change (Fragnière 2016; Wynes and Nicholas 2017). A longer-term perspective drawn from the mercury systems supports the claim that interventions that aim to modify behavior together with introducing new technology can reinforce each other in ways that are beneficial for human well-being.

Interventions differed based on where the targeted interactions (as leverage points) were located along the pathways of causal influence. Some "upstream" interventions addressing mercury uses targeted interactions early in a causal pathway, while other more "downstream" interventions on mercury discharges and exposure focused on interactions located later in a pathway. Upstream interventions have different capacities to influence system operations and outcomes than do those that are taken further downstream. For example, controls on discharges occur further upstream than efforts to provide guidelines on dietary consumption within the pathway involving exposure to methylmercury from food sources (HTE1). Limits on discharges can have long-term, comprehensive positive impacts, but can be slow to propagate through the system, especially through environmental components, and it can be difficult to evaluate their impact. In contrast, interventions further downstream can have more immediate desirable impacts on human well-being, but leave the underlying processes causing mercury discharges unmodified.

Analysts (and decision-makers) increasingly acknowledge that upstream and downstream interventions often need to occur simultaneously to maximize their impact. To protect the environment and human health from mercury it is necessary to address mercury use, discharges, and exposure in a comprehensive manner. This idea is related to the concepts of mitigation and adaptation in climate change, with mitigation looking to reduce greenhouse gas emissions and adaptation referring to efforts to adjust to a changing climate. Climate change experts increasingly recognize the need for societies to adapt to climate change while concurrently acting to curb emissions (Schipper 2006). How to "best" balance mitigation and adaptation efforts can be controversial; adaptation efforts may be viewed as taking away from the urgency to reduce pollution. Evidence from the mercury systems shows that conducting simultaneous upstream and downstream interventions can have greater influence on human well-being in the near and long term than either approach in isolation.

Spatial and Temporal Scales of Interventions Interventions in the five mercury systems ranged in spatial scales from local to global. The introduction of measures to protect workers from mercury exposure, such as wearing gloves and other protective clothing in workplaces or increasing ventilation in laboratories, addressed mercury exposure in a specific place. The cleanup of contaminated sites is also locally focused, as is publishing local guidelines on dietary consumption for seafood consumers. At the other extreme, much recent action on mercury has occurred in global forums, with government representatives from all over the world negotiating the provisions of the Minamata Convention and collaborating with other stakeholders under the Global Mercury Partnership. Interventions can occur at different scales than the interactions they ultimately aim to change. Interventions to protect local consumers of seafood, for example, can involve setting global emission standards under the Minamata Convention. Many interventions that affect local mercury use in ASGM emerged in the context of international development efforts and global-scale mercury policy, including bans on mercury mining and restrictions on reuse and trade in elemental mercury under the Minamata Convention.

Interventions can propagate across scales through both top-down and bottom-up dynamics. Recent global top-down interventions under the Minamata Convention prompted efforts to ban all remaining primary mercury mining and to phase out mercury use in chlor-alkali production worldwide, to be implemented and enforced by each party within its own jurisdiction in specific geographical places. In contrast, some efforts to ban specific mercury-containing products prior to the adoption of the Minamata Convention were driven by bottom-up efforts. Individual US states led many local efforts to ban mercury in several products, such as batteries, that were then adopted nationally. These initiatives prompted transnational private sector technological development as well as learning across different jurisdictions. In another example of interventions spreading from a smaller to a larger scale, the thresholds incorporated in the Minamata Convention on maximum allowable mercury content in specific consumer products such as batteries and light bulbs are the same as the thresholds already set by many national authorities and the EU, who advocated for their adoption at the global level.

Institutions and knowledge had substantial impacts on the degree to which interveners were able to effect change across different spatial scales.

The emergence of international institutions on mercury facilitated efforts to address domestic and regional mercury problems and also spurred global action. The Global Mercury Partnership provided a mechanism for supporting and coordinating mitigation efforts in different regions of the globe toward a common goal of reducing mercury use, emissions, and releases (but allowing for variations in domestic implementation). Networks of experts in one partnership area initiated the exchange of information on best available techniques (BAT) for controlling mercury emissions from coal-fired power plants in ways that later facilitated collective action under the Minamata Convention. Experts in another partnership area similarly supported the dissemination of information on ways to reduce mercury use and exposure in the ASGM sector. Governmental regulations in different regions also encouraged the development and international diffusion of mercury-free alternatives for products and manufacturing processes.

Interventions occurred over very different temporal scales. Initiatives to protect workers in mining and manufacturing evolved over centuries, going back to at least the 1500s. Government actions starting in the 1900s often developed over years to decades. For example, Swedish authorities prohibited the use of Panogen in the 1960s, but did not ban all forms of mercury pesticides until the 1980s. In many countries, regulations mandating the application of air pollution control technology were gradually strengthened over time. The political process that led to the negotiations of the Minamata Convention started with the global mercury assessment that was finalized in 2002; the treaty negotiations were completed in 2013, and the Minamata Convention entered into force in 2017. Several of its provisions on mercury mining and use as well as emission controls will only come into effect 5 to 10 years after its entry into force for a party. In contrast, some interventions are more immediate. Dietary advice to pregnant women or women who might become pregnant can change exposure rapidly. This can have relatively rapid benefits because the lifetime of mercury in the human body is a few months.

Role of Power and Influence in Interventions Interventions in the mercury systems varied depending on which actors were involved, and how they exerted power and influence. An intervener's influence can be assessed by analyzing that actor's ability to effect change. Governments initiated some interventions in the mercury systems, while the private sector took the lead in other instances. Most emission controls were government-led. In contrast, some of the earliest phaseouts of mercury in medicine and products and processes were initiated by the private sector. Many of the actions of governments and industry during the past 70 years intersected and reinforced one another, suggesting that each actor alone may not have sufficient power to comprehensively alter a system. Anticipation of future government controls, such as the phaseout of mercury in batteries, drove some industry action. Global voluntary partnerships beginning in the early 2000s both implemented interventions (for example, in reducing mercury use and emissions using retorts in ASGM) and facilitated the introduction of legal requirements (for example, the diffusion of BAT standards for point sources).

Non-state actors other than industry, and individuals acting in groups, also facilitated change in the mercury systems. Protests and advocacy on behalf of people affected by Minamata disease, and working through the Japanese judicial system, forced an eventual response by public officials and the Chisso Corporation as well as Showa Denko. Similarly, public protests in Tamil Nadu resulted in the government shutting down the mercury-using thermometer factory in Kodaikanal. Conservationists and ornithologists in Sweden first raised public concerns about the use of mercury-based pesticides, prompting the authorities to investigate and eventually take regulatory action. Public awareness and concerns about the dangers of mercury spurred governmental action in other cases as well. Discussions of mercury hot spots in the United States related to efforts by the US Environmental Protection Agency (EPA) to control mercury emissions from power plants in the early 2000s resonated with a broader public, prompting states and environmental groups to challenge the proposed federal regulation in court. Community concerns about methylmercury exposure shaped the formulation of dietary recommendations in many places, including for locally caught seafood.

Some interventions reflected learning among actors across different contexts and forums. In some instances, one political entity set a standard or adopted a law that was later used as a basis for passing a similar or identical standard or law in another jurisdiction. For example, China's current standard for mercury emissions from coal-fired power plants is modeled after (and set at the exact equivalent of) Germany's emission standard. China, South Korea, and California used the EU regulations on mercury and other hazardous substances in electronic and electrical equipment to adopt similar measures within their own jurisdictions. Yet there are also examples where a lack of knowledge possibly delayed interventions. Researchers in Kumamoto who were seeking an answer to what caused the strange disease in Minamata in the 1950s did not initially have access to information from Europe about methylmercury's dangers to human health. If this information had been available in Japan earlier, it may have helped the researchers to more quickly identify the link to methylmercury. This may (or may not) have resulted in a quicker political response.

Matrix Reloaded: Applying the Matrix Approach to Other Sustainability Challenges

The HTE framework and matrix-based approach that we present and apply in this book is not specific to mercury. Further research could therefore use the same framework and matrix approach to examine other human-technical-environmental systems beyond mercury. Selections of additional empirical cases might draw from the idea of focusing on "action situations" in the Institutional Analysis Development framework (Ostrom 2009; Ostrom 2011). Researchers can use the HTE framework to gain a deeper understanding of other important sustainability issues, and to identify similarities and differences among different cases through comparative studies, thereby further developing and modifying theories about the structure and functions of complex adaptive systems relevant to sustainability. The application of the HTE framework together with the matrix approach would allow for an analytically consistent comparison across different empirical systems.

The fact that the HTE framework centers on material interactions makes it a particularly useful tool for analyzing material flows, including those of pollutants, goods, nutrients, water, or energy. Applying the framework to other types of pollutants would push analysts to consider social and technical factors that interact with the environmental cycling of pollutants. Lead, for example, has a similarly long history of human use and exposure when compared to mercury, and is another element that continues to pose significant environmental and human health challenges in many local communities—even as its major modern emission source, leaded automobile fuel, has been phased out in the vast majority of countries worldwide.

Problems related to many persistent organic pollutants (POPs)—both pesticides and industrial chemicals—stem from their extensive use and transport in both the environment and international trade. Many different forms of plastics circulate in society, where they provide benefits to people but also cause much environmental harm, especially in aquatic ecosystems.

The applicability of the HTE framework is not limited to analyzing flows of materials across spatial scales; it can also be used to examine place-based systems. In chapter 2, we used the example of Minamata disease around Minamata Bay to introduce the framework and illustrate how we apply the matrix approach. This type of locally centered analysis could be extended further. In another mercury-focused example, the matrix approach can be used to analyze a specific community in which ASGM is practiced, such as in Madre de Dios. Applications of the HTE framework and the matrix approach to place-based case studies, particularly where interactions have been previously studied with other frameworks, might be useful to compare insights across different analytical frameworks and disciplines. If the HTE framework were to be applied to common-pool resource issues such as forest or fisheries management, for example, its focus on material interactions and technology might result in insights distinct from those gleaned from studies using a social-ecological systems framework (e.g., Ostrom 2009).

The HTE framework and matrix approach can also inform other analytical efforts to examine sustainability-relevant questions. This includes network analysis (e.g., Bodin et al. 2019), since all different pathways identified using the matrix approach can be displayed in a network diagram to illustrate the same information, as we discussed earlier in this chapter. Representing interactions as networks may help analysts disentangle multiple, complex causal pathways. Here, we chose illustrative pathways, but a full network analysis applied to a detailed matrix would more formally identify key nodes and multiple, interacting causal pathways. Network analysis methods may help those who interpret matrix analyses at higher levels of complexity, multiple levels of scale, and linkages between different systems. The HTE framework and matrix approach may also give some guidance to transitions researchers who seek to better understand system interactions and their dynamics. Transitions researchers have emphasized the need for new analytical approaches to assess transitions involving technological, economic, social, and ecological change (Turnheim et al. 2015).

The HTE framework and matrix approach could be further modified to address different aspects of issues important to sustainability in more detail. One such development may be to explicitly classify different types of interactions, which could be divided between flows of pollutants, energy, money, or information based on categories used in the engineering systems literature (e.g., de Weck et al. 2011). The matrix approach can also be used to categorize cross-scale system connections by classifying component attributes relative to common metrics of spatial or temporal scales (such as kilometers or hours, for example). As we noted in chapter 2, analysts may wish to use the matrix as an organizing principle for helping to design a quantitative systems model where the necessary data are available. The matrix could thus serve as a mechanism for bridging qualitative and quantitative analysis, which has been urged in the transitions literature (Turnheim et al. 2015; Köhler et al. 2017). Analysts could then use a quantitative model based on a matrix analysis to measure systems relative to different sustainability metrics, and their progress over time.

Further empirically grounded theory development is important to sustainability analysis. There is, however, an ongoing debate about what types of theories are most useful. Elinor Ostrom (2007) argues that scholars of social-ecological systems should move “beyond panaceas,” looking not for universal solutions to their problems but instead to diagnose the variables and outcomes that affect specific systems in their full complexity. Oran R. Young (2018) similarly suggests that analysts should focus on deriving mid-range theories about the effectiveness of international environmental regimes that can explain a subset of cases rather than looking for those that are universally applicable. Categorizing components, interactions, and interventions across systems in a common structure is one way in which analysts can begin to develop and test such mid-range theories. However, the complexity of the mercury systems illustrates the difficulty in deriving theories that can apply even to the entirety of the mercury problem. This suggests that even mid-range theories might be too ambitious, and that deep empirical engagement and the development of smaller-range theories could advance thinking and scholarship. In this vein, we draw some initial insights relevant to selected areas of scholarship in chapter 9.

The HTE framework coupled with a matrix-based approach offers analysts a valuable tool to see and study complex adaptive systems relevant to sustainability. The *matrix approach can be used to identify system components, examine their interactions, and analyze interventions. Our analysis of the mercury systems shows that identifying a relatively small number of aggregated system components at varying spatial scales can describe systems relevant to sustainability in ways that are analytically useful. Focusing on interactions among material system components in the context of institutions and knowledge can help trace important pathways of linked interactions that shape system dynamics across spatial and temporal scales. Interveners who have opportunities to influence either material or non-material components can alter system operations at different leverage points and geographical scales to effect change. Further studies could extend and apply the HTE framework and the matrix-based approach to examine additional topical or place-based systems relevant to sustainability.*

Mercury Stories

Understanding Sustainability through a Volatile Element

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