

SYSTEMS APPROACHES TO  
TRANSDISCIPLINARY SUSTAINABLE DEVELOPMENT ISSUES

by

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Systems Approaches to Transdisciplinary Sustainable Development Issues

Thesis directed by Professor Bernard Amadei

### **Abstract**

The goals of this dissertation are twofold. The first is to advance the discipline of sustainability science through the application of systems-based tools (primarily system dynamics) and civil engineering principles. Sustainability science is fundamental to implementing effective strategies for progressing sustainable development and improving human well-being around the planet, but it is still not fully developed as a science and needs new methods and approaches due to the field's inherent interdisciplinarity and complexity. Civil engineering as a foundation provides mathematical knowledge, computer modeling skills, and a wide breadth of technical understanding, but it lacks the societal, political, and economic transdisciplinary knowledge that sustainable development issues require and that the social sciences possess. Therefore, the second goal of this dissertation is to propose a new systems-based methodology that can analyze complex issues, usually addressed by social scientists, using analytical and engineering methods that are typically employed by technical scientists. This technique is called qualitative structural data analysis (QSDA) and is designed to take theories from the social sciences and, through a form of text analysis, use them to construct causal-loop diagrams and system dynamics models. Quantitative systems tools – cross-impact analysis, system dynamics modeling, and network analysis – can be used to further model the issues that have already been qualitatively analyzed using QSDA. Some issues are better suited to be analyzed qualitatively, some are more appropriate for quantitative tools, and others can be modeled through mixed-methods. With these quantitative tools, specifically system dynamics modeling, a new system archetype is introduced that can be applied to most, if not all, areas of sustainable development, including the Sustainable Development Goals, the water-energy-land-food (WELF) nexus, urbanization, hydropolitics, conflict, corruption, and natural resource governance. Three versions of the archetype are presented: a two-chambered and extended linear form, a three-chambered triangular form, and a four-chambered hierarchical form. The different versions can be used for modeling various social processes that are usually reserved for the social sciences and qualitative methods. The work presented in this thesis applies the QSDA technique and the new system archetypes to several issues of sustainable development.

## **Acknowledgments**

I am forever indebted to my thesis advisor, Bernard Amadei. From the first day I met him in February 2016, he saw something in me that I never saw in myself. He fostered that and gave me the confidence to find it in myself. With his mentorship, I have had the freedom to explore topics and issues across not just engineering but the social sciences. He didn't just allow me to embark on a non-traditional approach through my Ph.D.; he encouraged it. He never constrained my sometimes-overzealous approach to my research but gave me the guidance necessary to find my own path, while at the same time supporting me in whatever route I took. He was there to help me whenever needed, and without his support academically, financially, and personally, I'm not sure I would be attaining my Ph.D. Bernard is not just my advisor, he is my mentor, friend, and someone I will always look up to.

Additionally, my committee members (Amy Javernick-Will, Carlo Salvinelli, Lori Hunter, and Mark Meaney) have also made invaluable contributions to my Ph.D. experience. They have all had to familiarize themselves with unfamiliar topics in preparation for my defense. Coming from multiple disciplines they have all had unique input and expertise without which I would not be able to complete my research. They have made me a better researcher.

My time spent at the Arava Institute for Environmental Studies (AIES) was a wholly unique experience, and the people there were all incredible. The friends I made there were so supportive of my work, and they took a genuine interest in the research I was doing and even participated in some of my research.

Lastly, my friends and family supported me in every way possible. They endured frantic phone calls and times of almost no contact while I worked 90-hour weeks and forgot about life outside of school. They always pushed me to succeed, and their love and support were an inspiration to always finish the project. Can't even think of what I would have done without them.



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## 1. OVERVIEW

This dissertation, which lays the foundation for a planned larger body of work, spans multiple topics related to sustainable development: The Sustainable Development Goals (SDGs), corruption, natural resource governance, conflict, hydropolitics, the water-energy-land-food (WELF) nexus, urbanization (resulting from rural-urban migration), and community development. These topics are all cross-disciplinary in that they involve theories, analytical methods, and general expertise from multiple disciplines, namely civil and environmental engineering, ecology, political science, economics, and sociology, among others. These topics transcend individual academic and professional disciplines and fields, and as such, they require a transdisciplinary approach. This work borrows and combines methods and ideas from those areas to create a new approach to understanding and analyzing issues involving complex challenges in sustainable development bound together using systems science. As a result, the focus of this research is not so much on the topics covered as it is on the overall transdisciplinary systems approach and various methodologies detailed herein, by which these topics can be better understood.

By its very nature, a systems approach necessitates taking a big-picture view and aggregating many smaller pieces into a whole, the opposite of traditional reductionist thinking, which takes a complicated topic and breaks it down into simpler more easily understood parts without considering their interactions. Instead of following the traditional approach of most Ph.D. dissertations (i.e., focusing on a highly specialized, singular issue), this dissertation covers many areas and topics using a uniquely broad perspective. The only commonality among them is that they are extraordinarily complex (possibly chaotic) global challenges. Each topic described herein is one piece of a puzzle that forms a broader perspective of global sustainable development.

Table 1 lists the five main topics in the order that they are presented in this thesis. Since this research is ongoing, not all papers mentioned in that table have been published, and several of them are still in progress. Papers 1–5, 8, and 9 are published; paper 7 has been submitted for publication; and papers 6 and 10–12 are in progress. Paper 1 is an early version of paper 3; paper 2 is a summary of papers 3 & 4 but written for less technically-oriented academics and sustainable development practitioners. Papers 3–5 and 7–9 – Amadei & Zelinka (2018), Daher & Zelinka (forthcoming), and Zelinka & Amadei (2018b, 2018c, 2019a, 2019b) – can be found in the Appendices.

Table 1. The body of work (completed and pending) as of this dissertation's submission

<p><b>Sustainable Development Goals</b></p> <ol style="list-style-type: none"> <li>1. <b>Zelinka, D.</b> &amp; Amadei, B. (2017). A Methodology to Model the Integrated Nature of The Sustainable Development Goals. in <i>ASEE Annual Conference &amp; Exposition</i> (American Society for Engineering Education). Columbus, OH, USA.</li> <li>2. <b>Zelinka, D.</b> &amp; Amadei, B. (2018a). Analyzing sustainable development: systems-based methods and modeling tools for the Sustainable Development Goals. in <i>24<sup>th</sup> International Sustainable Development Research Society Conference</i>. Messina, Italy.</li> <li>3. <b>Zelinka, D.,</b> &amp; Amadei, B. (2019a). A Systems Approach for Modeling Interactions Among the Sustainable Development Goals Part 1: Cross-Impact Network Analysis. <i>International Journal of System Dynamics Applications</i>, 8(1):23–40.</li> <li>4. <b>Zelinka, D.,</b> &amp; Amadei, B. (2019b). A Systems Approach for Modeling Interactions Among the Sustainable Development Goals Part 2: System Dynamics. <i>International Journal of System Dynamics Applications</i>. 8(1):41–59.</li> </ol>
<p><b>Community development and wastewater treatment</b></p> <ol style="list-style-type: none"> <li>5. Amadei, B. &amp; <b>Zelinka, D.</b> (2018). Integrated modeling of the Water-Energy-Land-Food Nexus: Importance of Context, Scale, Boundary, and Community Capacity. in <i>the 24<sup>th</sup> International Sustainable Development Research Society Conference</i>. Messina, Italy.</li> <li>6. Halasah, S. &amp; <b>Zelinka, D.</b> (forthcoming). Scenario analysis of the effect of institutional capacity on household-scale wastewater and greywater using system dynamics. <i>Environmental Management</i>.</li> </ol>
<p><b>WELF nexus: Population dynamics and urban migration</b></p> <ol style="list-style-type: none"> <li>7. Daher, B. &amp; <b>Zelinka, D.</b> (forthcoming). Implementing Water, Energy, and Food Sustainable Development Goals. In <i>Encyclopedia of the UN Sustainable Development Goals: Clean Water &amp; Sanitation</i>.</li> <li>8. <b>Zelinka, D.</b> &amp; Amadei, B. (2018b). A modified S-shaped growth behavior to model complex anthropocentric systems. in <i>the 36<sup>th</sup> International Conference of the System Dynamics Society</i>. Reykjavik, Iceland.</li> </ol>
<p><b>Corruption and natural resource governance</b></p> <ol style="list-style-type: none"> <li>9. <b>Zelinka, D.</b> &amp; Amadei, B. (2018c). Governance systems analysis for sustainable development: corruption and natural resources. in <i>the 24<sup>th</sup> International Sustainable Development Research Society Conference</i>. Messina, Italy.</li> <li>10. <b>Zelinka, D.</b> (in progress). The complex interactions between corruption and the natural resource sector.</li> </ol>
<p><b>Conflict and hydropolitics</b></p> <ol style="list-style-type: none"> <li>11. <b>Zelinka, D.</b> (in progress). A system dynamics perspective of the Palestinian-Israeli conflict: archetypes. <i>Journal of Peace Research</i>, xx(xx):xx-xx.</li> <li>12. <b>Zelinka, D.</b> (in progress). A system dynamics perspective of the Palestinian-Israeli conflict: hydropolitics. <i>Journal of Peace Research</i>, xx(xx):xx-xx.</li> </ol>

Paper 1 advocates using a systems approach to model the integrated nature of the Sustainable Development Goals (SDGs) when presented in an engineering context. It introduces the value proposition of using systems thinking in sustainable development and applies a soft-systems approach (cross-impact analysis) to the SDGs, which function as a proxy for global sustainable development. Paper 2 provides a general overview of the first paper and then adds

system dynamics (SD), user interfaces, and a connection to the policy realm. Paper 3 further develops this analytic technique, applies network analysis to the SDGs, and introduces the concept of anthropocentric systems. Paper 4 directly picks up where paper 3 left off by adding SD modeling (a hard-systems tool) and the general systems modeling method to further analyze sustainable development by simulating the combined long-term effects of the interactions among the SDGs.

Paper 5 introduces community development and community capacity analysis. Paper 6 builds on paper 5 by applying real-world survey data to the general model presented in paper 4, proving that it is valid with not just quantitative data but also qualitative data. Then, it incorporates a highly complex sensitivity and scenario analysis into the general model using the Monte Carlo method along with other statistical techniques. This paper is being co-authored with a Jordanian researcher, Suleiman Halasah, from Ben-Gurion University of the Negev and the Arava Institute for Environmental Studies in Israel. The qualitative data set collected by Halasah for his dissertation were also used in Paper 6 and integrated into a system dynamics model in. In that forthcoming paper, the effect of institutional capacity (IC) in a community was analyzed in the context of household wastewater treatment systems. Multiple sensitivity analyses were used to determine how various interventions aimed at IC could improve the community as a whole.

The SDGs (papers 1–4) and community development (papers 5 and 6), are modeled herein with a (systems-of-systems) nexus approach. A nexus approach details the interconnections among various sectors (water, individual economic sectors, land, food, climate, health, etc.) and can be qualitative and quantitative. Papers 7 and 8 explore the nexus approach, specifically the water-energy-land-food-climate (WELFC) nexus and its relation to the SDGs. The WELFC nexus uses a systems approach that is particularly useful for specific resource-oriented sustainable development issues. There is an SDG for each WELFC sector: water (SDG 6), energy (SDG 7), land (SDG 15), food (SDG 2), and climate (SDG 13). Paper 7, co-authored with a Lebanese researcher (Bassel Daher) at Texas A&M, looks more specifically at those five SDGs in the WELFC nexus but is written for a more general audience. Paper 8 uses system archetypes (universal social behavior like the tragedy of the commons), SD modeling, and the WELFC nexus as a foundation to construct various standardized models that can be used to simulate common challenges in sustainable development. Paper 8 uses these tools and concepts to analyze and model urbanization, migration, and land-use change by altering and adding complexity to the model created for the SDGs in paper 4.



Paper 9 looks at the topic of corruption through a transdisciplinary lens. Traditionally, social scientists (mainly, political scientists and economists) have been the only researchers studying corruption, and they have examined the issue through their respective individual disciplines. Paper 9 applies system dynamics and engineering methods to a broad spectrum of social science theories (causal mechanisms) that attempt to explain corruption. Then, to delimit the complex topic, corruption is further bounded by the natural resource sector. Finally, a technique called qualitative structural data analysis (QSDA), which is used to extract structure from purposive text, is introduced as a method to organize complex, mostly socio-political issues, by transcoding relevant academic literature into highly sourced (and therefore more valid) system models; these system models can then simulate various interventions aimed at solving these problems. Paper 10 further develops the methods of paper 9 and is the first paper from this research to be written explicitly for a social scientist audience. (It is currently pending publication.)

The final two papers, 11 and 12, are at their earliest phases of development – relative to the others – and relate to conflict and hydropolitics (the effect of water resources on politics), respectively, which connects conflict with the water sector and the environment, from a system dynamics perspective. Like corruption, conflict is complex, pervasive, and damaging to human society; however, whereas corruption is long-term and slow-moving, like a drought, conflict is short-term and sudden, like a hurricane. Conflict is inherently political, economic, and social, so it covers all areas of sustainable development and epitomizes the types of complex issues for which systems approaches are designed. Using QSDA, two causal-loop diagrams were constructed to provide detailed, yet easily understood representations of conflict and hydropolitics in Palestine and Israel. Since there are no associated appendices for these two papers, as the research is so new, a more detailed overview of conflict and hydropolitics is included in the main body of this thesis.

Throughout this research, a unique problem became evident: writing is inherently linear, but systems are not; therefore, the iterative nature of systems is fundamentally at odds with the process of linear writing. To explain how the various sectors interact, a diagram detailing the structure of this dissertation was constructed (Figure 1). To accommodate the systems approach that was used to structure the overall body of research linearly, this work follows the letters A–I in Figure 1, which represents the order followed in this dissertation. It begins with two chapters that offer a historical background to sustainable development (A) and on how techno-environmental (B) and socio-political problems (C) arose. The third chapter discusses the methods used to analyze techno-environmental and socio-political problems: systems thinking (D), qualitative structure data analysis (E), and quantitative systems modeling (F). The

results are presented and discussed (G) in Chapter 4. Chapter 5 begins with a brief discussion of the implications for transdisciplinary research and collaboration (H) between technical and applied scientists and social scientists. It continues by exploring how systems approaches can advise the post-2030 world (I). What would happen if the field of sustainable development succeeded in eradicating poverty, controlling population growth, creating completely sustainable societies, and reducing humanity's environmental impact to a level below the ecological carrying capacity of Earth? This dissertation concludes with a brief discussion of that possibility.

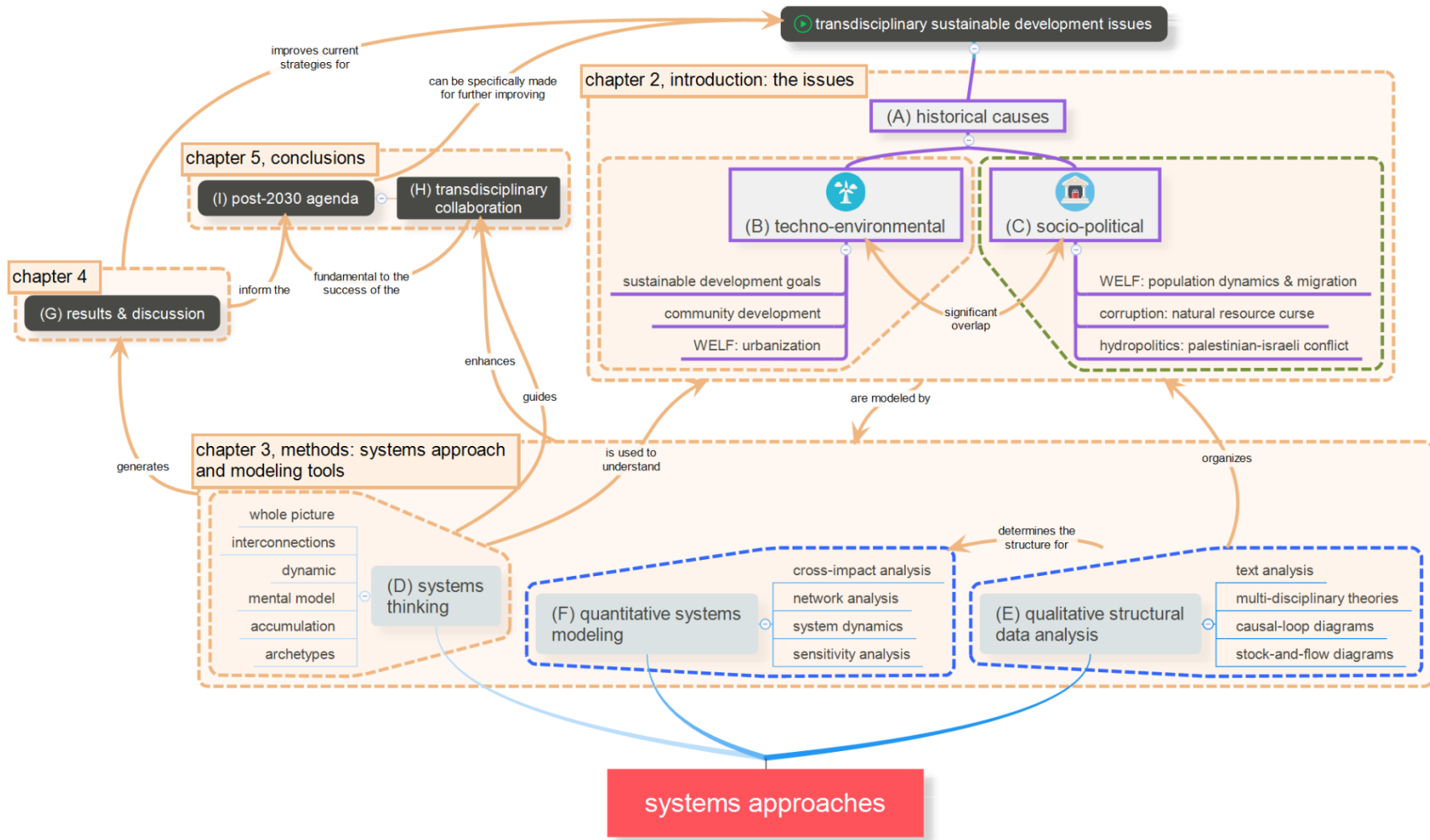


Figure 1. Dissertation outline using a systems representation

## 2. INTRODUCTION: COMPLEX TRANSDISCIPLINARY ISSUES

### 2.1. History: Why is there a need for sustainable development?

This section outlines the history of the world over the last 700 years as it pertains to the global *need* for sustainable development, not the history of the discipline itself. In researching for this introduction and background, virtually no articles focused on the deep history that culminated in the present day need for sustainable development were found. The vast majority of related research focuses on the history of the concepts of sustainability and the theories underlying sustainable development. Understanding why the world has such a large division in the standards-of-living among the poorest and wealthiest people will serve to understand how sustainable development can fix that global inequality. That inequality can be summed up with the following statistics: half of the world's wealth has been captured by 1% of people; 10% of people hold 85% of global wealth (implying that 90% of people only have 15% of global wealth); and the top 30% of people have 97% of the total wealth world-wide (Keating et al. 2013). This section is the basis for a forthcoming paper, so new it could not be listed in Table 1.

Most historical analyses of sustainable development date back to the Brundtland Report from 1987 (Pisani 2007; Redclift 2005) – a “shallow” recent history at best – or early sustainability theories that are often related to early ecological theories (Grober 2017). There are virtually no historical analyses of the world as it pertains to the necessity for sustainable development, although some economists touch on the subject in the context of natural resources and physical geography (Mccord and Sachs 2015), while others look at the economic history of development – which overlaps sustainable development as discussed later in this section that occurred in the reconstruction that followed World War II (Berend 2016).

Sustainable development has a history literally as old as the modern world itself. The necessity for sustainable development broadly traces the 700-year history of 1) the expansion of globalization and 2) the growing socioeconomic divides between the current developed and developing nations overall level of progress and development (referred to as the Great Divergence; see Grinin & Korotayev 2015; De Zwart 2016). This is accomplished by following the significant events and major time periods starting from the mid-Renaissance (if not earlier) with the European discovery of the New World (the Americas) in the late 15<sup>th</sup> century as is shown in Figure 2. A few books that look at similar topics (broadly, global economic history, colonialism, and imperialism, and globalization) are used as general references (see Grinin & Korotayev 2015; De Zwart 2016; Rogan 2011) throughout this section and with multiple articles focusing on specific events cited throughout.

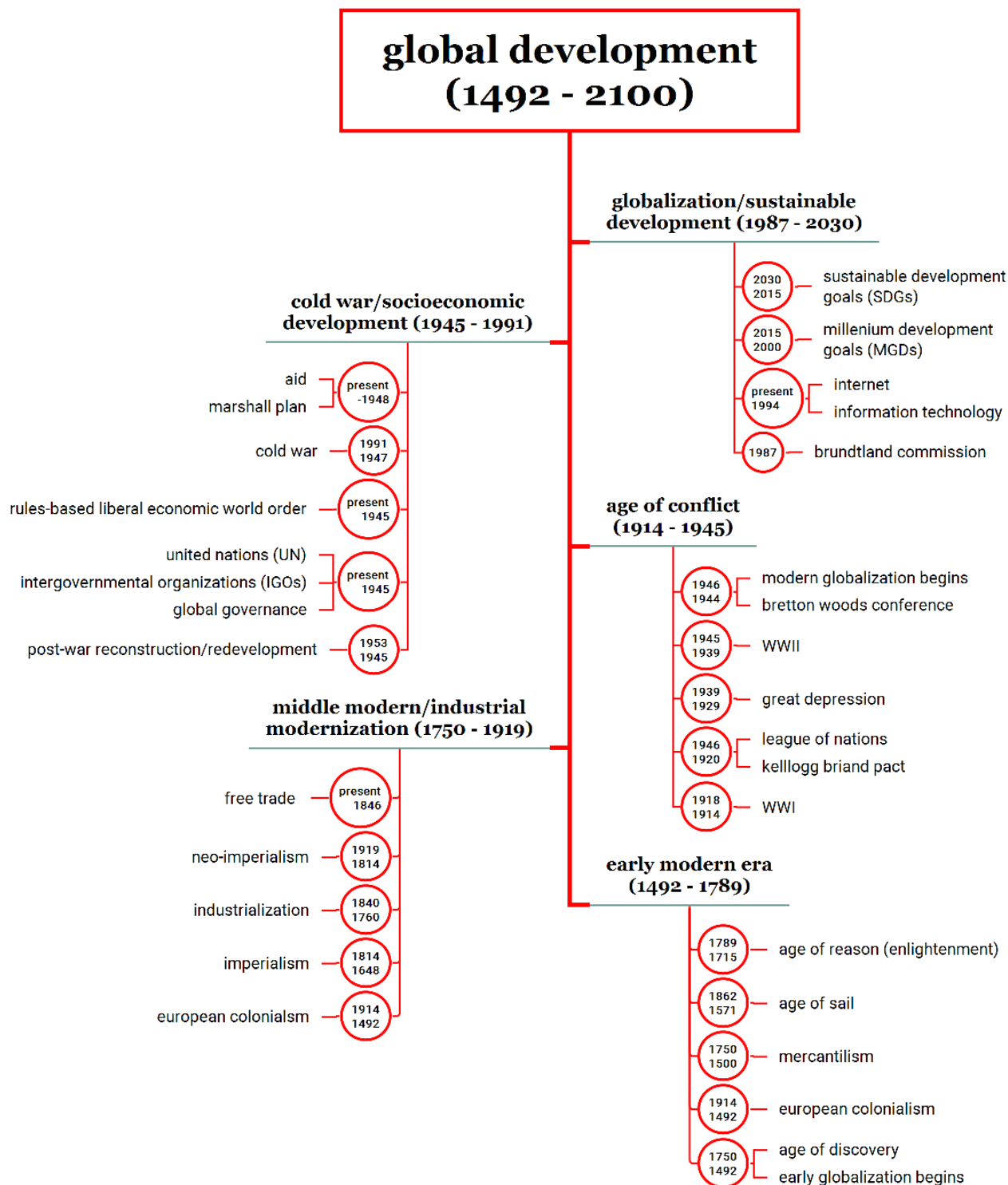


Figure 2. Historical framework of globalization of sustainable development

The story of sustainable development is the story of modern world history that began with the Renaissance and the discovery of the new world in the 14<sup>th</sup> and 15<sup>th</sup> centuries with a particular focus on global inequality,

technology, and globalization. Modern history is composed of all the time since 1492 and can be categorized into three eras – Early Modern, Middle Modern, and Contemporary. The European Renaissance (ca., 1300-1600) was a bridge between the Middle Ages (specific to Europe) and the Post-Classical (globally), both of which occurred roughly from 500 to 1450 (Editors of Encyclopaedia Britannica 2018a), and the Modern Era, and as such it fits into both but neither periods according to this work. It is not directly included, but it necessitates mentioning. The most crucial development during the Renaissance was the creation of the scientific method that helped foster so many technological advancements. Many significant time periods (i.e., Age of Discovery, European colonialism, and the Age of Sail) began in the Renaissance.

The Early Modern and Middle Modern eras laid the foundation for the problems that have caused the current divide between today's developed and developing countries (i.e., the Great Divergence). This divergence in the development of the countries of the world is why sustainable development is even necessary; had all countries of the world developed in unison, there might only be developed countries today, which would negate or mitigate the need for global sustainable development.

World War I signified humanity's transition from the Middle Modern Era to the Contemporary Era and acted as a catalyst for most of the critical events that have shaped what sustainable development is today. The contemporary era (1914–2030)—the era that human civilization currently occupies—can be further subdivided into three sub-eras: The Age of Conflict (1914–1945), the Cold War/socio-economic development (1945–1991), and globalization/sustainable development (1987–2030). These three eras are not mutually exclusive and have sub-eras that can span across their parent eras. A general timeline of these five time-periods with significant events is shown in Figure 2. This dissertation concludes by discussing the possible future of sustainable development through 2100.

Had the Renaissance occurred not in Europe but in another region of the world, how would history have played out?

### **2.1.1. Modern Era: The Great Divergence**

The *Early Modern Era* (ca., 1492–1789) began with the discovery of the new world (the Americas) and the rapid colonization of the planet by European empires. At the same time, scientific reason began to take hold, pulling the European continent out of the religious orthodoxy of the Middle (Dark, called such because of the lack of historical

records) Ages (Editors of Encyclopaedia Britannica 2018a; Mommsen 1942). The Renaissance (ca., 1300-1600) gave way to the Ages of Reason, Discovery, and Sail, enabling Europeans to colonize the rest of the world, as well being a significant factor that led to imperialism (Goffman 2015). Meanwhile, global commerce began to take root with the formation of the first international companies (i.e., the Dutch East India Company, 1602–1799), international trade started to connect the planet, and technological innovation accelerated, all of which were crucial to the future economic development in the Middle Modern Era (De Zwart 2016).

These socioeconomic benefits were focused mainly in Western countries – starting with Great Britain, followed by the rest of Europe – because the legacy of the Renaissance didn’t happen for the non-Western (Africa, Asia, and the Middle East) developing countries (Grinin et al. 2015). European countries began to leverage their new power and might to expand not just territorially with imperialism, but economically with mercantilism—an early manifestation of capitalism that aimed to maximize the trade surplus through a mostly protectionist economic policy (i.e., isolationists approach that aims to reduce an economy’s reliance on international trade) (Editors of Encyclopaedia Britannica 2018b, 2018c)—that dominated European economic thought from the 16<sup>th</sup> to the late-17<sup>th</sup> centuries (Editors of Encyclopaedia Britannica 2018b; LaHaye 2018). Mercantilism naturally increased tensions among countries. As a result, it caused multiple conflicts, and is argued by historians to be the primary influence for European imperialism, which dominated the Middle Modern Era and influenced many of the issues in the Contemporary Era that continue to affect the world today (LaHaye 2018).

Imperialism is an approach to geopolitics whereby a country attempts to extend its power and dominion outside its borders (Editors of Encyclopaedia Britannica 2018d). The previous Ages of Reason, Discovery, and Sail gave European powers significant technological advancements and military supremacy that enabled them to subjugate much of the planet less developed nations. As they continued their conquest, a divide arose between levels of development between Europe (generally, the present-day developed countries) and the rest of the world (generally, present-day developing countries). Unfortunately, this socioeconomic divide has worsened over the centuries.

This very wide socioeconomic gap (whose emergence was much later called “the Great Divergence”) between Europe and Asia became a fact that did not require proof; it was so evident that there was an idea that this superiority was something perfectly natural and permanent (Grinin & Goldstone, 2015, pg. 2).

As imperialism took root, the world transitioned into the *Middle Modern Era/industrial modernization (1750–1919)*, with the end of mercantilism giving way to free trade that has been promoted by economists for the last two centuries (LaHaye 2018). The scientific and technological developments that began in the early modern era advanced so rapidly during the middle modern era that entire societies, economies, and geopolitics were affected. International trade was growing 5% each year from the 1850s to the 1870s due to the combined effects of free trade and the effects of the industrial revolution, especially technological advancements that facilitated long distance transportation (Grinin & Goldstone 2015).

The Industrial Revolution began in Great Britain in 1760, and by its peak in 1913, the British Empire controlled nearly a quarter of the Earth's land area, making it the largest empire in history (Taagepera 1997). Seeing Great Britain's success, other European powers followed their lead and focused their economies on improving their industrial and manufacturing capacities. Coupled with the long-term effects of mercantilism, these technological advancements led to widespread neo-imperialism, whereby European imperial powers were able to expand their influence and power through diplomacy and military dominance, ultimately making imperial claims over much of the world (Editors of Encyclopaedia Britannica 2018a; Grinin & Goldstone 2015; LaHaye 2018).

Centuries of imperialism (and neo-imperialism) have widened the development and socioeconomic gap between the European empires and their satellites, their colonies, and other nation-states in what is today the developing world, particularly in the Middle East (Rogan 2011) and Africa (Meredith 2014). This increasing developmental divide has been referred to as the *Great Divergence*, which began to accelerate at the beginning of the 19<sup>th</sup> century. But by the 1970s, the discrepancies between the West and the “Rest” began to narrow. This trend has been called the *Great Convergence* (Grinin & Goldstone 2015); although the differences are still vast.

The world at the beginning of the 20<sup>th</sup> century was becoming more advanced, interconnected, and less equal (among and within countries)—circumstances that naturally bred the complex problems that have come to define the 20<sup>th</sup> and 21<sup>st</sup> centuries. Ultimately, complicated alliances; long-term effects from mercantilism, nationalism, colonialism, and imperialism; and technological advancements from the Industrial Revolution converged to create a very volatile and unstable situation in the Balkans (colloquially, “the Balkan Powder Keg”) that eventually ignited the First World War (WWI).



The fall of the Ottoman Empire, which created a power vacuum, concurred with the rise of nationalism in the Balkans led to increased tensions in the region. The Balkans contained many nationalities, ethnicities, and religions that have historically been at odds with each other. Major mostly European powers vied for influence over the region (as a direct result of their imperialist inclinations) and formed many alliances with other countries of the world. When a nationalist (funded by Serbia) from one of these countries, Bosnia, assassinated the heir (Archduke Franz Ferdinand) of a rival country, the Austro-Hungary war was declared between Bosnia and Serbia, and all countries involved in these alliances were mandated to declare war on all others (Royde-Smith and Showalter 2018; Wikipedia 2019a). This started WWI and the Age of Conflict and brought the (Western) world into the Contemporary Era.

### **2.1.2. Contemporary Era: Towards sustainable development**

The complex entanglement of alliances (namely, the Triple Alliance and the Triple Entente) and the “Balkan Powder Keg” meant that if two countries went to war, all the countries with whom they were allied would be directed to go to war, as well. This event plunged the world into WWI (Royde-Smith and Showalter 2018; Wikipedia 2019a) and marked the beginning of the first part of the Contemporary Era, *the Age of Conflict (1914–1948)*. For four years WWI raged on until Germany signed an armistice in November 1918. The following year, the Paris Peace Conference formed the League of Nations, a precursor to the United Nations, which was tasked with maintaining world peace. In 1929, the Kellogg-Briand Pact attempted to eradicate war by renouncing it, focusing on peaceful resolutions to disputes and conflict, and hoped to tie the United States into a system of defensive alliances with the goal of countering possible German aggression in the future if it were able to recover and seek to retaliate (Editors of Encyclopaedia Britannica 2018e; “The Kellogg-Briand Pact, 1928” n.d.). History has shown the Kellogg-Briand Pact failed to end war (or any war for that matter). It has been panned as ineffective and irrelevant (Stephen 2017). as it was an overly simplistic and reductionist approach but insufficient to promote world peace and end war; an incredibly complex and systemic problem. It was admirable, nonetheless.

Just as there were complex conditions that led to the outbreak of the first World War, there was also a complex interplay of factors that converged making the interconnected global economy vulnerable to shocks. The most significant economic shock in history became known as the Great Depression (1929-1939); it started because of a sharp decline in stock prices which led to investor panic and the most significant stock market crash in history on October 1929 (Black Tuesday). The crash propagated throughout the global economy causing global GDP to fall by 15% in four years, massive unemployment, and significant drops in trade and manufacturing capacity in nearly all

countries (“End of the Great Depression” n.d.; Folsom 2010; Pells and Romer 2019; Romer 1992; Smiley 2018; Wikipedia 2019b). Of course, the effects were not felt equally around the planet: they “were particularly long and severe in the United States and Europe; it was milder in Japan and much of Latin America” (Pells and Romer 2019).

Less than a decade after the Kellogg-Briand Pact was enacted, the world was plunged into the Second World War that damaged or destroyed much of Europe and parts of Asia and Africa. Most economic historians concede that World War II (1939 – 1945) was, at least, a significant factor in bringing an end to the Great Depression, although the degree to which is up for debate. The need for manufacturing capacity and industrial might to fuel the war efforts produced an economic boost (Folsom 2010; Romer 1992). Another factor is thought to be President Roosevelt’s social programs and the New Deal in America (“End of the Great Depression” n.d.; Folsom 2010; Pells and Romer 2019). Realistically, some mix of both (and other factors) were probably responsible. In July 1944, the Bretton Woods Conference was held, laying the foundation for the current international monetary and financial world order that led to the expansion of modern globalization and international development (Chen 2018; De Long and Eichengreen 1991; Wikipedia 2018).

After World War II, the Age of Conflict gave way to the *Cold War and socio-economic development (1945–1991)*. As with the end of the First World War, the conclusion of World War II saw the creation of an intergovernmental organization (i.e., the United Nations [UN]) tasked with not just avoiding war, but the betterment of all of humanity (United Nations 1945)—an idea that would give way to international development. Thus, the purpose of the UN is to manage globalization and organize sustainable global development. Because peace is part of that focus, the UN views war as a symptom of poor development. To promote peace, it looks at development issues from a global perspective and seeks multidisciplinary solutions from all sectors of sustainable development (United Nations 1945; United Nations General Assembly 2015).

The creation of the United Nations (UN) coincided with the beginnings of the modern concept of aid (i.e., the Marshall Plan and post-war reconstruction), international development, and the rules-based Liberal World Order, as well as the rise of the United Soviet Socialist Republic (USSR) and the United States to a new class of nation-state, the superpower, which transcended great powers of earlier eras. This was the epitome of a paradigm shift on a civilization-wide-scale, even more significant than the shift into the Age of Conflict. From the United States, Europe received grants and loans in the form of the Marshall Plan (1948–1951), valued today at \$100 billion (2018 \$USD), while the rest of the world would receive an equivalent of \$375 billion (1945–1953) (De Long and Eichengreen 1991;

“Postwar economic reconstruction and lessons for the East today” 2019; The Marshall Plan: Fifty Years Later 2001). Because the world was already very interconnected after WWII, the US realized that their economy would be affected as well. By focusing on international economic development, the US would be able to avoid an economic recession and speed up the much-needed economic recovery as the world rebuilt itself after the Age of Conflict. This sizeable socioeconomic development and post-war reconstruction program were intimately linked to the relatively new Bretton Woods system, which was the basis for the current international order.

With the success of the Marshall Plan, American influence grew in western Europe, while the proximity to the USSR brought eastern Europe under the sphere of the Soviets (Editors of Encyclopaedia Britannica 2018f; Leffler and Painter 2005). The desire by these two nations to maintain and grow their spheres of influence put their ultimate goals at odds with each other, and they often clashed with one another. This led to increasing tensions and deteriorating relations that nearly caused multiple instances of military confrontations (hot wars) and sparking many proxy wars, which is “when a major power instigates or plays a major role in supporting and directing a party to a conflict but does only a small portion of the actual fighting itself” (Byman 2018). These proxy wars killed millions of people around the world (Editors of Encyclopaedia Britannica 2018f).

The period that followed the Age of Conflict, the Cold War, was dominated by technological innovation, exponential growth in global interconnectivity and information technology advancements (due to the espionage requirements from the intelligence community), and military build-up (because of the arms race between USA and the USSR) (Editors of Encyclopaedia Britannica 2018f; Leffler and Painter 2005). Although the technological advancements during this era occurred in all areas of society and the economy, computer and information technology (CIT) made some of the fastest progress, which increased the rate of globalization and democratization. CIT (namely, the internet) provided the capability needed to connect the world (globalization), and with the internet, people were able to access information and see how other people lived. This global understanding enabled people to learn of other forms of governance and demand accountability among their governments leading to democratic reform, desired by the USA, and opposed by the USSR; the Arab Spring is a recent example outside the Cold War (Lynch 2017). Until the early 1990s, the world focused on economic development, while geopolitically the two superpowers engaged in the Cold War and many proxy wars and conflicts, affecting much of the world (and even outer space at times). This economic development was the first real attempt to provide aid to countries that needed it (as a new form of foreign policy that was not focused on military, but political and economic influences) and was a precursor to sustainable

development. Unfortunately, the Cold War contributed to pulling the resources away from the economic development that the developing world sought and needed. The end of the Cold War saw the world officially move into the current era of (mature) Globalization and Sustainable Development (1987 – 2030).

In 1987, international economic development programs began to shift toward a *sustainable development* paradigm (1987–2030). This shift was, at least partially, influenced by the Brundtland Commission's report, *Our Common Future*, which was the first-time sustainable development as a concept made its way into the mainstream (Brundtland Commission 1987; Redclift 2005). The challenges of sustainable development were really brought to light with this report. Environmental issues started to be considered alongside economic issues, rather than being superseded by them. By 1994, the internet was starting to diffuse into everyday society with the first internet service providers and general commercialization of the internet with the World Wide Web (Campbell-Kelly and Garcia-Swartz 2013; Wikipedia 2018b), further interconnecting the planet, while technological innovations were accelerating at an ever-increasing rate.

By and large, the 20<sup>th</sup> century started with massive human conflict and great power wars, followed by a fundamental change that led to improved human well-being and overall political development. Wars between superpowers and large-scale conflict died down, and the invention of the internet increased globalization and democratization. People's lives began improving (Ridley 2011; Rosling 2015), and for the first time in human history that progress was felt by almost all of humanity, not just the richest. Perhaps because living conditions in the developed world rose to a threshold where people could afford to care about sustainability or maybe because environmental degradation started to be too noticeable to ignore, the latter part of the 20<sup>th</sup> century also saw a desire to improve not just the human condition but also to protect the environment (Brundtland Commission 1987; United Nations 2015a; United Nations General Assembly 2015).

In a first attempt to organize humanity's capacity for sustainable development, the UN released the eight Millennium Development Goals (MDGs) in 2000, which covered poverty, health, education, gender equality, food, global partnerships, and environmental sustainability (United Nations 2015b). These ushered in the 21<sup>st</sup> century and the problems and challenges facing humanity today. The issues addressed by the MDGs are highly complex, interconnected, and span multiple disciplines (Hieronymi 2013). They belong to a class of problems deemed messy, ill-defined (sometimes called wicked and chaotic) and are characteristic of the challenges that sustainable development

attempts to address. These problems are fundamentally more complex than the ones that dominated earlier human eras. They cannot be solved through the same traditional and reductionist approaches that caused them and will require global cooperation, long-term planning, and more resources than any one country can provide (Peters 2017).

The MGDs made significant progress by July 2015, but not all goals were met, and some even worsened. Poverty was more than halved (exceeding the goal); employment opportunities were unchanged; the proportion of people that were hungry nearly halved (almost meeting the goal); and forcibly displaced persons from conflict increased by more than 50% (worsening) (United Nations 2015a). Together these data indicate that MDG 1 (eradicate extreme poverty and hunger) was only partially successful. The other seven MDGs had mixed outcomes.

### **2.1.3. The world today: The United Nations' Sustainable Development Goals**

In 2015, as the MDGs expired, the UN introduced the SDGs as a second attempt to a new 15-year-long roadmap for global sustainable development (United Nations Economic and Social Council 2016). As described in the resolution adopted by the General Assembly of the United Nations on 25 September 2015, the SDG framework aims to cultivate and expand humanity's desire to "do good" while also organizing its efforts toward that goal. In launching the SDGs, the General Assembly "recognize[d] that eradicating poverty in all its forms and dimensions (including extreme poverty) is the greatest global challenge and an indispensable requirement for sustainable development" (United Nations General Assembly 2015). The SDGs consists of 17 goals as shown in Table 2, and are further subdivided into 169 targets (e.g., target five of goal 16 on corruption aims to reduce corruption and bribery). Despite this considerable number of goals and targets, eradicating extreme poverty (SDG 01) is the ultimate goal, but only if it is accomplished in an environmentally benign way. The other goals can, therefore, be understood as constraints and requirements that the goal of eradicating extreme poverty must also satisfy.

Table 2. The 17 Sustainable Development Goals (adapted from Global Goals 2016)

<b>Goal</b>	<b>Title</b>	<b>Description</b>
SDG 01	Poverty	End poverty in all its forms everywhere
SDG 02	Food Security	End hunger, achieve food security, and improved nutrition and promote sustainable agriculture
SDG 03	Health	Ensure healthy lives and promote well-being for all at all ages
SDG 04	Education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
SDG 05	Gender Equality	Achieve gender equality and empower all women and girls
SDG 06	Water and Sanitation	Ensure availability and sustainable management of water

Goal	Title	Description
		moreover, sanitation for all
SDG 07	Energy	Ensure access to affordable, reliable, sustainable, and modern energy for all
SDG 08	Economy	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all
SDG 09	Infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation
SDG 10	Inequality	Reduce inequality within and among countries
SDG 11	Cities	Make cities and human settlements inclusive, safe, resilient, and sustainable
SDG 12	Consumption	Ensure sustainable consumption and production patterns
SDG 13	Climate	Take urgent action to combat climate change and its impacts
SDG 14	Ocean	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development
SDG 15	Land	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
SDG 16	Governance	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable, and inclusive institutions at all levels
SDG 17	Partnerships	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

The SDGs can be thought of as unfolding in an *anthropocentric system (APS)*, a system whose main actors are directly and strongly influenced by complex human socio-economic-political-environmental interactions but are themselves not humans (Zelinka and Amadei 2019a). An *actor* is any entity that interacts within a system, like a person that requires food from within an agricultural system. APSs tend to be highly interconnected, have complex and sometimes chaotic structures, are ill-defined (or wicked, like climate change), involve humans as significant stakeholders, and address human well-being. Understanding the network dynamics in which the SDGs unfold cannot be done using deterministic tools; system science and engineering are needed instead and are described in Chapter 3. APSs are ubiquitous throughout all sustainable development, so understanding how these types of systems function is crucial towards creating effective strategies to improve human well-being in the developing world.

Human (anthropocentric) and Earth systems are the focus of the SDGs, making the SDG framework the most complex and large-scale attempt to effect change for all of humanity and the planet. That complexity requires new approaches, multidisciplinary understanding, and advanced tools to be effectively analyzed so that development

initiatives and strategies are more likely to succeed. In the next section, the nexus approach is introduced as a way to organize the complexity of the SDGs, as well as many other issues including the water-energy-land-food nexus, community development, and any system that is composed of interconnected sectors (like an economy composed of many sectors). By looking at just a few sectors that have strong linkages with the SDGs, the nexus approach can simplify and structure their analysis.

Although the UN does recognize a need to account for the complexity in sustainable development (United Nations General Assembly 2015), the way it does so is relatively unguided (see Section 3.1). For instance, the UN has many departments and affiliations spread throughout the world, many of which work with relative independence, whereas solving complex problems requires collaboration among multiple agencies. Without adequate collaboration and coordination, the outcomes could be worse than no intervention at all. Still, the UN is in a perfect position to solve complex global problems because of its many resources, global reach, and a mission that touches all areas of human civilization. If the UN were to guide worldwide sustainable development successfully, it must base its approach on sustainability sciences/engineering, systems thinking, and transdisciplinary knowledge as these three enable complex issues to be analyzed more effectively than current linear and reductionist approaches. The UN recognizes this limitation (Zelinka and Amadei 2017), but implementing new tools and approaches to account for interlinkages between the SDGs requires more than just recognition; it requires political will among the member states. Because of their global recognition and importance, the SDGs are the primary focus of this work and are used as a proxy for sustainable development. The other topics discussed throughout are all incorporated within the SDGs or somehow involve them in some significant manner.

## **2.2. A Nexus approach**

### **2.2.1. The WELF+ nexus**

Because the SDGs dealing with food (SDG 02), energy (SDG 07), and water (SDG 06) are crucial for human survival and are considered to be fundamental human rights/services, they have been deemed of a higher priority (Weitz et al. 2014) than many of the other goals (Food and Agriculture Organization 2018; United Nations General Assembly 1948, 2010). Food, energy, and water are so inextricably linked (Table 3) that they are often referred to using a single term: FEW (food-energy-water) resources. Over the next 40–50 years, rapid population growth and global economic development will create unprecedented FEW resource demands. By 2050, global food demand is expected to grow by 60%, energy demand by 80%, and water demand by 55% (Ferroukhi et al. 2015). This growth

will occur in an existing context of scarce FEW resources that are highly interconnected with one another; for example, a water scarcity makes food production more difficult. Thus, the security of these resources is of great concern.

For the last decade, *resource security* – an integrated concept that encompasses the combined security of food, energy, water, and other crucial resources for human civilization – has become of significant concern to decision makers in the private and public sectors and civil society involved in development worldwide. Simply put, the challenge is how “to feed more people with [less] water, in a context of climate change and growing energy demand, while maintaining healthy ecosystems” (UN-Water 2018). This challenge is a prime example of complex and wicked problems this work aims to address. It’s not so much that climate change is the problem, it is how improve human well-being in the face of climate change – one of the missions of sustainable development (Von Stechow et al. 2016).

Table 3. WELFC-related SDGs and targets (adapted from Weitz et al. 2014) with land (L) and climate (C) added by the authors from the United Nations General Assembly (2015); edited for length

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<p><b>SDG 02 FOOD/AGRICULTURE (F)</b></p> <ul style="list-style-type: none"> <li>• End hunger &amp; ensure access for all people to safe, nutritious, &amp; sufficient food all year (W, E, L, C)</li> <li>• End all forms of malnutrition &amp; address the nutritional needs of vulnerable people (W, E, L, C)</li> <li>• Double the agricultural productivity &amp; the incomes of small-scale food producers (W, E, L, C)</li> <li>• Ensure sustainable food production systems &amp; implement resilient agricultural practices (W, E, L, C)</li> </ul>
<hr/> <p><b>SDG 06 WATER AND SANITATION (W)</b></p> <ul style="list-style-type: none"> <li>• Achieve universal &amp; equitable access to safe &amp; affordable drinking water for all (E, F)</li> <li>• Improve water quality by reducing pollution, halving the proportion of untreated wastewater, and increasing recycling &amp; safe reuse (E, L, F, C)</li> <li>• Substantially increase water-use efficiency across all sectors &amp; ensure sustainable withdrawals (E, L, F)</li> <li>• Implement integrated water resources management at all levels (E, L, F)</li> <li>• Protect &amp; restore water-related ecosystems (E, L, F)</li> </ul>
<hr/> <p><b>SDG 07 RENEWABLE ENERGY AND ENERGY EFFICIENCY (E)</b></p> <ul style="list-style-type: none"> <li>• Ensure universal access to affordable, reliable, &amp; modern energy services (W, L, C)</li> <li>• Increase substantially the share of renewable energy (L, C)</li> <li>• Double the global rate of improvement in energy efficiency by 2030 (W, L, C)</li> </ul>
<hr/> <p><b>SDG 13 CLIMATE CHANGE (C)</b></p> <ul style="list-style-type: none"> <li>• Strengthen resilience &amp; adaptive capacity relating to climate-related hazards &amp; disasters (W, E, L, F)</li> <li>• Integrate climate change measures into national policies, strategies, &amp; planning (W, E, L, F)</li> <li>• Improve education, awareness, and human and institutional capacity on climate change mitigation, adaptation, impact reduction, &amp; early warning (W, E, L, F)</li> </ul>
<hr/> <p><b>SDG 15 LAND AND TERRESTRIAL ECOSYSTEMS (L)</b></p> <ul style="list-style-type: none"> <li>• Ensure the conservation, restoration, &amp; sustainable use of terrestrial &amp; inland freshwater ecosystems &amp; their services in line with obligations under international agreements (W, F, C)</li> <li>• Promote the implementation of sustainable management &amp; restoration of forests (W, E, F, C)</li> <li>• Combat desertification &amp; restore degraded land and soil (W, E, F, C)</li> </ul> <hr/>



- 
- Ensure the conservation & restoration of mountain ecosystems (W, F, C)
  - Take significant action to reduce the degradation of natural habitats & stop biodiversity loss (W, F, C)
  - Promote fair & equitable sharing of the benefits from using genetic resources as internationally agreed (F)
  - Take measures to significantly reduce the impact of invasive species in land & water ecosystems (W, F)
- 

Land is sometimes associated with the FEW nexus, since it is vital to produce food, energy, and maintain the water supply, as well as other ecosystem services (Hurni et al. 2015; Müller et al. 2015; Ringler et al. 2013; Weigelt et al. 2015). Figure 3 shows a tetrahedron representation of the water-energy-land-food (WELF) nexus where each node corresponds to one sector of the nexus. A fifth node (defined as X) can be connected to the other nodes to yield the WELF+ nexus. This node usually corresponds to population (which is typically a driver of the nexus), climate (SDG 15), or any number of sectors (e.g., health, soils, transport, communication, state security, human rights, labor, trade, natural resources, governance) that can be added to the WELF nexus as needed to model a specific context. Including transport in the nexus, for example, could link the food sector even more closely to urbanization, since distribution significantly affects food. The more efficient the distribution systems are (which is closely related to transportation), the less impactful the overall agricultural/food sector will be on the climate sector because transportation emits large quantities of greenhouse gasses into the atmosphere.

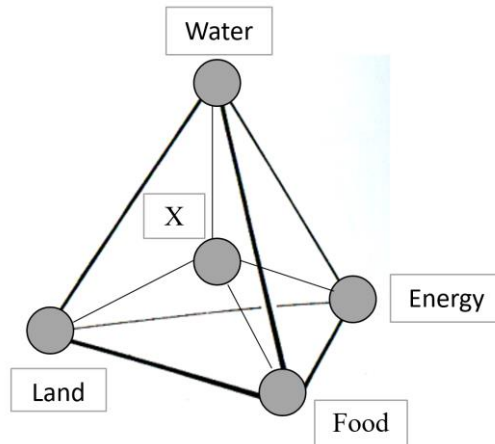


Figure 3. The WELF+ nexus representation (from Amadei and Zelinka 2018)

The WELF+ nexus is often analyzed using a cross-impact matrix (see Sections 3.2.1 and 4.1.1 and Appendix A). Table 3 shows, for example, the linkages between the water-energy-land-food-climate (WELFC) sectors. Each sector has a specific row and column. Each cell represents the interaction of the row and the column. For example, the intersection of the last row and fourth column depicts the effect of climate on food: climate change will lead to extreme and unpredictable weather variability that can damage crops and reduce agricultural productivity and consequently affect food supply. It is important to note that the cells are directional. The reciprocal effect of food on climate can be

found at the intersection of the fourth row and last column: food production releases significant amounts of greenhouse gases (i.e., the decay of biological matter) that increases the energy trapped in the atmosphere. Table 4 is just one broad way to look at the WELF+ (in this case, WELFC) nexus; greater specificity can be applied to adjust the context and scale. A cross-impact matrix of a city, for example, will have different considerations than a rural town; a city facing a drought will have different challenges than a water-rich city.

Table 4. Example of a WELFC cross-impact matrix

	<b>water</b>	<b>energy</b>	<b>land</b>	<b>food</b>	<b>climate</b>
<b>water</b>		mining of fuel stock; thermo-electric cooling/evaporation	erosion; mudslides; fight desertification	irrigation; raising livestock; cleaning food	
<b>energy</b>	treatment/sanitation facilities; water pollution; distribution; hydropower and biofuel energy increase pressure on water resources; energy efficiency reduces those pressures		generation facilities; solar PV, wind, and biofuels require land; energy efficiency; environmental degradation	fertilizer; processing; transportation and distribution;	emits GHG; air pollution
<b>land</b>	treatment facilities; distribution	mining of fuel stock; generation facilities; distribution		agricultural land-use; grazing land	land-use change alters the land's capacity to absorb/emit GHGs
<b>food</b>	agricultural field run-off pollutes water and aquatic ecosystems	biofuels	agricultural land conversion; agricultural field run-off pollutes habitats		agriculture is a significant source of GHGs
<b>climate</b>	changing precipitation patterns		desertification; floods	extreme and unpredictable weather variability	

The expanded nexus (WELF+) approach is one of the leading frameworks used to analyze complex systems that are structured as a nexus (i.e., with multiple interacting sectors). The WELF+ nexus is especially useful in connecting essential human services (i.e., water, food, energy) to other major sustainable development processes and drivers such as population, urbanization, migration, and so on.

### 2.2.2. Urban population dynamics

As shown in Figure 4, urbanization (SDG 11) has been a significant global trend since at least 1960, beginning at the end of the Age of Conflict (1945) and with the birth of modern globalization. It has been especially noticeable in developing countries due to their rapid population growth, economic development, and industrial modernization (Gries and Grundmann 2018). Urbanization occurred during the Industrial Revolution for the modern-day developed countries (namely, Europe and the United States), but today it is happening faster than most developing countries can

effectively accommodate (Liotta and Miskel 2012). Liotta and Miskel (2012) label these massive cities (megacities, which have populations in excess of ten million) that fall prey to these combined affects (think Lagos in Nigeria, Dhaka in Bangladesh, Cairo in Egypt, and Karachi and Lahore in Pakistan) Leviathans, as they outstrip the capacities of their national governments to manage. Leviathans has its roots in biblical terminology (referring to an uncontrollable entity), and the political philosopher Thomas Hobbes used the term to describe a Leviathan-city that is beyond the control of the state. This problem is exemplified by the fact that Egypt is building an entirely new capital city to escape the problems of its current Leviathan-capital-city (Liotta and Miskel 2012; Pinto and Badawy 2018). Cairo is currently managed by the national government, not a municipal government due to its size and problems (Liotta and Miskel 2012). These Leviathan megacities are to proliferate around the globe as urbanization continues and can be considered complex and wicked problems by themselves.

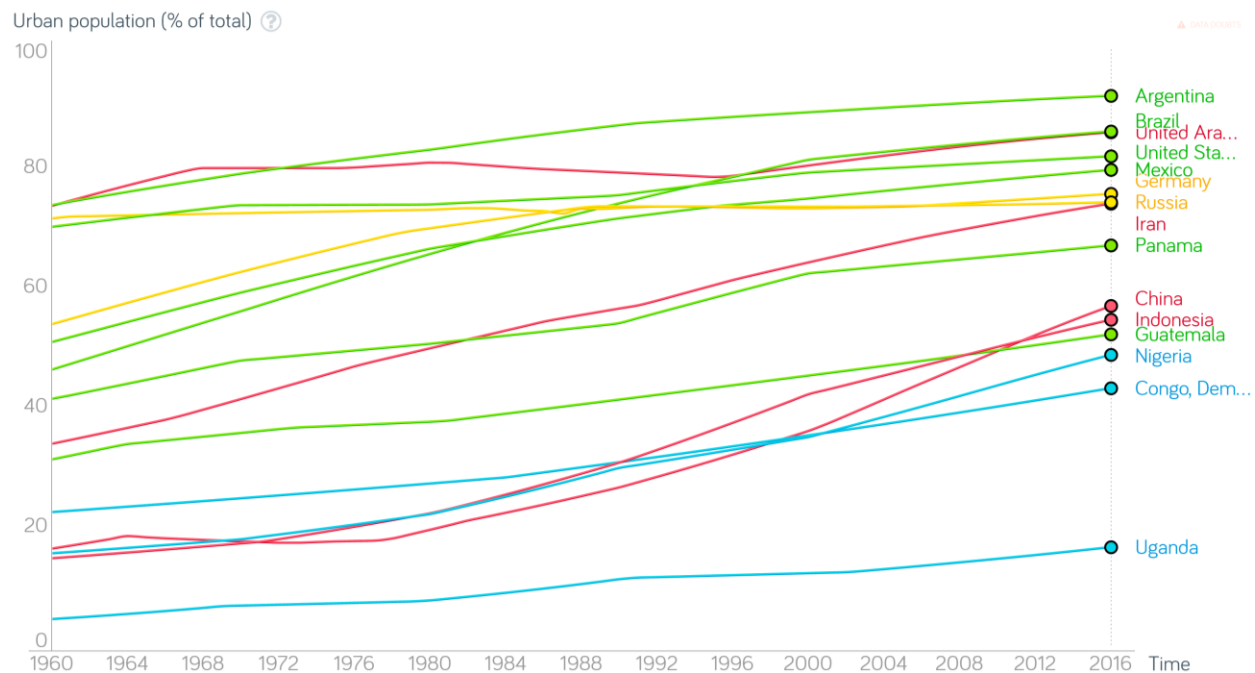


Figure 4. Time vs. urban population (% of total); colors represent countries by region of the world: yellow is Europe, purple is Africa, green is the Americas, and red is Asia/Oceania (Gapminder 2017; World Bank 2018a)

Income (SDG 01), along with health (SDG 03) and education (SDG 04), are used to calculate the Human Development Index (HDI) (United Nations Development Programme 2018), the UNs primary index for measuring the overall well-being and economic development for a particular population. It ranges from 0 (low development) to 1 (high development). Figure 5 shows the positive exponential relationship between urban population and income. As a country moves from low-income to low-middle income status, urbanization occurs very rapidly implying that people

move to cities because of prospects for a better life through financial security. There are also strong connections among the economic SDGs: income (SDG 01), the economy (SDG 08), inequalities (SDG 10), and consumption/production (SDG 12). The connection between income and urbanization imply that the economic SDGs are closely aligned with urbanization as well.

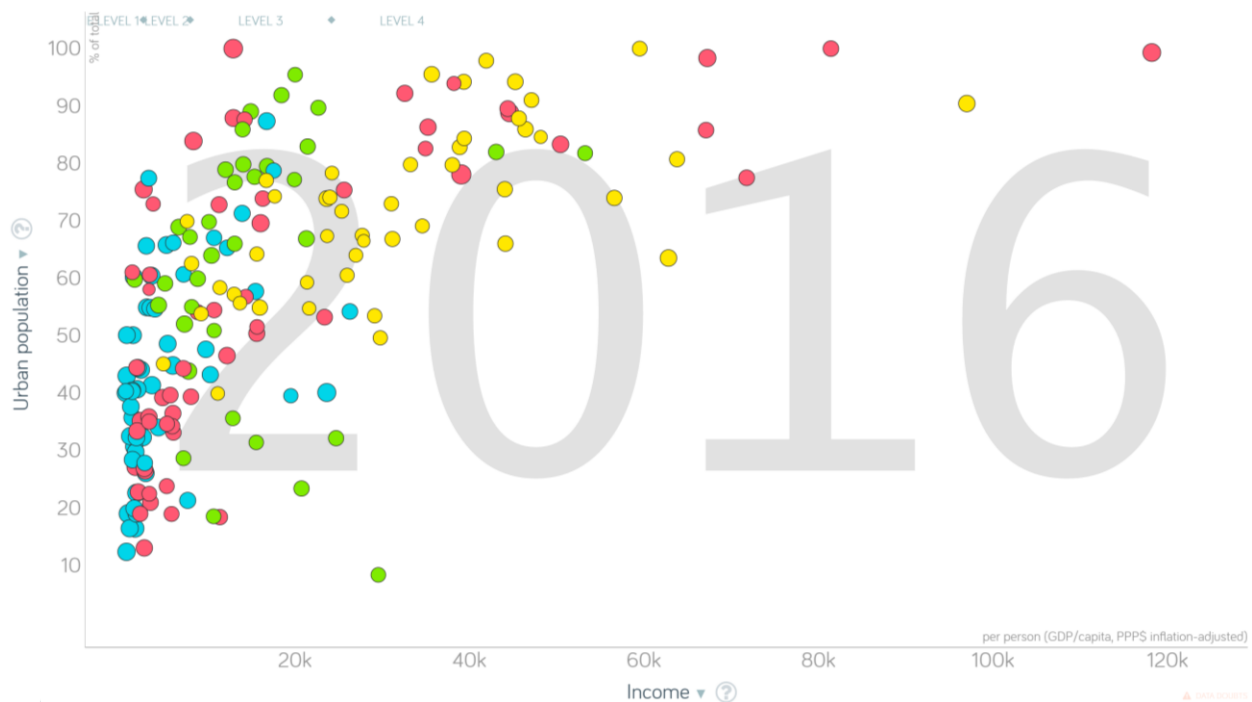


Figure 5. Income vs. urban population in 2016 for countries; colors represent countries by region of the world: yellow is Europe, purple is Africa, green is the Americas, and red is Asia/Oceania (Gapminder 2017; United Nations Population Division 2018a; World Bank 2018b)

Urbanization is also linked to climate change. Figure 6 shows a negative exponential relationship between urban population growth and CO<sub>2</sub> emissions. As a country urbanizes, its environmental impact decreases quickly. There is much variability, but in general urban centers are more efficient at providing goods and services and resources because of the high concentration of people compared to rural areas. The variability of CO<sub>2</sub> emissions is mostly caused by varying levels of technology and environmental policy in a given country. Urbanization also has similar relationships with oceans and land, which in addition to climate, constitute the three environment SDGs (13 climate, 14 oceans, and 15 land). Many more connections can be made between urbanization and the other SDGs lending evidence to the importance of urbanization on sustainable development. Furthermore, Figure 6 also shows that most countries are urbanizing as the urban population growth (x-axis) for most countries is above 0%.

Urbanization involves significant aspects of the social sciences and engineering and cross-cuts multiple SDGs. The desired outcome of SDG 11 is to make “cities and human settlements inclusive, safe, resilient, and sustainable” (United Nations General Assembly 2015) for people. Therefore, it is necessarily linked to SDG 02 (food security), SDG 06 (clean water and sanitation), SDG 07 (energy), SDG 13 (climate), and SDG 15 (land), as well as being indirectly linked with all the other SDGs, especially when considering socio-economic factors (Zelinka and Amadei 2019a). Population growth and demographic change directly affect the demand for resources and services, including increased food consumption, land use, and water demands, which then in turn indirectly affects climate change, environmental degradation, and even human rights. There is no sector in which population is not a factor, so in that way, population is a fundamental driver for sustainable development; population must be considered in long-term strategic planning for improving human well-being. Hence, anthropocentric systems can be seen as ubiquitous throughout sustainable development.

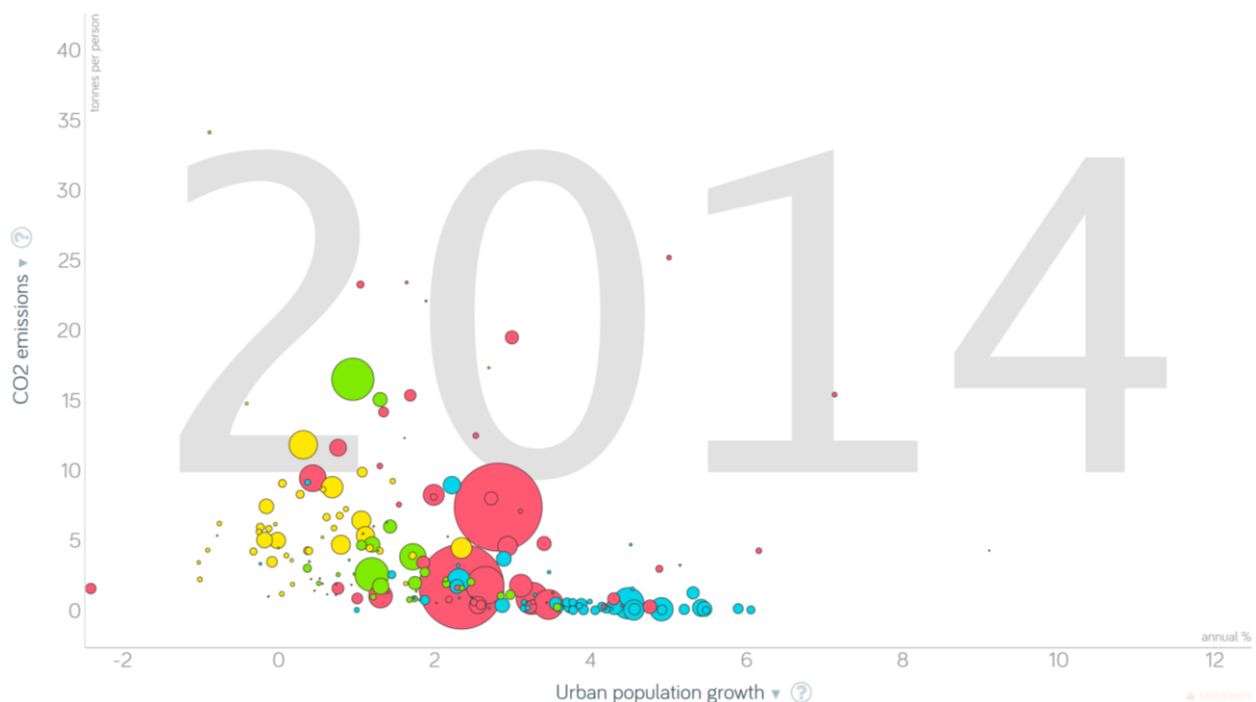


Figure 6. Urban population growth vs. CO<sub>2</sub> emission per capita in 2014 for countries; colors represent countries by region of the world: yellow is Europe, purple is Africa, green is the Americas, and red is Asia/Oceania (Gapminder 2017; United Nations Population Division 2018b; World Bank 2018a)

A growing population with changing demographics will require more housing, resources, and services; cities can accommodate these population dynamics better than rural areas assuming that the population growth doesn't overpower the capacity of the infrastructure to deliver those services (Liotta and Miskel 2012). Slums – informal settlements in and around cities where the impoverished people, who lack land rights, are forced to live because they

cannot afford actually to live in the city legally – form when cities cannot (or will not) keep pace with their changing populations. Slums are especially pervasive in the developing world but exist to varying extents in most countries (Liotta and Miskel 2012). Slums have become a significant problem, and many development initiatives are aimed at managing and providing them with services.

In the modeling of sustainable development, population demographics usually do not receive much attention due to their complex interconnections with so many areas and long time-horizons. Generally, simple models with a wide range of values are used. However, because of how significantly population factors (specifically through urbanization) can influence sustainable development, a proper understanding of urbanization is needed.

Urbanization has traditionally been understood through two theoretical approaches: the ecological (or humanitarian) approach and realism. The ecological perspective focuses on societal issues like conflict, globalization, pollution, and climate change, while the realist approach looks at economic, political, and military interactions among major powers, namely the United States, European Union, Russia, China, and India (Liotta and Miskel 2012; Pincetl et al. 2012), of which international relations is a relevant and salient discipline. Merging the ecological perspective and realism (perhaps ecological realism, urban social ecology, the urban nexus, or other fields and concepts) with theories from other fields and systems science and engineering is crucial to see a complete picture of urbanization within the context of sustainable development. These two theories are good at explaining certain macro-level aspects of urbanization, but other perspectives can fill in gaps at smaller scales (neighborhoods, communities, slums, and so on) and sectors (food security, poverty, education, health, transportation, and so on).

Psychology and sociology can identify specific reasons why individuals or families move. For example, employment opportunities are frequently a reason why people move (i.e., labor migration) to cities (de Brauw et al. 2014). A systems approach can then combine all the ideas together into a less fragmented and holistic picture. One familiar concept appears in all concepts that attempt to explain urbanization – push-and-pull. People are pushed away from the source because of relatively poor conditions and are driven to a new place that has better conditions. Taking the previous example: if unemployment in a rural area is higher than that of an urban area, people will want to migrate to that city. The more significant the difference in the unemployment the higher the likelihood a person will migrate, or (taken another way) the higher the fraction of people that will move (i.e., rural-urban migration rate).

## 2.3. Corruption

The previous section described population and urbanization as important forces in sustainable development as they are specifically crucial for technological, political, economic, social factors, and the environment. Urbanization can be used as a force of good or bad; it depends on how well urban growth is managed. This section looks at corruption that mainly operates within the social and political pillars of sustainable development. Corruption is arguably problematic in most cases. The remainder of this chapter covers – in addition to corruption – conflict and hydro-politics (explained later), which together represent socio-political issues. This section is an abbreviated form of the paper found in Appendix F (Zelinka and Amadei 2018a).

### 2.3.1. Political corruption

Corruption is a broad term with definitions spanning multiple disciplines. Transparency International's (TI, 2016) definition is most widely used in the corruption literature: “the abuse of entrusted power for private gain.” Multiple definitions have been put forth by Iyanda (2012), but when they are aggregated, they sound familiar: (i) unlawful use of official power to enrich oneself usually at the expense of others; (ii) when someone knows better but chooses the worse option; and (iii) when someone acquires something to which he or she are not entitled. The general definition that will be used is when *someone does something they are not supposed to for personal gain and at the expense of another*.

When something is a corrupt act: (i) it is an illegal, secret, or informal exchange of formally allocated resources; (ii) at least one corrupt party is formally involved with the entity from which resources (broadly defined) are extracted; and (iii) the corrupt act is against formal rules, laws, or policies (Jancsics 2014). However, corruption is not a universal concept and varies by culture or community. Nepotism is an example of a corrupt act (Table 5), but the community where it is committed might merely view the act as doing a favor (Seleim and Bontis 2009), helping a friend, or even a form of economic bartering. For each new analysis and scenario, a unique and contextual definition of corruption should be created, although the definitions might share multiple overlaps. There is no one-size-fits-all approach to anti-corruption campaigns, so utilizing a universal definition is inherently self-defeating and misses cultural nuances and unique situations.

Table 5 lists and explains actions that are considered to be corrupt according to Rose-Acker and Palifka (2016) and Iyanda (2012). Given the commonalities of the items in this list, corruption is the prevalence of and damage caused by corrupt acts. In this work, corruption is synonymous to rent-seeking, which is the desire and tendency for

an entity to engage in corrupt acts for extracting illegal rents. Rents are the benefits (financial, favors, or otherwise) acquired through the corrupt acts.

Table 5. Examples of corrupt actions; adapted from Rose-Acker and Palifka (2016) and Iyanda (2012)

<b>Bribery</b>	Money, gifts, or favors given to a government or corporate official in exchange for breaking the rules to give preferential treatment, an advantage, or otherwise some benefit to be received (see extortion)
<b>Extortion</b>	Demanding a bribe or favor from an official, where the official usually is in a position of lesser power (see bribery)
<b>Exchange-of-favors</b>	The exchange of one broken rule for another
<b>Clientelism/patronage</b>	General favoritism to a specific group (see nepotism and cronyism)
<b>Nepotism</b>	Putting someone into a position of power based on the strength of social connections rather than on merit or the legal process (see clientelism/patronage and cronyism)
<b>Cronyism</b>	Giving preferential treatment to one's group (racial, ethnic, religious, political, or social) over other groups (see clientelism/patronage and nepotism)
<b>Judicial fraud</b>	A decision based on any of the preceding types of corruption, or threats to the judge, rather than on the merits of the case
<b>Accounting fraud</b>	Intentional deception regarding sales or profits, usually regarding a corporate entity, but also applicable to government spending and budgets
<b>Electoral fraud</b>	Manipulation of election results, through any mechanism
<b>Public service fraud</b>	Any activity that undermines the legal requirements of public services. Essentially, any actions that negatively affect the delivery or quality of public services like education, police, health, etc. Public teachers might not show up with work due to low pay or inadequate incentive, harming the quality of the education system
<b>Embezzlement</b>	Theft from the employer (firm, government, or NGO) by the employee
<b>Kleptocracy</b>	An autocratic state that is managed to maximize the personal wealth of the top leaders and is closely related to economic inequality; there are virtually no differences between the economic elites and the political elites, with Russian oligarchs as a prime example
<b>Influence peddling</b>	Using one's power of decision in government to extract bribes or favors from interested parties
<b>Tax evasion</b>	Avoiding tax can be legal or illegal. It can be a subset of bribery and is a mechanism that reduces the efficiency of revenue-generating tools. Utilizing legal loopholes is a form of corruption in that the citizen is not paying all the taxes that they are supposed to due to structural inefficiencies or problems in the revenue accumulation systems of a government
<b>Cheating</b>	Cheating is usually the goal of bribes when coming from the societal perspective. People bribe government officials at the DMV to get a driver's license without having to take a test. Cheating can happen at any scale and can be severe or not harmful at all
<b>Conflicts-of-interest</b>	Having a personal stake in the effect of the policies one decides; although not directly a corrupt act, a conflict-of-interest can heavily influence corrupt practices
<b>Other corrupt acts</b>	Money laundering, fraudulent trade practices, misappropriate or diversion of funds, kickbacks, under- and over-invoicing, false declarations, abuse-of-office, collection of illegal tolls, impairment of integrity, negative virtue or moral actions, and unauthorized use of resources



Corruption is an endemic socio-political issue that has existed since the dawn of human civilization. It is prevalent in all human systems, is a societal problem, and is a global phenomenon that “transcends national boundaries and frontiers” (Iyanda 2012). Some interesting statistics about corruption include:

- If bribes alone were an industrial sector, they would represent 3.3% of the global economy (Goel and Nelson 2010).
- Five to twenty-five percent (\$26–130 billion) of World Bank funds were lost or missing due to corrupt practices (Berkman et al. 2008), with more recent estimates as high as a \$1 trillion (Liotta and Miskel 2012).
- Corruption exacerbates income inequalities and poverty. The Gini coefficient, a measure of income inequality ranging from 0 (perfect equality) to 1 (perfect inequality), worsens by 11 percentage points, and income for the bottom quartile of people falls by 4.7% with a one standard deviation increase in corruption as measured by Transparency International’s Corruption Perception Index (Gupta et al., 2002).
- Developed countries also suffer from the economic impacts of corruption; for instance, 1% (\$170 billion) of the European Union’s GDP is lost due to corrupt actions each year (Oberoi 2014).
- India lost \$11.3 billion a year (in 2018 \$USD) – between 1948–2000 in illegal capital flows (i.e., money extract from corrupt acts) with corruption reducing the effectiveness of the business and private sector by roughly 40% (Oberoi 2014).
- Between twenty-five and forty percent of any given African country’s GDP is lost from all corrupt acts (Oberoi 2014).
- A one standard deviation reduction in corruption has been shown to improve annual foreign direct investment in a country by 4% of GDP and increased GDP’s annual growth by 0.5% (Oberoi 2014).
- Corruption in any given year depresses the Kenyan economy by 12% of GDP (Liotta and Miskel 2012), almost equivalent to the worth of the entire industry and manufacturing sector (14% of GDP; (“Economy of Kenya” 2017).
- The average Kenyan income was 424 times less than the salaries that parliamentary members paid themselves—a direct indicator of corruption (Liotta and Miskel 2012).

Corruption can operate at any level, from petty corruption between everyday citizens to grand corruption among the political and economic elite. *Grand corruption* involves a small number of powerful actors dealing with massive quantities of money and can be political and corporate (Rose-Ackerman and Palifka 2016). This form of corruption is out of reach to most citizens, who are generally guilty of *petty corruption*, small-scale corrupt acts like when a citizen bribes a government official to attain a driver's license (Rose-Ackerman and Palifka 2016). As a result, grand corruption is more pervasive in national governments and parts of the economy that deal with influential people operating in positions of power with large sums of money (Iyanda 2012; Rose-Ackerman and Palifka 2016), such as is the case in the military and defense (Gupta et al. 2001), natural resource (Bulte and Damania 2008; Busse and Gröning 2012; Corrigan 2014; Dimant and Tosato 2017; Kolstad and Søreide 2009), and infrastructure sectors (Tanzi 1998).

*Business corruption* (petty corruption's private sector counterpart) occurs with low- to medium-sized businesses that interact with average citizens, while *corporate corruption* (grand corruption's corporate counterpart) involves large multinational companies interacting with governments usually on large construction projects in, again, military and defense (Gupta et al. 2001), natural resource (Bulte and Damania 2008; Busse and Gröning 2012; Corrigan 2014; Dimant and Tosato 2017; Kolstad and Søreide 2009), and infrastructure sectors (Tanzi 1998). Businesses and corporations often act corruptly to avoid regulations. For example, Mitchell (1994) describes a situation where to detection and fines oil tankers would illegally dump their waste oil in the ocean before entering port. These oil tankers do not want to obey the law, as it adds financial burden, so dumping their excess waste oil outside the watchful eyes of port authorities was the easiest and cheapest way to get around the law and extra costs associated with compliance. This compliance problem is a form of corruption, in which businesses act in ways that prioritize company gain over societal good; this views corruption as a collective-action problem as opposed to the principle-agent problem (Bauhr 2017; Mungiu-Pippidi 2013; Persson et al. 2013; Rothstein 2011). The first attempt to solve this problem was to use helicopters and boats to police each oil tanker individually before they made port; this proved much too expensive and difficult to administer. Eventually, the *structure* of the environmental policies and regulations governing how tankers disposed of their waste oil was successfully reformed to disincentivize this negative *behavior*. This structural approach involved mandating that each tanker install equipment that reduced waste oil, making it very easy to police since a tanker could be inspected in the port to see if they had the equipment or not.

This solution was cheap and virtually 100% effective; it eliminated the need for expensive helicopters and boats policing a large area of water for each tanker.

The common theme across the literature is that corruption is structural. Poorly structured social, political, governance, or economic systems act as “opportunity structures to conduct corrupt practices” (Jancsics 2014). Thus, corruption requires three conditions to arise and persist: (i) discretionary power or authority among relevant people; (ii) the incentives to be corrupt; and (iii) weak institutional systems, which make it easier for corruption to happen and persist (Aidt 2003). Corruption can, therefore, be used as a tool to identify—and fix—weak systems, as a “high level of corruption indicates that something is wrong with the state’s underlying institutions...[signaling] a need for structural reform – not just more vigorous law enforcement” (Rose-Acker and Palifka 2016) which in turn would help to reduce corruption. A systems solution would be to restructure the governance *system* through *structural* reform to alter the negative *behavior* (reduce corruption).

Taking a systems approach to understanding corruption requires a systems-oriented definition: *corruption is anything a human does to enrich themselves at the expense of the system efficiency; that individual goes against the rules and structure of the system*. This definition is broad enough to contain virtually all acts considered corrupt, as well as most definitions of corruption regardless of whether they are economic, political, social, or environmental. The definition is dynamic in that if the perspectives of people change the general systems definition still holds true. What might “look like corruption to outside observers might serve crucial social and symbolic functions from the inside or in a local context” (Jancsics 2014; Torsello and Venard 2016). If the population views their government as corrupt, evade their taxes, which is considered a corrupt act, the citizens of corrupt government might view paying taxes as political corruption in their country. Ultimately, corruption is “what every society decides it is; it simply has to be internally consistent with formal institutions of a given society” (Oberoi 2014).

### **2.3.2. Sustainable development and corruption**

In creating the SDGs, the United Nations General Assembly (2015) realized that corruption was a severe hindrance to socio-economic development. As a result, seven targets within SDG 16 (governance) directly involve or address corruption:

16.3 - Promote the **rule of law** at the national and international levels and ensure equal access to justice for all

16.5 - Substantially reduce **corruption** and **bribery** in all their forms

16.6 - Develop effective, **accountable**, and **transparent** institutions at all levels

16.7 - Ensure responsive, **inclusive**, **participatory**, and **representative** decision-making at all levels

16.8 - Broaden and strengthen the **participation** of developing countries in the **institutions** of global governance

16.10 - Ensure public **access to information** and **protect fundamental freedoms**, in accordance with national legislation and international agreements

16.a - **Strengthen relevant national institutions**, including through international cooperation, for **building capacity** at all levels, in particular in developing countries, to prevent violence and combat terrorism and crime

While Target 16.5 directly mentions corruption, the other six targets address the underlying structural causes of corruption to varying extents. Corruption target 16.5 can only be mitigated with considerable progress toward the other five targets – not to mention other SDGs and their targets – which in turn require input from many other areas. However, despite the substantial work necessary to address all of these targets (and their related SDGs and targets), progress toward these targets will significantly improve governance, which will then positively affect all of the other SDGs.

Section 2.3.3 relies heavily on the social sciences to explore and begin to understand and model corruption systematically; if corruption is not understood, it cannot be adequately addressed. To quantitatively understand how to model corruption, corruption must first be qualitatively understood across multiple disciplines; doing so guides the quantitative model using qualitative research and improves overall model validity. Therefore, corruption is approached from a system dynamics perspective so that it can be deconstructed into its fundamental components in order to ascertain the underlying structural reasons why corruption in a particular context exists and how to begin to address it. Because corruption is a very complex issue that cross-cuts nearly all areas within sustainable development, the focus of this work looks at the effects of corruption in natural resource governance (i.e., the natural resource curse). Although not as inclusive as a general model of corruption, the natural resource curse provides a proof-of-concept that illustrates important connections between corruption, governance more broadly, and the environmental SDGs (13, climate change; 14, oceans; and 15, land). Using this proof-of-concept, corruption can then be applied to other areas like business, healthcare, and education; all the models can ultimately be connected to create an intricate, universal,

and transdisciplinary corruption model. The next section shows this proof-of-concept applied to the natural resource curse.

### 2.3.3. Natural resource curse

The natural resource curse is a phenomenon in which countries with large quantities of natural resources and mineral wealth counterintuitively suffer from lower economic and social development (Bhattacharyya and Hodler 2010; Busse and Gröning 2012; Corrigan 2014; Frankel 2010; Kolstad and Søreide 2009; Teksoz and Kalcheva 2016). It occurs throughout the Global South but is especially pervasive in many African and Middle Eastern countries—for instance, all 12 of the oil-exporting countries in Africa are in the bottom half of the United Nations Human Development Index (Diamond and Mosbacher 2013).

The ultimate goal of researchers investigating the natural resource curse and governance is to understand “why some countries succumb to the resource curse while others seem to benefit economically from their natural resources” (Corrigan 2014). The most common reason proposed in the literature involves poor governance and institutional quality. While that is only part of the picture, there are a few specific and well-documented causal pathways that connect natural resources with governance, namely the rentier, repression, and modernization effects (Bhattacharyya and Hodler 2010; Busse and Gröning 2012; Corrigan 2014; Kolstad and Wiig 2009).

The *rentier effect* depends on the size of revenues (rents) that the government can extract from natural resources (e.g., oil) and occurs when those revenues are *substantially* relative to other sources of income. (Substantially in this context refers to when resources revenues are so significant that the government does not need to rely on other sources of income.) The effect comes from what the national government does with those revenues (Teksoz and Kalcheva 2016). The resource revenues could be used to reduce the need to tax the population (*taxation effect*), making them happier with the government, which in turns reduces their desire to hold the government accountable (Busse and Gröning 2012; Corrigan 2014) and increases their tolerance for governmental corruption. This money can also be used for development projects to appease or distract the population. Along the same lines, Busse and Gröning (2012) describe a *group formation effect* which occurs when the government uses the resource rents to prevent the formation and operation of social and special interest groups who would otherwise pressure the government to reduce corruption. The same effect can happen when those revenues are spent on cronyism (or, more broadly, favoritism), which Busse and Gröning (2012) refer to as the *spending effect*. Through a reduction in taxes

and increase in general favoritism, governmental accountability is reduced because the population sees higher relative incomes from lower expenses and is willing to look the other way when the government or political officials participate in corrupt acts. Collectively, the cyclical nature of these effects leads to more economic policies that accelerate the extraction of the natural resources upon which the government—and, in turn, the populace—has grown dependent. In the short- to medium-term, revenues increase, feeding back into the cycle. Over time, however, the amount of resources diminishes, with little long-term benefit to the population actually making them worse off (Corrigan 2014).

The *repression effect* occurs when the government uses revenues to actively repress opposition, usually through force, as opposed to gaining favor among the populace. It is a more extreme version of the group formation effect and can be violent or militaristic. The rents again come from the significant natural resource wealth contained within a country's borders, but can also come from individual government officials who receive money from corrupt acts like bribery (Busse and Gröning 2012; Kolstad and Wiig 2009). With more financial capital, these officials can more easily fund their repressive and corruption actions. In this circumstance, the government might spend more on the military, further entwining the political and military spheres in a country. When this happens, it is easier for the military to oppress or terrorize the people because of their larger budgetary allocation. In extreme cases, the repression effect can take the form of violent suppression of protests or attempted revolution, such as in the case of the Arab Spring. In short, the repression effect “could impede aspirations among the population for more democracy or better institutions and government services” (Busse and Gröning 2012). An even more extreme case, the repression effect can resemble occupation or large-scale oppression of a populace, especially a demographic not represented in the government. (This is the case in the Palestinian-Israeli conflict, discussed later in this paper.)

Finally, a *modernization effect* occurs when the government actively inhibits modernization and industrialization within their country, because such a society will have alternative sources of economic and political power with which to oppose the government (Busse and Gröning 2012, Corrigan (2014), Kolstad and Søreide 2009). In some cases, this can be viewed as a passive and indirect version of the repression effect. Delaying modernization prevents an environment from forming in which protests and revolts might succeed. For instance, education positively correlates with demand for political reforms. However, if the government keeps its country's economy based on natural resources and agricultural, there will be little need for a large skilled labor force, and in turn little need for education. In this way, the government actively comes in the way of social and cultural change for fear of losing

power. Many countries in the Middle East, namely Iran and Saudi Arabia, have been especially susceptible to this form of corruption (Frankel 2010).

The effects mentioned above are not mutually exclusive and work in concert with one another; depending on the socio-political contexts, different mechanisms are more influential than others. Corruption is just one of the negative behaviors that can emerge from poor governance and other factors; conflict is another. Corruption and conflict are very strongly linked, and as such, they can be analyzed using the same methods described herein. The next section introduces conflict in the context of the Palestinian-Israeli conflict. Although corruption and conflict are analyzed separately, they can be coupled, yielding a more in-depth and insightful picture of two complex issues that permeate sustainable development and affect every country in the world. Doing so is out of the scope of this work due to the highly complex nature of both corruption and conflict.

#### **2.4. Conflict**

Conflict is a chaotic process and – like most social and political processes – it is very difficult to analyze let alone model. Conflict occurs when two groups have opposing views on some fundamental (seemingly irreconcilable) issue or issues causing tensions that can escalate to violence or war if no efforts are made to address the differences. The Palestinian-Israeli conflict (PIC), explored in this section, has a long history that has been extensively researched. Consequently, the academic literature regarding the PIC is myriad, which makes for an excellent application of systems analysis to conflict. The researchers who tend to study conflict are most often political scientists, so most of the literature has focused on the political explanations of the PIC conflict. Since real conflict is chaotic and multifaceted, a systems analysis must also so draw from other sources and disciplines (economics, sociology, anthropology, environmental science, etc.).

A (hyper) arid region, such as the Middle East, is particularly susceptible to environmental influences, particularly water resources, and geopolitical factors. Together the political economy and water resources are critical determinants of conflict. At the nexus of these three sectors is hydropolitics (water's effect on politics and governance), the leading theory used to frame the more significant conflict. Although conflict is a complex topic in general, there are a few crucial components at play perpetuating the PIC: relative power (Zeitoun 2012); national security (Aronson 2009; Bergman et al. 2018); ethnoreligious identity (Akcem and Asal 2005; Spangler 2015; Stroh 2011); knowledge structure, media bias, and propaganda (Stroh 2011; Zeitoun 2012); and water and resources security (Grey and Sadoff

2007; Haddad 2014; Jad and Hilal 2011; Selby 2005; Zeitoun 2012). Although the latter is emphasized herein, due to complex interactions, all aforementioned components cannot be separated, and must all be discussed in any analysis of the Palestinian-Israeli conflict.

#### **2.4.1. Conflict theory and power asymmetry**

Early theories of conflict, which are today generally addressed by the field of political science, came from economics.

Conflict theory, suggested by Karl Marx, claims society is in a state of perpetual conflict because of competition for limited resources. It holds that social order is maintained by domination and power, rather than consensus and conformity. According to conflict theory, those with wealth and power try to hold on to it by any means possible, chiefly by suppressing the power and powerless. (“Conflict Theory” n.d.)

This theory is used to explain class divides within a society and economic inequalities among countries (“Conflict Theory” n.d.; Selby 2005). It also explains European imperialism, i.e., when a more powerful society sought to amass wealth and power by expanding its empires and influence over the weaker nations of the non-Western World. The Age of Conflict then happened when there were no longer significant parts of the world left to subjugate. Ultimately, territory can be thought of as a finite resource that, if not adequately managed, succumbs to the tragedy of the commons.

The common theme here is power, power asymmetry, and its interactions with conflict. This means that to understand conflict, one must understand power and its various features. Zeitoun (2012) provides an excellent overview of the features of power, namely coercion, influence, authority, force, and manipulation, which all describe how power can be projected.

- Coercion is “the exertion of power where A secures B’s compliance through the use of threats.”
- Influence happens when “A causes B to change their course of action without threat (overtly or tacitly)”
- Authority is “when B complies because they recognize that A’s command is reasonable and legitimate.”
- Force “helps A to achieve their objectives by stripping B of the choice of compliance or non-compliance.”



- “[M]anipulation is an aspect of force, occurring when B complies without full realization of the nature of A’s command.”

Based on which features are most prevalent, power as a theory can be categorized as hard, soft, or geographical. These three forms of power utilize the five features of power above to project power, albeit to varying extents. For example, force is the predominant feature of **hard power**, which is the ability of one party to mobilize its material capacity (in the form of military might or industrial production) to gain the compliance of another. The more pronounced the power differential between two belligerents, the easier it is for the stronger country to dictate the terms of negotiations or if they even happen at all. Zeitoun (2012) calls hard power, “[d]omination dressed up as cooperation” and “disguise of cooperation” (Cascão and Zeitoun 2010; Lukes 2006; Zeitoun 2012).

**Soft power** is “the ability to get what you want through attraction [or repulsion] rather than coercion or payments” (Nye 2004). In general, soft power is more likely to yield peace than hard power, although it is much more difficult, long-term, and indirect (Cascão and Zeitoun 2010; Lukes 2006; Zeitoun 2012). There are two types of soft power. One type, **bargaining power**, (i) represents influence acquired by legitimacy and authority; (ii) strips the weaker party of the capacity to choose compliance and non-compliance; (iii) is the illusion of choice; and (iv) occurs when the significantly weaker side has very little, if any, voice. Bargaining power can shift if the international community backs one side of a national or international conflict, for instance, which gives that side legitimacy (via international law, support, and pressure) and is backed by hard power (the militaries of other countries). **Ideational power**, another kind of soft power, can prevent people from having grievances by shaping their perceptions, cognitions, and preferences in such a way that they accept their role in the existing order of things. Ideational structure can be shaped by knowledge structure: “the strong implant their ideas, even their self-serving ideology, in the minds of the weak, so that the weak come to sincerely believe that the value-judgments of the strong really are the universally right and true ones” (Zeitoun 2012:29) Ideational power is a form of ideological control.

**Geographic power** is power derived from a country’s geographical location. For example, countries that have a long border or are upstream in a river system have high geographic power because they can more easily defend and control the water supply. Geographic power can only really be directly affected by a change of territory between countries, usually as a result of war. Therefore, geographic power would seem to be the most important type of power to protect; however, other forms of power can negate geographic power to some extent. For instance, in the PIC,

Palestine is actually in a better position to use the Jordan River, but Israel's strong hard and soft powers enable that country to control it.

The relative differences in these three types of power – soft, hard, and geographical – influence the dynamics of conflict between the belligerents. Regardless of the source of the power differential between Palestine and Israel, that differential is undeniably a large part what perpetuates the conflict. It is difficult to quantify this differential, but some estimates put the power ratio of Israel to Palestine from 1:10 to 1:25 (Zeitoun 2012). Israel is significantly more powerful than Palestine, and as such Palestine has a tough time of resisting and forming effective defense (militaristically or otherwise) against Israel. Israel's occupation of the West Bank and blockade of Gaza (i.e., hard power) exemplify this concept in that Palestine has very few options, if any, to counteract Israel. Furthermore, because of the large discrepancy, Palestine has little bargaining (i.e., soft power) when it comes to negotiations. This extreme power differential is one of the main reasons why the PIC has been so persistent; the next two sections describe other factors that are significant and particularly salient to the PIC.

#### 2.4.2. Significant factors and concepts in the Palestinian-Israeli conflict

General conflict theory originated with Karl Marx, as an economist, who theorized that conflict occurs because of **resource inequality** between groups; when one group has something another wants or lacks, the second group will try to acquire that resource. Conflict arises if there are no alternative resources or if the first group is unwilling to negotiate for that resource. In the Palestinian-Israeli conflict, instead of resources, there are two groups (i.e., Palestinians and Israeli) that each have goals that fundamentally oppose the goals of the other (Table 6). The conflict comes from the inability to reconcile these primarily mutually exclusive goals. These goals have been influential historical factors that have increased each side's desire for national security, nationalistic sentiments, and chronic ethnoreligious tensions, and has led to a knowledge structure that spreads misinformation and disinformation, prompting strong emotional responses and making facts challenging to isolate.

Table 6. Key rights and interests in the Palestinian-Israeli conflict (Bisharat 2008)

Israelis	Palestinians
<ul style="list-style-type: none"> <li>• Rights to individual and collective security</li> <li>• Preserving Israel as a Jewish democratic state</li> <li>• Sovereignty in Jerusalem</li> </ul>	<ul style="list-style-type: none"> <li>• The right of return for Palestinian refugees and compensation for losses they suffered</li> <li>• Rights to equality for the Palestinian citizens of Israel</li> </ul>

Israelis	Palestinians
<ul style="list-style-type: none"> <li>• Continued access to residence in parts of the country of particular historical importance to Jews</li> <li>• Regional acceptance and friendly relations with the surrounding Arab countries</li> </ul>	<ul style="list-style-type: none"> <li>• Palestinian rights to national self-determination and sovereignty in their land</li> <li>• Control over East Jerusalem</li> <li>• Freedom from the Israeli occupation of the West Bank and Gaza Strip</li> </ul>

**National security** can be thought of as a macro-scale perspective of an individual's human security: national security deals with the defense of a nation-state, while human security is a broad concept incorporating "human rights, safety from violence, and sustainable development" (Schäfer 2013). One's country is supposed to provide the means of human security in the form of (i) military protection from foreign forces; (ii) domestic protection via law enforcement; (iii) infrastructure for transportation and other related services like food, water, and energy supply and distribution; (iv) environmental and ecological services protection; and (v) effective governance and regulatory systems. To provide these forms of human security, a nation-state should be able to defend itself, govern itself, and exercise supreme authority within its borders—those are the requirements for national sovereignty and being a country (Philpott 2016). If a country is incapable of supplying any one of those components, it cannot assure national security and defense. This is the current problem faced by the Palestinians (Mavroudi 2010; Young 2005): they cannot adequately defend themselves from Israeli forces, resulting in Palestinians' fear of the people of Israel.

Meanwhile, the Israelis are equally fearful. Most of the Middle Eastern countries are unfriendly or openly hostile to Israel primarily due to ideological and historical reasons. Because Israel sits at the center of the Middle East, Israelis feel themselves to be in a precarious and volatile situation. Just as the Balkans were an especially volatile region before World War I, the Middle East is unstable now due to a chaotic interplay of factors from diverse areas. This hostility instills fear and an aggressive defensive stance by Israel.

Israel is a country that is completely and utterly surrounded by enemies. This creates feelings of paranoia and fear of destruction on a daily basis for most Israeli people. Due to this, the Israeli government is always on its guard and works to increase security and power in the region. By gaining a stronger foothold in the region and decreasing the power of those around it, Israel uses realist policies to ensure its survival (Godlewski 2010).

Does being a sovereign country guarantee their national security? Palestinians might say that it does, because they do not have sovereignty, nor do they have any real national security. On the other hand, Israel, which does have these things, was placed in a region of the world where people already lived, inciting resentment by its original inhabitants. That resentment eventually led to retaliation and violence, increasing Israel's need for military defense, which in turn increased the resentment (and ultimately violent retaliation) of the neighboring Arabs (Stroh n.d.). After decades of this vicious self-reinforcing cycle, there seems to be no way out. Israel sees a strong military as essential for its protection. In turn, Palestine sees Israel's increasingly aggressive self-defense and growing military force as a threat that must be countered (with violence in many cases).

Similarly, the surrounding Arab countries have viewed this military aggression and build-up as a cause for concern. This brings us back to how "Israel is a country that is completely and utterly surrounded by enemies" (Godlewski 2010). Israel's security concerns are understandable, but its response—to increase its military strength—raises the question of thresholds, a term common in systems science; there is a fine line between enough national defense to ensure national security and so much military that neighboring countries are threatened, and tensions escalate. In short, strong Israeli nationalism, which is a direct result of the ingrained fear of the Israeli Jews, has encouraged overly aggressive national security policies that perpetuate the conflict through escalation (Bisharat 2008). The solution is designed for a misdiagnosed problem yielding unintended consequences (increasing tensions and violence as a response to Israel's aggressive national security policies) further worsening the situation.

The desire for national security, or rather, a fear of insecurity, is closely aligned with **ethnic and religious (ethnoreligious) identity** and the overall power of ideology. Jews are both an ethnic and religious group and, since 1947, also a nation. The strength of nationalism (a significant influence for national security) is, in the case of Jewish identity, augmented by Jewish ethnoreligious identity. Jewish nationalism, ethnicity, and religious identity cannot be disaggregated from each other; thus, for an Israeli Jew's identity, national security is the same as ethnoreligious security. When Israeli Jew's national, ethnic, or religious identity feels threatened, all three identities are perceived to be endangered and Israel is inclined to respond to perceived threats.

Besides identity, a **knowledge structure** plays a huge role in all areas of society, especially in conflict. It disseminates nationalism influences among the populace, and because of large biases in the media and governmental propaganda, the other side is only portrayed as the enemy and aggressor, while their side is always portrayed as the

victim. This victimization has been happening for so long that few people alive can recall a time when it was not so. It is the epitome of the effects of small effects sustained over a long time – generations in this case. Knowledge structure can influence a population to support continued aggression or negotiations to end the conflict peacefully.

### **2.4.3. International perspectives**

Much of the discussion surrounding the PIC has a relatively narrow focus, in that it focuses solely on Israel and Palestine, without considering the international context or perspectives. Yet the complexity of the conflict requires a broader geopolitical view to account for all the causes and effects of conflict fully.

**Sovereignty** – the ability for a country to self-govern itself, protect its territory, and be viewed as legitimate among its population and by other countries in the world – is an essential aspect for designing instruments to address conflicts reliably. It endows governments with specific abilities and legal options. Without sovereignty, nations would be unable to form binding, enforceable agreements. Because Palestine is not a sovereign country, it is not eligible to use some international instruments, which contain many legal mechanisms through which Palestine could use to counteract Israel. Without sovereignty, the extreme power differential between the two nations puts Palestine at a considerable disadvantage.

There are many kinds of international instruments; two that are significant in the PIC are agreements and treaties. As with definitions such as corruption and power, agreements and treaties have been given many definitions, none of which are universal, but they all share commonalities. The remainder of this section will define the terms, outline the similarities and differences between the two, and discuss their implication for the PI conflict.

The terms “agreements” and “treaties” are often used interchangeably, but they are not synonymous. A treaty is sometimes the generic catch-all term, covering all international instruments including conventions, agreements, charters, and acts, although that does not necessarily make them treaties in the strictest sense (Shaw 2016). In reality, however, agreements are the catch-all term. All treaties are agreements, but not all agreements are treaties; treaties are subsets of agreements, which is the prevailing view in this work (European Commission 2015).

According to Shaw (2016), a treaty differs from a broader agreement in that it is a “binding formal *agreement*, contract, or other written instrument that establishes obligations between two or more subjects of international law (primarily states and international organizations).” Typically, agreements deal with issues of economic, cultural, scientific, and technical cooperation, which have less severe implications if they fail. On the other hand, the formal

and binding nature of treaties is essential for issues such as peace treaties; border, delimitation, and extradition treaties; and meaningful friendship, commerce, and cooperation issues (European Commission 2015).

A treaty “must be concluded by states or international organizations with treaty-making power” (European Commission 2015) of which sovereignty is a requirement. Therefore, because Palestine lacks the sovereignty necessary to enter into a treaty, it can only be part of an agreement. This exacerbates the already severe power asymmetry between Israel and Palestine, giving Israel a clear upper hand in any negotiations. If an agreement is signed, there is little reason for Israel to uphold it, and few formal enforcement mechanisms to make it do so. For this reason, the international community becomes the de facto enforcer, to make sure both sides honor any agreements (European Commission 2015). The United States and Europe, who wield much of the power in the international community, currently supports Israel, severely inhibiting Palestinian sovereignty.

Another international factor is **international pressure** or direct involvement from international community ranging from economic sanctions (geoeconomics) to military engagement. The power differential between Palestine and Israel might be significant, but it is much larger between Israel and the international community. Therefore, involvement on behalf of Palestine by third-party countries organized through intergovernmental organizations IGOs, spearheaded by the UN, could make a significant difference – for better or worse – for the conflict as a whole. The only question is what would need to happen (i.e., what threshold would need to be passed) for the international community to take more direct action, whether economically, politically, or otherwise, to influence the PIC conflict.

#### **2.4.4. Overview of potential solutions: Scenario analysis**

Most academic literature examines only one solution to the PIC at a time. A brief, high-level comparative analysis might sometimes occur, but only to describe how one solution is better or worse than another. In this section, the eight solutions identified in the literature (Figure 7) will be discussed. These eight solutions fall into three categories: business-as-usual, the one-state solution, and the multi-state solution. These scenarios share commonalities, are not individually discrete from one another, and some of them might serve as prerequisites for others. Only a brief discussion of each solution is given below. A detailed analysis of each scenario is out of the scope of this work but has been covered elsewhere in the literature (see Bakan and Abu-Laban 2010; Bisharat 2008; Frenco 2009; Grinberg 2010; Karmi 2011; Mavroudi 2010; Scheindlin and Waxman 2016; Todorova 2015).

Business-as-Usual	
One-State Solution	Israeli Apartheid State
	Palestinian Islamic State
	Secular Palestine
	Bi-National Democracy
Multi-State Solution	Confederalism
	Two-State Solution
	Federation

Figure 7. The eight identified solutions as identified by the author in Bakan and Abu-Laban 2010; Bisharat 2008; Frendo 2009; Grinberg 2010; Karmi 2011; Mavroudi 2010; Scheindlin and Waxman 2016; & Todorova 2015.

**Business-as-usual (BAU)** implies that the situation remains unchanged. Although this does not necessarily mean that nothing changes, it means that no solutions are agreed upon and enacted, no peace agreements are signed, and the situation continues. The future, so far as one can see or project, looks hopelessly like the past. BAU at its core is a dynamic stalemate, with a continued Israeli occupation of Palestine. Whatever the outcome of the current prolonged conflict, a BAU scenario is unlikely to lead to a peaceful or nonviolent end organically (although, BAU can pave the way to other solutions, with the most likely outcome being an Israeli Apartheid State, discussed below (Bakan and Abu-Laban 2010; Bisharat 2008)).

As the conflict stands today, Israel is increasingly pushing farther into the West Bank with illegal (as determined by international law) settlements (Godlewski 2010) while maintaining its tight grip on the Gaza Strip with its blockade. Much of the West Bank falls under the control of the Israeli military and Jewish settlements, which – as an unfortunate consequence – causes more of the Palestinian freshwater supply to also fall under Israel’s control, exacerbating the problem; Israel already controls 80% of Palestinian water resources in the West Bank (Godlewski 2010). The importance of water in conflict will be discussed in the final two parts of this section; in short, it has been theorized to be a deciding factor between conflict and cooperation.

This BAU cannot continue ad infinitum, as there is only so much land on which to settle, and much of the growing population is already experiencing water-stressed conditions. BAU could very quickly turn into a repeat of World War I, when one seemingly small event—the assassination of Archduke Franz Ferdinand—ignited a much larger conflict. If BAU runs its course, a breaking (threshold) point will eventually be reached (i.e., some relatively insignificant, short-term, and unexpected event), and the current situation will give way. A regional war is a probable

outcome, with a worst-case scenario resulting in the war spilling over into other parts of the planet. Whichever side wins that war would almost certainly determine what current Israel and Palestine resemble after – a one-state or two-state solution or something else as discussed below.

If Israel won, the post-war system might very well resemble a one-state **Apartheid “solution”** that would resemble South Africa during Apartheid. Yet even without a war, an apartheid-like model of some form seems to be the most likely outcome of a BAU trajectory (Bakan and Abu-Laban 2010). It is important to note that an apartheid scenario would not necessarily directly resemble the South Africa Apartheid case; the reference merely provides context from which researchers might extrapolate, especially when conducting analyses in comparative politics literature (Bakan and Abu-Laban 2010). Still, there are many similarities. The apartheid solution refers to a racial (ethnoreligious) power differential that exists in a society, a racial contract “meaning state-sponsored ‘separateness’ of ‘races’ . . . and draws attention to the exclusionary and violent character of the Israeli Zionist project regarding the indigenous Palestinian population” (see Bakan and Abu-Laban 2010 for a thorough analysis).

In South Africa during the Apartheid, a minority oppressed a majority, while in Israel, the majority is subjugating a minority (Bakan and Abu-Laban 2010), enabled by a demographic balance policy that attempts to keep that imbalance of power in place (Karmi 2011). The military occupation of Palestine further complicates the matter because, although the Israeli government does not have sovereignty over Palestine, military occupation and illegal settlements do impose some form of Israeli legal structure and political influence (Treaties, States Parties, and Commentaries 1949). Similarly, Israel might “face the kind of international isolation and condemnation that South Africa faced during the apartheid era” (Bakan and Abu-Laban 2010). The international boycott, divestment, and sanctions (BDS) movement against Israel is a manifestation of this long-term effort to delegitimize Israel (Bakan and Abu-Laban 2010; Bisharat 2008; Spangler 2015; Todorova 2015). The apartheid case is not mutually exclusive from other solutions and has been viewed as something between a one-state and two-state approach (Bakan and Abu-Laban 2010); many of the solutions fall on a multi-dimensional continuum, and all solutions share aspects of the others.

Due to the risks of allowing a BAU or apartheid solution to unfold, the international community is likely to step in at some point as the situation in Israel and Palestine deteriorates. The crucial question is: When the UN or other countries become involved, what will they do, and will it be enough? That analysis is out of the scope of this research,



but the military power of an international effort might avoid an apartheid outcome, forcing a different solution to come to pass.

A **two-state solution** (a sovereign Israel and a sovereign Palestine) has been thought to be exceedingly infeasible mostly, because of Israel's policy to address the "demographic dilemma" (fear of Jews no longer being a majority in Israel), how entrenched Israel already is in the West Bank (Bakan and Abu-Laban 2010; Frenco 2009; Grinberg 2010), and the continued failure of a two-state solution peace process. The infeasibility of the solution is reflected in its waning support: only 43% of Palestinians and Israelis currently support it, down nearly 7% from just last year (Rasgon 2018), and some even believe it to be dead (Scheindlin and Waxman 2016). National leaders concur: the Obama Administration acknowledged that the two-state solution is no longer viable (Scheindlin and Waxman 2016), and Israeli Prime Minister Benjamin Netanyahu and his administration mostly admit the same. Meanwhile, although Palestinian opposition against the two-state solution has always existed (Grinberg 2010), it is still the official stance of the Palestinian Liberation Organization (PLO) and favored by the UN and the international community (Bisharat 2008). Consequently, most peace proposals aim for the two-state solution along pre-1967 borders, in accordance with the Oslo Accords; unfortunately, these proposals often ignore the possibilities of other solutions (Stroh n.d.).

Thus far, all the solutions that have been described will lead to worse situations for most people in the region. However, three scenarios exist by which rights for all people in Palestine and Israel can be secured (Scheindlin and Waxman 2016), regional security is improved, and socio-economic development can become the most pressing concern superseding national security. The first of these possibilities is the one-state **bi-national democracy (BND)**; Frenco 2009; Grinberg 2010). As the likelihood of the two-state solution dwindles, a BND becomes a more attractive and real, albeit small, possibility. Primarily, the BND would see all people currently living in Israel and Palestine to become citizens of one shared state within those borders under a single secular democracy and to possess equal rights (Bisharat 2008; Frenco 2009). Although support for this solution is relatively low, it is increasing, especially among Israeli and Palestinian scholars and Western leftists (Scheindlin and Waxman 2016). The main criticism is of how to implement such a state and ensure that both groups have equal power in governance (Frenco 2009). Another problem is how to overcome the animosity and hatred prevalent on each side for the other, although proponents of the solution point to Rwanda as an example of it being entirely possible (George 2016; Megan 2017).

A slight variation of the BND is the **confederal** model, which also falls somewhere between a one-state and two-state solution. There would be “two independent states, with an open border allowing for freedom of movement and residence and some limited shared governance” (Scheindlin and Waxman 2016), somewhat resembling the European Union governance structure. As with any potential solution, if it could be implemented properly, many, if not all, rights desired on both sides could be realized, with only small compromises relative to those proposed in other scenarios. It could also be used as an intermediary solution to “test the waters” until trust grew, time passed, and other solutions became viable.

Similar again to the BND, but closer to a one-state solution, is the **federation model**, where a secular democracy would govern the combined Palestinian and Israeli territories. However, the difference is that the governance structure would resemble the United States or European Union models in that it would be comprised of many states with sovereignty over certain areas, but a central authority would control some critical aspects like national security, migration, and other international factors. One such variant sees six federal states, each with its own state authority. This might include multiple states within Israel proper, such as one encompassing central and northern Israel and another for the Negev region in the south. There would also be states for the more contentious regions, including Jerusalem, the Golan Heights, the West Bank, and Gaza (Hollander 2018).

In an unlikely event of a Palestinian victory, there are two possible (but improbable) one-state solutions: a **secular Palestine** and an **Islamic state**, with the latter being even less likely than the former. The two are fundamental opposites; the secular state would be at least partially democratic, open, and free, and would ensure equal rights to all, while an Islamic state would be one of religious nationalism. Such a governance model could resemble an extreme form of Israel’s government today, with a much more powerful theocratic ruling class (the Rabbinate in Israel’s case), or it could replicate the current theocratic political structure of Iran, for example.

No matter whether Palestine or Israel prevails in the conflict, the resultant governance structure will fall somewhere on the democracy spectrum, where one end is something like a true direct or participatory democracy, while the other end resembles an absolute monarchy or a personalist dictatorship (Ezrow and Frantz 2011). Additionally, the solution that is chosen will also result in different levels of ethnoreligious influencing the new government, where one end of the spectrum shows no ethnoreligious influence and the other end shows complete

influence by ethnoreligious factors, as in an extreme theocracy. Each potential solution is graphed according to these two dimensions in Figure 8.

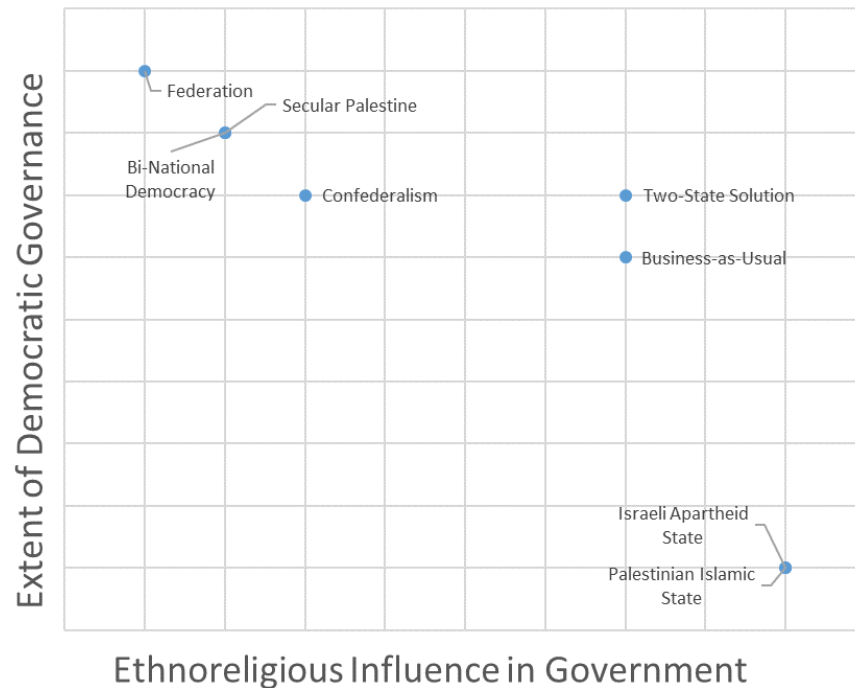


Figure 8. Ethnoreligious influences vs. democratization in the government after the implementation of any potential solution to the PIC; this graph is a semi-quantitative representation based on the author's research

## 2.5. Hydropolitics of the Palestinian-Israeli conflict

Because the Middle East is a desert and categorized as arid or hyper-arid, water is a huge problem. It can exacerbate preexisting issues (i.e., conflict). The term hydropolitics is used to describe the effect of water resources on politics, specifically conflict in this case. Water is a vital resource with no substitute, and in a water-poor area like Israel and Palestine, the lack of water is likely to increase tensions possibly being an influencing factor in the PIC. This section details some of the salient and vital aspects of hydropolitics in relation to the PIC.

### 2.5.1. Water security

Water is essential to the biological functions of every known organism; without it, we would cease to exist in three days. Yet humans seem to believe themselves immune to water issues, due to our technology and apparent global dominance. It is true that we are and have been Earth's only technological apex predator, but we are just as (if not more) susceptible to water-related problems than any other species. Humanity has stratified itself along geopolitical boundaries in complete disregard of hydrological boundaries, which has created the unique need to govern water. Humans cannot just migrate to new places where water is bountiful, because we have already settled all over

the planet and marked our territory; we can only invade the lands of others or form treaties to share water supplies that are ever-diminishing due to mismanagement of water resources.

There is no one specific definition of water security, nor is there one universal catch-all description of what designates a person, a population, or a place as being water secure or water insecure (Siwar and Ahmed 2014). Often, water security refers to human needs, directly (consumption) or indirectly (agriculture, energy, virtual water, etc.), but in the last two decades, definitions have been expanded to include social and environmental components (Grey and Sadoff 2007). More broadly, water security and its inverse, water scarcity, have been a focal issue within the sustainable development and WELF nexus literature. In short, definitions span multiple academic disciplines and issue areas (Cook and Bakker 2012).

Definitions differ based on the needs of the people at the spatial scale or the specific context at which an organization operates (Bigas 2013). Rural development NGOs might want a detailed definition that focuses on local water availability based on annual weather patterns, while a large development organization like the US Agency for International Development (USAID) might use a broad meaning to encompass all its work. Somewhere in the middle, a large city might define water security to be more in line with its climate—wet versus arid, for example. A literature synthesis of water security has found many definitions that together cover most, if not all, areas of sustainable development and beyond:

- “Water security represents a unifying element supplying humanity with drinking water, hygiene and sanitation, food and fish, industrial resources, energy, transportation, and natural amenities, all dependent upon maintaining ecosystem health and productivity” (UNEP 2009).
- Water security exists when sufficient water of good quality is available for social, economic, and cultural uses while, at the same time, adequate water is available to sustain and enhance essential ecosystem functions (Bigas 2012).
- The availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems, and production, coupled with an acceptable level of water-related risks to people, environments, and economies (Bakker and Morinville 2013; Grey and Sadoff 2007).

- The overarching goal where every person has access to enough safe water at an affordable cost to lead a clean, healthy, and productive life while ensuring the environment is protected and enhanced (Global Water Partnership 2000).
- “Reliable access to water of sufficient quantity ‘and quality for basic human needs, small-scale ‘livelihoods and local ecosystem services, coupled ‘with a well-managed risk of water-related disasters” (WaterAid 2012).
- “...the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability” (Bigas 2013).
- “The availability of clean drinking water, important in the engineering and municipal infrastructure” (Guthrie et al. 2010).
- “Reliable basic water services, vital for any plans for development” (Schäfer 2013).
- “Measures to ensure the security of drinking water infrastructure against potential terrorist attacks, as promoted by the US Department of Homeland Security” (Schäfer 2013).
- “As a dimension of environmental security, and in order to manage conflict, reduction of the potential for conflict, especially with regard to concerns of national security” (Pachova et al. 2008).

When taken together, these definitions are fairly broad but imply that water security is the supply of water of sufficient quality and quantity to ensure human well-being across all dimensions of human security in the present and in conditions that are expected in the future. Water cross-cuts virtually all sectors (gender equality, education, health, infrastructure, transportation, agriculture, environment, recreation, housing, economics, politics, culture, etc.), which explains the difficulty in devising universal definitions. That being said, as summarized by Bigas (2013), there are many fundamental components shared by most definitions:

- Access to safe and sufficient drinking water at an affordable cost in order to meet basic needs, which includes sanitation and hygiene, and the safeguarding of health and well-being;

- Protection of livelihoods, human rights, and cultural and recreational values ;
- Preservation and protection of ecosystems in water allocation and management systems in order to maintain their ability to deliver and sustain the functioning of essential ecosystem services ;
- Water supplies for socio-economic development and activities (such as energy, transport, industry, tourism);
- Collection and treatment of used water to protect human life and the environment from pollution;
- Collaborative approaches to transboundary water resources management within and between countries to promote freshwater sustainability and cooperation;
- The ability to cope with uncertainties and risks of water-related hazards, such as floods, droughts, and pollution, among others; and
- Good governance and accountability, and the due consideration of the interests of all stakeholders through appropriate and effective legal regimes transparent, participatory, and accountable institutions that plan, operate, and maintain infrastructure capacity.

Closely related to and often synonymous with water security is the concept of water resource vulnerability (i.e., water stress and water scarcity; Perveen and James 2011). *Water stress* “occurs when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use” (Guthrie et al. 2010). Water scarcity is closely related to water stress, in that water is lacking. According to UN-Water (2006), *water scarcity* is the “point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be satisfied fully.” Thus, water scarcity and water insecurity—which are treated as synonymous in this dissertation—are the cause of the effect of water stress (WaterAid 2012; White 2012).

Water scarcity is a relative concept (similar to water security or opposite of water insecurity) and can occur at any level of supply or demand; it may be a social construct (a product of affluence, expectations, and customary behavior) or the consequence of altered supply patterns stemming from climate change (UN Water 2006). However, water scarcity can be a more appropriate focus at smaller scales, whereas the concept of water security is mostly used in the context of large-scale sustainable development. It is broadly understood as the lack of access to adequate

quantities of water for human and environmental uses (White 2012), and its causes and effects can be physical or socio-economic. Physical scarcity is when the demand is greater than the supply due to overexploitation of water resources, whereas socio-economic scarcity results from “insufficient investment, skills or political will . . . to keep up with growing demands for water, preventing access to the resource” (Molden 2007; WaterAid 2012). Both forms come from poor governance, which helps to explain the prevalence of water issues in the developing world and conflict zones, such as that of the PIC (WaterAid 2012; White 2012).

Accurate definitions of water security are crucial because discrepancies can create confusion. It can be more important to use effective measurement methods, as they are quantitative in nature since crafting policy necessitates accurate data. Definitions must be based on quantifiable data to ascertain if a population is water secure or not. A commonly used method to measure water security is the Falkenmark Indicator or the Water Stress Index. It uses the renewable freshwater available per capita to measure water scarcity (Rockström et al. 2014; WaterAid 2012; White 2012). Below 1700 m<sup>3</sup>/person is the threshold for which a country is considered water-stressed; under 1000 m<sup>3</sup>/person indicates water scarcity, and 500 m<sup>3</sup>/person is the threshold for absolute water scarcity, which occurs when there is insufficient water resources to meet human and ecosystem demands (Rockström et al. 2014; WaterAid 2012; White 2012). However, while this measure is simple to calculate and use, it is aggregated at the national level, ignores water quality and accessibility, and doesn't account for the various water needs among countries. Furthermore, all countries are assumed to need the same amount regardless of economic level and climate (White 2012).

The Water Resources Vulnerability Index (WRVI) is another measurement option. Unlike the Falkenmark Indicator, which divides a country's available water resources by its population, the WRVI divides the total annual water withdrawals, or demand, by the total available water resources in a given area. A WRVI between 0.2 and 0.4 is water scarce; any value above 0.4 indicates severe water scarcity. The WRVI approach is simple and allows for heterogeneity regarding water needs among countries. It is inflexible, however, when it comes to artificial water supply and water infrastructure (e.g., desalination), water reuse and recycling, and adaptation strategies (Perveen and James 2011; Srinivasan et al. 2017; White 2012).

Other more complex measurement indicators exist in the literature, such as the International Water Management Institute's index for “economic water scarcity.” This index incorporates aspects of a country's existing water infrastructure and potential future development, but it focuses only on consumptive use (i.e., those that remove

water from the hydrological cycle like direct human consumption). Water for cooling thermoelectric power plants is non-consumptive because it is returned to the ecosystem. In doing so, water infrastructure investment and efficiency initiatives are included, but socio-economic factors like demographics, health, education, and so on are lacking (Molden 2007; Srinivasan et al. 2017; WaterAid 2012; White 2012). Another measure, the Water Poverty Index (WPI), attempts to include those socio-economic factors, as well as access to water, physical availability of surface and groundwater, the various uses of water (domestic, agriculture, and industrial), and ecosystem services. Its more complex formulation allows for a more detailed understanding of water security, but it was initially designed for the community-level and local scales (Sullivan 2000; WaterAid 2012; White 2012). Even so, it can be adapted and repurposed relatively easily for most other scales and contexts.

All the definitions and metrics for water described above help to categorize important dimensions and interconnections, which cross-cut with other areas. The definitions identify the qualitative aspects of what sectors link to water security. Overall, the definitions do not just focus on consumption for direct human uses; they look at other areas like how to supply enough water of sufficient quality to produce food, ensure human health, and maintain or improve labor productivity. These areas involve poverty (SDG 01), food (SDG 02), health (SDG 03 and 06), cities/infrastructure (SDG 09 and 11), the economy (SDG 08 and 12), and all other SDGs to various extents. Food and water are both parts of the WELF nexus, while all are incorporated into the SDGs implying that they are essential for sustainable development. The WPI can connect water with poverty and other socioeconomic factors; the Falkenmark Index looks at overall water resources, while the WPI looks more at the capacity to satisfy the demand and to quantify the total water withdrawals that result from that demand. The next section discusses how water affects politics and governance broadly, and the PIC specifically.

### **2.5.2. The hydropolitical perspective**

Because of high water scarcity in the Middle East, water can often be a point of contention, but it can also be leveraged for peace. That is the underlying hypothesis for this section: hydropolitics and transboundary cooperation among riparian countries on the Jordan River can be used as a geopolitical tool to identify and most effectively strategize a feasible solution to the PIC. This section analyzes the conflict through the lens of hydropolitics by utilizing the concept of hydropolitical sustainability (Rai et al. 2017)—which is essentially the concept of sustainability applied to water conflict—and the interest-power-position (IPP) framework. Although sustainability incorporates five pillars – political/governance, economic/financial, environmental/ecological, social/cultural, and technological/infrastructure



– this section focuses exclusively on the political pillar and to a lesser extent on the environmental pillar. The interactions of the other pillars can be found by utilizing other theories and frameworks from other disciplines in the same fashion as the IPP framework was incorporated herein.

As complex as the concept of water security is, governing and managing it is even more so.

*Water governance* refers to the political, social, economic, and administrative systems in place that influences water's use and management. Essentially, who gets what water, when and how, and who has the right to water and related services, and their benefits. (UNDP Water Governance Facility 2016)

Water governance can also be described as:

the range of political, organizational and administrative processes through which community interests are articulated, their input is incorporated, decisions are made and implemented, and decision-makers are held accountable in the development and management of water resources and delivery of water services. (Bakker and Morinville 2013)

*Hydropolitics*, on the other hand, is the effect of water resources on politics (Waterbury 1979). The difference between water governance and hydropolitics is therefore based on the direction of effect: in water governance, politics affect water resources, whereas, in hydropolitics, water affects politics.

Each year, the Global Risks Report (summarized in Figure 9) describes trends, phenomena, and events that are of concern for humanity as a whole. The x-axis is the severity of the impact, and the y-axis is the likelihood of it occurring. The red boxed problems are directly related to water crises and general water insecurity, either as an influencing force or dependent factor. As the graph indicates, most of these events are both impactful and likely to happen.



Figure 9. Global risks landscape; likelihood of occurring (y-axis) vs. impact (x-axis); red boxes are conflict- and water-related issues, i.e., hydropolitical in nature (World Economic Forum 2018); most water-related global risks are relatively impactful and/or likely to happen

While researchers have theorized that water insecurity is likely to increase conflict, apocalyptic “water wars” have not yet manifested themselves (Wolf et al. 2006; Zeitoun 2012). According to Zeitoun (2012), there are three main reasons that large-scale waterborne conflicts have not come to fruition: (i) the economic and strategic importance and value of water means that countries will always find a way to supply enough water to meet their needs (i.e., water is too crucial a resource to risk going to war over it); (ii) international trade and virtual water – the total direct and indirect volume of water used to produce a product – allow for the import of water from regions with high water availability and low scarcity to regions that are water insecure, like the Middle East; and (iii) power differentials among the transboundary riparians (countries that share a water body or watershed) means the respective governments forgo the need for military (hard) power in lieu of soft power to secure water for the most powerful country in the region (e.g., local hegemon). This means that a powerful country (relative to a weaker country) has the capability to

use soft power instead of hard power because the weaker nation (Palestine) knows it can not defend itself against the stronger country's (Israel) military force using conventional means. The power differential between Palestine and Israel is an extreme case in which the Israeli government makes virtually unilateral decisions about water rights in the region because, on its own, Palestine is incapable of challenging Israel, whether politically, economically, or militarily.

Due to climate change, population growth, and changing geopolitical conditions, there might come a time when the benefits of going to war over water resources will outweigh the drawbacks. Even so, violent conflict and military action are expensive compared to alternatives such as trade embargos and other nonmilitary interventions, and even those interventions come with a cost. This could explain why cooperation occurs more than twice as often as conflict when water is involved. Wolf et al. (2006) quantify and describes this cooperation-over-conflict phenomenon, and more recent research (see Cahan 2017) further corroborates Wolf's claims:

In the last 50 years, only 37 [water-related] disputes involved violence, and 30 of those occurred between Israel and one of its neighbors. Outside of the Middle East, researchers found only 5 violent events while 157 treaties were negotiated and signed. The total number of water-related events between nations also favors cooperation: the 1,228 cooperative events dwarf the 507 conflict-related events. Despite the fiery rhetoric of politicians—aimed more often at their own constituencies than at the enemy—most actions taken over water are mild. (Wolf et al. 2006)

The Middle East, specifically Israel, is an outlier in this trend. The Middle East is an arid region that suffers from water scarcity, with many countries sharing—and relying on—the same bodies of water, thus increasing tensions. At the same time, many different religions, cultures, ideologies, and historical factors create an inherently unstable area in which any small event can lead to more destructive and violent conflicts. In the case of World War I, it was the assassination of Franz Ferdinand (a seemingly small event) and the complex entanglement of alliances (the volatile and unstable conditions) that led to war. In the PIC, it could be a water crisis that causes the many interacting sectors to erupt into a broader conflict. In essence, water might be the proverbial “straw that breaks the camel's back” and causes the situation to pass a threshold into conflict.

### 2.5.3. Analysis of hydropolitical conflicts

While research shows that—so far—water is rarely the singular source of conflict, water is used as a tool (and weapon) in existing conflict in a variety of ways: as a way to increase or decrease water scarcity; for criminal activities and personal gain; as a tool for terrorism; as a military tool; as a military target; and/or as a bargaining chip in development disputes (Gleick 2008; Homer-Dixon 1999; Zeitoun 2012).

In short, the evidence shows that water is actually not something that tends to cause conflict; more often than not, it leads to cooperation. The literature explains this by describing the importance of water to human survival. If in a war over water humans were to contaminate or otherwise ruin the world's water supply, everyone would lose; the risk is not worth it. The Water Events Scale (WES) in Table 7 illustrates this point. The average value of any given event is somewhere between 1 and 2 on the WES scale; this means that water usually leads to a small improvement in the local conditions of a conflict, rather than increasing tensions or exacerbating the conflict. That being said, with the worsening effects of climate change and population growth on water resources, conflict might become more prevalent due to water scarcity in the future, so it could become crucial to understand the relationships between water and conflict so that future water wars can be avoided.

Table 7. Water Events Scale (Bernauer et al. 2012)

WES Value	Description and Example	Events Recorded Over All Human History
5	Events that are likely to or do result in substantial improvement concerning water quality/quantity in the country as a whole. National emergency water plan is implemented—comprises mini stations for desalination, drillings, transfers from other dams, etc. in Algeria.	0.3% (31)
4	Events that are likely to or do result in substantial improvement concerning water quality/quantity at the regional level within the respective country. Ministerial meeting agrees to reduce the price of water per m <sup>3</sup> for Sheikh-Zayed canal and pumping station in Egypt.	1.1% (111)
3	Events of moderate intensity that may result in an improvement concerning water quality/quantity at the regional or national level within the respective country. Lebanon inaugurates water project.	11% (1138)
2	Agreements signed, or other measures formally adopted that signal commitment to improvement concerning water quality/quantity at the regional or national level. Jordan and Italy sign agreement to finance water network project.	9.5% (985)
1	Events that are likely to or do result in a minimal improvement concerning water quality/quantity at the local level. Workshop organized by the ministry of mines, energy, and water resources on the provision of potable water in Mali.	13.5% (1400)
0	Routine and purposive actions on water issues that have no identifiable positive or negative impact on water quality/quantity. Algerian and Yugoslav businesspeople discuss cooperation in different sectors—including water supplies and dams.	46.7% (4837)
-1	Events that are likely to or do result in a minimal negative impact on water quality/quantity at the local level. Janjawid militia controls water wells—residents of camp run out of water in Sudan.	6.2% (639)

WES Value	Description and Example	Events Recorded Over All Human History
-2	Tensions within government (intrastate) or between countries (interstate) that may affect water quality/quantity at a domestic level. Syrian-Israeli talks on reaching an agreement on water in the Golan region—talks fail.	4.1% (425)
-3	Large-scale and general opposition of the public toward policies and actions that have negative implications for water quality/quantity at the regional to national level. Niger Delta rebel group complains about lack of water supply—explicit warning against the president.	3.2% (328)
-4	Events that are likely to or do result in deterioration concerning water quality/quantity at the regional level within the respective country. Water supply is interrupted on the island of Vis, Croatia.	2.8% (293)
-5	Events that are likely to or do result in deterioration concerning water quality/quantity at the national level; physical violence associated with water problems. People killed in tribal clashes over water points in Ethiopia.	1.6% (165)

The water conflict literature describes two vital interrelated frameworks (discussed in detail later) that can be used to understand water conflict, both of which come from political science. The first is the *interest-position-power (IPP) matrix* (Frey and Naff 1985; Zeitoun 2012), which is an essential tool for the water conflict analysis conducted in this work. The other, hegemonic hydrogeopolitics, forms a somewhat more specific and descriptive narrative for understanding IPP and is of particular salience in the Palestinian-Israeli conflict (Rai et al. 2017; Wegerich 2008; Woodhouse and Zeitoun 2008; Zeitoun 2012; Zeitoun et al. 2013; Zeitoun and Warner 2006). The concept of the hydro-hegemon focuses on the concept of power and power differentials from Section 2.4.1, as well as geographic locations. The hydro-hegemon is the most powerful country in a given water basin; it is summed up by Rai et al. (2017) as follows:

Hydrogeopolitics are considered to be characterized by hegemonic configurations, wherein the most powerful riparian states have an advantage over their riparian neighbors to influence the allocation of the resources. Notably, the power available to the “basin hegemon” assumes different forms – geographical, material, bargaining and ideational. The pillars of hydro-hegemony suggest that a hegemonic situation on transboundary waters is built on the four fields of both covert [soft] and overt [hard] forms of power.

Allan (2001) explains that “economic strength combined more or less with hegemonic advantage explains the privileged outcome” of Israel in the Jordan River basin regional water conflict (Figure 10), even though it does not hold the most advantageous position (i.e., its riparian position) within the watershed (Zeitoun 2012). This implies that water conflict is not governed by a single determinant but is a multi-dimensional complex system that depends

on several factors including relative strength and hegemonic advantage (both of which span the areas of national defense, governance, and economics), international support and involvement, riparian position, and all areas of sustainable development. None of these factors can be ignored, as all play a fundamental part in conflict and water security. The hydropolitical hegemony is found by comparing the relative strengths of the four forms of power: hard material, soft bargaining, soft ideational, and geographic power. In looking at the absolute power of Israel and Palestine, depicted in Figure 10, their relative differences are apparent. Israel is more powerful in all categories, making it the hydro-hegemon (HH).

In addition to power and position (geography) to the four forms of power, countries have an interest, which is fundamentally how vital, or interested, a country is in acquiring or controlling water resources (through power). This is the basis of the Interest-Power-Position (IPP) framework, mentioned earlier. Of course, water is crucial, but some countries in a basin might have more or less access to that water or greater needs of water due to population or water-heavy industries. A country with a higher need or desire for accessing water resources is more likely or desperate to instigate conflict. That is the fundamental argument of water wars; that a country could reach a point of desperation causing them to use hard power more readily or to a more severe degree.

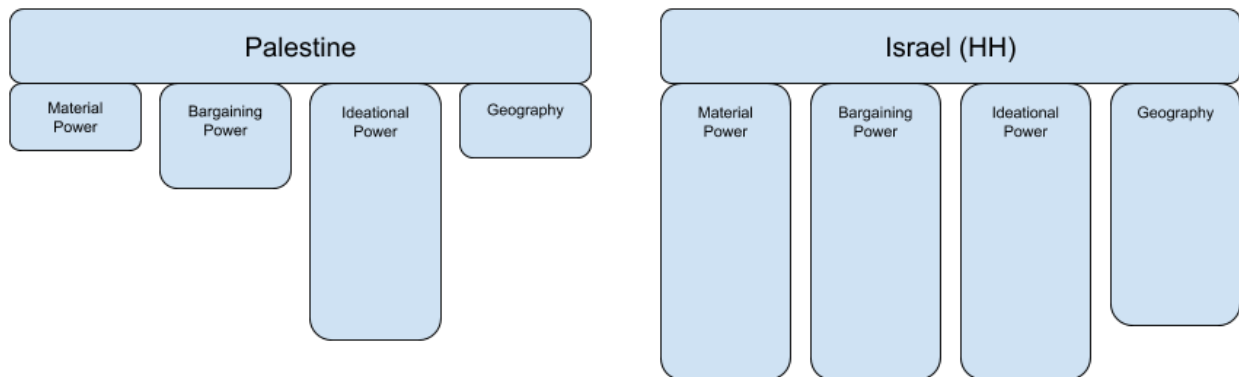


Figure 10. Absolute power (per category) for Palestine and Israel

Hydropolitics cross-cuts all areas of sustainable development virtually, so the term hydropolitical sustainability has been proposed to explain this concept. It covers each of the five pillars of sustainability (i.e., political/governance, economic/financial, environmental/ecological, social/cultural, and technological/infrastructural) and dimensions from the perspective of water security (Section 2.5.1), although only the political/governance is the focus of this work. It is along these same dimensions that water security connects to conflict (e.g., the Palestinian-Israeli conflict). The various kinds of power from Section 2.4.1, shown in Figure 10 is the main framework used to

analyze the Palestinian-Israeli conflict, but it could be used to examine any conflict or tense region suffering from water scarcity. With the understanding of the IPP and the HH frameworks and the concept of hydropolitical sustainability, a systems-based framework was created to more thoroughly address the complex interactions between these various elements at play in water conflict (Figure 11). Figure 11 shows the current status of the framework. It will go through multiple changes in the future as the system dynamics model forms. This hydropolitical sustainability framework is eventually transformed into a causal-loop diagram detailed in the results in Section 4.2.3. By performing this transformation, the potential solutions (e.g., one-state solution, two-state solution) can be connected with hydropolitics and sustainable development.

Many states in the Middle East are vulnerable to water-based conflicts. This can be described by the term “hydropolitical vulnerability,” which is the risk of a political dispute over shared water systems. Wolf et al. (2003) suggested the following relationship between change, institutions, and hydropolitical vulnerability: “The likelihood of conflict rises as the rate of change within the basin exceeds the institutional capacity to absorb that change.” It can be said that very rapid change, either on the institutional side or in the physical systems, that outpaces the institutional capacity to absorb those changes is at the root of most water conflict (Wolf 2006).

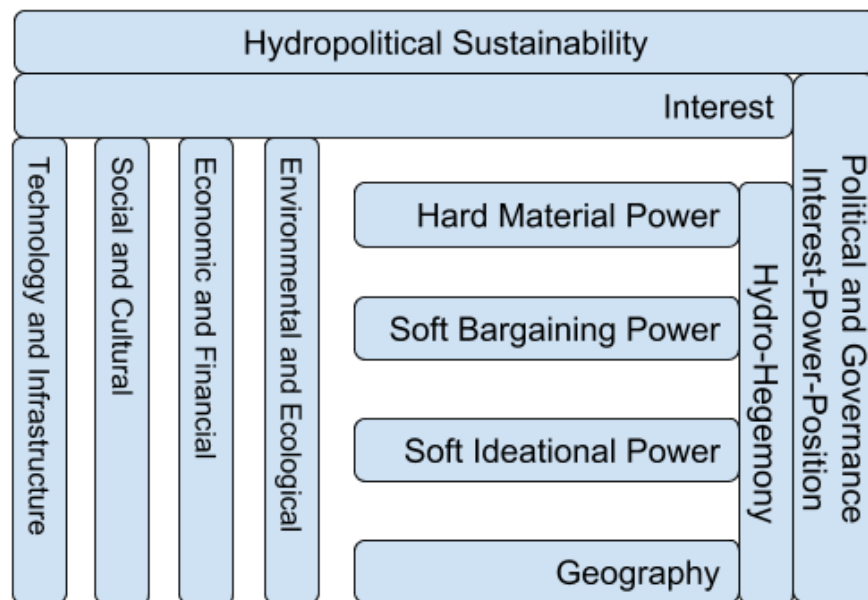


Figure 11. Systems analysis framework of hydropolitical water conflict

### **3. METHODS: SYSTEMS APPROACH**

This chapter introduces the system tools and science required to analyze the issues outlined in the previous chapter: the SDGs, the WELF nexus, urbanization, migration, corruption, conflict, and hydropolitics. The chapter begins with a discussion on systems thinking followed by a review of system archetypes. After that, it transitions into quantitative modeling tools: cross-impact analysis, network analysis, system dynamics modeling, and sensitivity analysis. The chapter concludes with a newly created qualitative social systems methodology, which is designed to couple engineering and technical sciences tools with general social science techniques and theories to produce a new way to analyze complex social systems.

#### **3.1. A systems approach to sustainable development**

##### **3.1.1. Systems thinking for the SDGs**

The authors of the SDGs were mostly heads of state, government officials, and high-ranking positions which means that the process of creating the actual goals and their targets was largely politicized (United Nations General Assembly 2015); thus, political consensus (also, partisan compromise) drove the process rather than academic consensus and the rational deliberation among relevant experts. A consensus is a general agreement, a shared opinion, or a long-standing dogma or paradigm to which most members of a group subscribe. Consensus can be reached by different sources (political vs. academic) about the same topic and at different times. Political consensus focuses on making all parties happiest and agreeing on a single course of action, while academic consensus relies on the findings of many peer-reviewed academic articles and reports to have similar conclusions and findings after which time the most effective strategy can be devised. The difference between political consensus and academic consensus is small but significant. For instance, a political or public discourse may lag behind any academic consensus by years, as exemplified by climate change and other complex and ill-defined issues at play today. For example, the research of 97% of publishing climate scientists corroborate that climate change is occurring and is primarily caused by humans (Cook et al. 2013), but only 65% of Americans believe the same (Gallop 2016). If the public and political consensus matched academic consensus, these two figures would be roughly the same.

Political consensus seems to be about making the most people happy in the broadest sense as possible, so more frequently than not, the most popular opinion is the consensus. On the other hand, academic consensus strives for objectivity using the scientific method, which is designed to remove bias and identify the most likely truth based on empirical findings. In science, for instance, a consensus is reached when the majority of the research corroborates



the same information, and various studies' general conclusions agree, not when the researchers agree with one another's opinions. This type of consensus is ideal; however, because academic consensus still involves people, it can also be subject to human error and bias. This is the purpose of following a scientific methodology: to try and mitigate these biases and errors and maintain long-standing academic rigor.

Engineers (applied scientists) and other technical scientists have not been asked to play a significant role in formulating the SDGs and developing the goals' indicators and measures. The SDGs were devised mostly from political consensus, not scientific consensus, which has led to problems with addressing and implementing these goals. The best way to accomplish the mission of sustainable development is to research, plan, and act, not to guess and act. Therefore, while the people in charge of drafting the SDGs undoubtedly had good intentions, they stopped short of fully promoting and integrating science, engineering, and technology (SET) to formulate and then address the goals. Simply put, the contribution of STE is needed to better define the goals, their targets, and their respective success indicators in a quantifiable and analytical manner. This can be done by creating a "community of practice" in which development practitioners and researchers contribute to addressing the SDGs between now and 2030 and in the post-2030 agenda.

The integrated nature of the SDGs requires many disciplines (e.g., engineers, policymakers, economists, development practitioners) to work together outside of their academic silos. A critical role of engineering is to address the pressing large-scale societal challenges spanning civilizations across the planet is widely recognized. Since engineering functions as the interface among science, technology, society, and nature, it is critical for fostering sustainable development and, therefore, implementing the SDGs. In fact, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) has identified dozens of sub-disciplines within engineering that have a crucial part to play in international sustainable development (UNESCO 2010). The literature contains many references to how engineers could become directly involved with the SDGs and sustainable development in general (Kelly 2010; Roberts 2002; UNESCO 2010; World Federation of Engineering Organizations 2015). To that end, engineers should maintain an understanding of the social sciences.

The remainder of this chapter describes the systems-based approaches that can be used to analyze complexity in sustainable development. The systems approach first requires systems thinking, qualitative analysis, and quantitative modeling. Systems thinking, defined by Richmond (1994), "is the art and science of making reliable

inferences about behavior by developing an increasingly deep understanding of underlying structure.” Another definition proposed by Sterman (2006) considers systems thinking to be a new mindset with both depth and breadth, and “an iterative learning process in which we replace a reductionist, narrow, short-term, static view of the world with a holistic, broad, long-term, and dynamic view that reinvents our policies and institutions accordingly.” System thinking recognizes interconnections, reinforcing and balancing feedbacks (loops), time-delays, leverage points, nonlinearities, and emergent behavior unfolding in complex systems.

Because of their global recognition and importance, the SDGs are the primary focus of this work and are used as a proxy for sustainable development. A systems approach to addressing the SDGs is an appropriate means to account for the complexity and uncertainty at play in sustainable development at the country-level or other scales of interest. It can be used to (from Zelinka and Amadei 2019a in Appendix A):

- better understand how meeting the goals and their targets depend on context along with capacity, vulnerability, and structure at the local, city, country, or global levels;
- explore how certain structural variables or factors influence that dynamic, including feedback mechanisms, by carrying out various parametric and sensitivity studies;
- explain existing patterns of human development at different spatial and temporal scales;
- interpret emergent properties of human development such as poverty/wealth, peace/conflict, health, resilience, and sustainability that may involve one or several goals;
- examine various perspectives of human development interventions and consider possible (intended and unintended) consequences of decision making and policies and their implications;
- identify and explore leverage or tipping points, those critical places to intervene at different scales that will most benefit human development;
- predict how countries or regions may respond to various constraints and disturbances and strategies of capacity development;
- monitor and evaluate the performance of development interventions and decide on how to adjust as development projects unfold, thus leading to more successful projects in the long term; and

- develop approximate but good enough sustainable development solutions that are more flexible and adaptive to change than the traditional deterministic, rigid, and ultimately inappropriate long-term solutions.

While addressing and implementing the SDGs, accounting for their effects on one another is crucial to success. Because of their complex formulation, some goals are bound to affect others (positively or negatively), whereas others may not have any direct effect, but will influence other SDGs through an indirect path. Furthermore, the interactions are context- and scale-specific—that is, each country, city, or entity attempting to adhere to the SDG framework has unique characteristics and situations. For example, rural Kenya will not have the same conditions as an island nation; a city will have different issues than a country; a water-poor country will struggle with problems that a water-rich country will not; and unique political factors might constrain or enable specific outcomes for the SDGs. Thus, the factors affecting the success or failure of the SDGs are innumerable.

Adopting a systems mindset in addressing the SDGs enables development practitioners and decision makers to understand how prioritizing certain aspects of sustainable development could influence all SDGs. The interaction of SDG 01 (reduce poverty) with the other SDGs illustrates this point. Attempting to reduce poverty (SDG 01) directly is ultimately self-defeating, as poverty is dependent on virtually all other goals and areas of sustainable development (energy, sustainable consumption, reducing inequalities, environmental sustainability, good governance, etc.). When reducing poverty is the goal, the other SDGs end up being neglected. Therefore, because all the other SDGs also influence poverty, addressing poverty specifically negatively affects the other goals. Hence, focusing on poverty alone is counterintuitively detrimental to its alleviation (Zelinka and Amadei 2019a).

Even though the UN and the academic literature recognize that the SDGs are interconnected (see Allen et al., 2017; Coopman et al., 2016; Le Blanc, 2015; Nilsson, 2017; Nilsson et al., 2013, 2016, 2017; UN-Water, 2016; United Nations Economic and Social Council et al., 2015; United Nations General Assembly, 2015; Vladimirova and Le Blanc, 2016; and Weitz et al., 2014), a limited number of tools and methods have been proposed to analyze SDG interactions in a systemic or integrated manner. These publications are, however, great starting points, as they focus on the science of linkages, but fall short of quantifying the impact of these interactions. They serve as the scientific foundation (ICSU and ISSC 2015) on which a systems-based methodology to understand the long-term trajectory and success of the SDGs can be built.

Before considering various system-based methods, it is necessary for decision-makers interested in an integrated approach to the SDGs to acquire a certain level of awareness and decision-making maturity. Systems thinking is learned, and anyone can become a systems thinker by adjusting his or her perspectives and adopting new habits. These habits are best described by the *Waters Foundation* and are listed in Table 8. Even though these habits were developed to help integrate systems thinking in primary and secondary education, they apply to a wide range of situations where the thinker is faced with complex issues associated with messy, wicked, or ill-structured problems. These habits can also be understood as thinking strategies (visual, listening and speaking, and kinesthetic) that a decision maker, such as someone who makes decisions about addressing the SDGs, might want to follow to address complex problems. Table 8 gives examples of how each habit can be used when addressing the SDGs.

Table 8. Habits of system thinkers and the SDGs (adapted from Benson and Marlin, 2017)

<b>Habit</b>	<b>Description: As it pertains to the SDGs</b>
Big picture	A systems thinker “steps back” to examine the dynamics of a system and the interrelationships among its parts. They see the forest, rather than the details of any one tree. To understand the SDGs’ framework, analyzing all of the SDGs, not just one, is required.
Change with time	Dynamic systems are made up of interdependent elements, the values of which change over time. The status of the SDGs and sustainable development are governed by elements that change over time, such as education, infrastructure, and governance.
System’s structure	Focusing on the structure of the system facilitates an understanding of the outcomes of the system (i.e., structure determines behavior). The institutions involved with the SDGs have an organizational structure that cannot be ignored when considering strategies for implementing the SDGs. The success of the SDGs is closely related to the strength of the institutions on which they rely.
Interdependencies	A systems thinker knows that the cause-effect relationships within dynamic systems are circular rather than linear. Complex cause-effect relationships include balancing feedback, which happens when the system is trying to reach and maintain a goal, e.g., the heating system in a house. There also may be reinforcing feedback, such that the larger the starting value, the more it increases over time, e.g., population. Each SDG is intimately tied to the other SDGs; thinking of the SDGs in their silos ignores the interdependences on which the SDGs are affected.
Connections	A systems thinker intentionally makes connections in order to understand the relationships in systems better. A systems thinker creates meaning by considering how new information connects to previous knowledge by adding, modifying, transferring, and synthesizing the information into a deeper understanding. Seeing how the SDGs are connected is required to understand how they will change over time, thereby affecting the strategies for their implementation.
Change perspectives	To understand how a dynamic system actually works, a systems thinker looks at the system from a variety of different angles and perspectives, perhaps in collaboration with others. Changing perspectives enables multiple alternative strategies to be considered for the implementation of the SDGs. A strategy might not work for all situations, countries, or cultures, so various perspectives are needed.
Assumptions	A systems thinker will rigorously examine assumptions in order to gain insight into a system, which can lead to improved performance. It is crucial to understand how and why assumptions

<b>Habit</b>	<b>Description: As it pertains to the SDGs</b>
	are made, beliefs are developed, and actions are taken based on perceived data to avoid incorrect assumptions. An SDG implementation strategy based on incorrect assumptions could run over budget, not have the desired outcome, create risks, or fail.
Fully considers issues	A systems thinker is patient. S/he will take time to understand the system's structure and its behaviors before recommending and implementing a course of action. A systems thinker also understands that succumbing to the urge for a quick solution can create more problems in the long term. The complexity of the SDG framework requires a deep understanding of the issues to make sure an appropriate strategy is used.
Mental models	In any given situation, an individual perceives and interprets what is happening, thus creating a picture, or mental model, which is comprised of assumptions, beliefs, and values that people hold, sometimes for a lifetime. A systems thinker is aware of how these mental models influence their perspectives and, ultimately, any actions taken. Mental models often govern how people implement the SDGs, and if those mental models are comprised of misleading or incorrect assumptions, strong biases might corrupt the strategy to implement the SDGs.
Leverage	Based on an understanding of the structure, interdependencies, and feedback within a system, a systems thinker implements the leverage action that seems most likely to produce desirable outcomes. Identifying leverage points for the SDGs will most effectively use resources to forward the mission of the SDGs; they are locations on which policies should be focused.
Consequences	Before acting to change a dynamic system, a systems thinker weighs the possible short-term, long-term, and unintended outcomes of the action. Without understanding possible consequences, any actions taken to improve the outcome of the SDGs might backfire and make the situation worse.
Accumulations	Systems are made up of many elements including accumulations, i.e., amounts that can increase and decrease over time, and their rates of change. Sustainable development, and therefore the SDGs, are based on things (population, money, infrastructure, etc.) that change (flow), or accumulate, over time.
Time delays	A systems thinker recognizes that when an action is taken within a complex, dynamic system, the outcome of the action may not be seen for some time. Implementing policies for the SDGs will take time, which will differ based on the specific policy and sector in which it will function, and the effects of those policies will take time to be felt. For example, constructing infrastructure takes a lot of time and investment before that infrastructure can even be used.
Successive approximations	Trying a solution to an issue and then assessing (monitoring and evaluating) the results helps systems thinkers to understand that issue better. Over time, each cycle, or successive approximation of checking results and changing actions if needed, will move the system closer to a desired goal. The desired and actual effects are generally not the same when a policy or strategy for SDG implementation are made, so the outcomes need to be monitored. Sometimes, course corrections must be made to bring the desired and actual effects closer together.

Current guidelines for implementing or even just understanding the SDGs do not account for their interconnectivity. Most guidelines consider one—or at best a group of—goal(s). That being said, system-based techniques and tools exist in the literature that can be adopted or repurposed to analyze the SDGs and their linkages quantitatively. The proposed research considers the following tools: network analysis (NA), cross-impact analysis (CIA), system dynamics (SD) modeling, and sensitivity analysis (SA). Before those tools can be introduced, there will be a discussion of system archetypes, as they occur in every discipline and are very common in sustainable

development. Archetypes aid in organizing and structuring the theory and concepts of the systems approach discussed below (Sections 0 and 4.1.3).

### 3.1.2. System archetypes

Several archetypes, sometimes called generic structures, have been proposed in the system dynamics literature (Braun 2002; Forrester 1969; Goodman 1994; Kim 2000; Meadows et al. 1982; P. Senge et al. 1994; P. M. Senge 1994). They represent common patterns of behavior in complex or chaotic systems. According to Meadows (2008), archetypes are traps or grooves that force a system to produce the same answer under the same conditions; they create *habits* that, in turn, define the character of the system and, ultimately, its destiny. Thus, archetypes demonstrate that the structure of a system controls its behavior—a guiding principle in systems science.

All archetypes are based on how various balancing and reinforcing loops interact, resulting in the behaviors that define the archetypes. According to Sterman (2000), these behaviors are: (i) linear growth or decay; (ii) exponential growth or decay that can be modeled by a single reinforcing or balancing loop; (iii) goal-seeking that can be modeled using a single balancing loop; (iv) delay; and (v) oscillation, which can occur when a delay is combined with a balancing loop. Other more advanced forms of behavior can be obtained by combining the aforementioned basic behaviors such as S-shaped growth (a sequence of reinforcing and balancing loops), S-shaped growth with overshoot and oscillation, or overshoot and collapse (a sequence of multiple reinforcing and balancing loops with or without delay). Other system behaviors include equilibrium, random behavior, and chaos.

Reinforcing and balancing loops are at the core of the nine main system archetypes (Braun 2002; Kim 2000):

- In **Fixes that Backfire** a strategy is quickly made or only addresses the symptom; it ignores that actual problem, which gets worse over time.
- **Limits to Success** is essentially the Law of Diminishing Returns. As the output or complexity increases, the productivity of the system declines. For example, as systems ages, they break down.
- **Accidental Adversaries** occurs when a mutually beneficial partnership stops being beneficial to one of the partners due to some relatively insignificant event sustained over time. One of the parties will take an action that accidentally undermines the other, creating tension that will build up over time.

- **Success to the Successful** occurs when some sector or project becomes the focus of resource scarcity (material, financial, and others), resulting in a single successful outcome for one area while others fail due to neglect. Vulnerable groups suffer from this: when they are not represented in government, vulnerable groups' voices are drowned out by the loud voices of more dominant groups. Success to the Successful is another way to think of a zero-sum game; when one party receives resources, it happens at the expense of another. The rich get richer and the poor get poorer. The outcome of Success to the Successful is worsening inequality over time. Recall from Section 2.1 regarding the Great Divergence when the rich (Western/European) countries were able to overpower and subjugate the other poorer countries of the world, which became worse starting from the Renaissance through today.
- With **Growth and Underinvestment**, spurts of growth are followed by periods of little or no growth. For instance, a startup might have tremendous initial growth, which tapers off because that growth is unsustainable; this occurs in the existence of a carrying capacity or some limit. Populations exhibit this pattern with S-shaped logistic growth (i.e., population growth under a carrying capacity). This archetype overlaps with the Change-of-State archetype, which will be proposed later in this paper.

The next four archetypes are especially applicable to this work and form the basis for much of the qualitative systems analysis of corruption and conflict. All of these archetypes are common throughout sustainable development, especially the Tragedy of the Commons. The last three archetypes listed deserve special consideration, as they are the main archetypes that explain why conflict such as the PIC discussed in section 2.4 continues.

- **The Tragedy of the Commons** occurs when, as a resource is used, its quality depreciates, and its quantity decreases, eventually causing the cost of that resource to increase and possibly leading to its depletion. A tragedy of the commons occurs when the markets fail to manage common goods in the interest of the community (Hardin 1968).
- **Shifting the Burden** occurs when the symptoms of the problem are addressed, but not the underlying cause, providing instant gratification by reducing short-term pressure to solve the actual problem.
- **Drifting/Conflicting Goals** is similar to Shifting the Burden, in that there is a discrepancy between the perceived state and the actual state of the system. This archetype occurs when information about a system as

it existed in the past is used to make estimates about the current state of the system. The goal must then be changed to meet the current state of the system, but there is a delay in doing so. Changing goals is similar to making or devising new policies and strategies – it takes time. Over that time, this causes the goal of the system to drift away from its original intention. Colloquially, the system goes “off on a tangent.”

- **Escalation** exists when two parties view each other as threats, which results in increasingly competitive actions between the two over time. Escalation is the quintessential archetype underlying conflict, but also what fuels market competition, sports rivals, and arms races. The Accidental Adversaries archetype is similar to Escalation.

### 3.2. Quantitative systems modeling tools

Once an issue is understood qualitatively through the lens of systems thinking and system archetypes, system-based modeling tools can be applied to provide a deeper understanding through quantitative approaches. This section presents the first of two types of tools: (i) cross-impact analysis which is a semi-quantitative soft-systems tool combined with network analysis and (ii) system dynamics which is a quantitative hard-systems tool. is then described, after which the system dynamics model is applied to qualitative survey information regarding wastewater systems at the community-level that incorporates an advanced scenario/sensitivity analysis. Collectively these tools and methods can analyze virtually any complex system in sustainable development.

#### 3.2.1. Cross-impact analysis

Cross-impact analysis (CIA), also called double-causality analysis, is a mathematical approach used in Futures Research studies. It originated in the mid- to late-1960s (Gordon, 2014; Gordon & Hayward, 1968) and was initially developed to analyze weakly (soft) structured systems for which theory-based computational (hard) models do not work due to the systems’ complexity, uncertainty, and disciplinary heterogeneity. Since its inception, cross-impact analysis has been a general soft-system method for assessing the “interrelations [among] the most important influential factors in a system by experts who evaluate [subjectively] pairs of these factors” (Weimer-Jehle, 2006, p. 336). The various methods of cross-impact analysis differ on how the interrelations are formulated (probabilistically or deterministically) and whether a qualitative, quantitative, or mixed approach is used to describe causalities (Serdar Asan & Asan, 2007).



The cross-impact analysis represents a system with an  $(n \times n)$  matrix (cross-impact matrix) with zeroes along its diagonal and  $n^2-n$  off-diagonal terms, where  $n$  is the number of sectors (SDGs, in this case) or elements in that system. The off-diagonal terms define how each variable (row) *directly* influences or impacts the other variables and how each variable (column) depends on, or is sensitive to, the other variables. It should be noted that the matrix is not symmetric. The strengths of the influence between two variables can be described *qualitatively*, using qualifiers such as high, medium, or low, or scored *semi-quantitatively* over an appropriate scale—e.g., from 0 (no influence) to 3 or more (high influence)—or quantitatively when specific data exists.

CIA is particularly appropriate for tackling large-scale human societal issues such as those addressed by the SDGs. Due to its flexibility and versatility, it is apt for comparing multiple scenarios and effectively identifying the actual causes of a problem, as opposed to using intuition or an educated guess (i.e., the Fixes That Backfire archetype). In this way, CIA enables decision-makers and project managers to (i) attain a better qualitative and quantitative understanding of the way the various sectors interact in the development of a community; (ii) detect emerging patterns resulting from those interactions; (iii) use context-specific information about direct impacts to identify indirect effects; and (iv) identify leverage points hidden within the community system where an intervention can be applied to most effectively elicit change.

### **3.2.2. Network analysis**

The cross-impact analysis helps to describe the influence and dependence of multiple interacting variables such as the SDGs. Their interactions can also be represented as a network diagram or graph consisting of multiple nodes (vertices or actors) representing each SDG and links (edges or ties) between them. In directed graphs, arrows pointing toward or away from some nodes can be added to map how the SDGs influence or depend on each other. When the strength of and the connectivity between nodes are represented by symbols of varied sizes, such as lines with different thicknesses or colors, the network is defined as a valued network (Borgatti et al., 2002) or weighted network (Newman, 2010). Network analysis complements cross-impact analysis, as it provides a mathematical approach to understanding patterns of interactions among the SDGs. The term cross-impact network analysis is proposed to describe the synergistic aspect of these two forms of analysis.

A network approach to the SDGs has not received much attention until recently. Le Blanc (2015) looked at the SDGs as part of a network where the interconnectivity was assumed to take place at the target level; the network

analysis in that paper was carried out considering the relationships that exist between the 17 goals and their 169 targets (17 x 169). In the network literature, this type of analysis is referred to as a two-mode network. The approach selected in this dissertation is slightly different, as it considers how the 17 goals interact with each other, which can be described as a one-mode network. It starts with the same (17 x 17) matrix considered in the cross-impact analysis (e.g., Figure 15). The matrix, also called adjacency matrix in network analysis, was input into the network analysis software UCINET, which is available through Analytic Technologies based in Lexington, KY (Borgatti et al., 2002).

Of the many topics and concepts in network science, the most useful for analyzing the SDGs is centrality. Centrality represents a family of concepts that help indicate the significance of the contribution that a node makes on the network as a whole. Centrality can be understood as the extent to which a specific actor (a single person, SDG, or whatever unit in the network is being measured) in a network is essential. The simplest measure of centrality is the *degree centrality*, which is the number of actors to which each other actor connects (Borgatti et al., 2013). As an example, an actor with high degree centrality could be considered a hub and would have connections to many other actors, which translates into having high influence in the cross-impact analysis.

Since the network of the 17 SDGs is directed and valued, the centrality of each node of the network (each SDG) needs to be broken down into *outdegree centrality* and *in-degree centrality* (Borgatti et al., 2013). The outdegree centrality (sum of values of outgoing links) and indegree centrality (sum of values of ingoing links) of the SDGs are respectively equal to the row sums (total influence) and column sums (total dependence) of the adjacency matrix in Figure 1.

Network analysis can often complement systems-based modeling, and the two analytical techniques share commonalities. A network is represented using a cross-impact matrix. Some topics are better analyzed using systems compared to networks, and vice versa, for example, urbanization is better modeled using systems tools, but the global migration network (i.e., the flow of people among different geographical locations, or nodes) is, by definition, a network. The determinants and influences of urbanization and migration are governed by systems science, but they are more appropriately modeled through network science. Most issues have aspects that can be modeled using both, and each method provides unique and complementary insight into the context of the problem.

### 3.2.3. System dynamics modeling

As noted by Checkland and Poulter (2006), the limitation of a soft-systems approach such as cross-impact analysis (CIA) is that it uses an action- and group-oriented learning process to address problem areas instead of the content of the challenges (theoretical and academic approach); this means that the CIA is carried out in a participatory setting where all relevant stakeholders, ideally, are involved. The second limitation of cross-impact network analysis (combining cross-impact with a network analysis) is that it is static; it represents a snapshot of a system in time and cannot handle dynamic (time-dependent) issues. A third limitation is that cross-impact analysis is entirely based on human input, but, ideally, expert judgment. The cross-impact matrix, which is at the fundamental core of cross-impact analysis, requires expert judges to estimate how variables interact with each other, the degree of their interactions, and the possible results of their impacts (Weimer-Jehle, 2006). At the core of the analysis, the quality depends on the accuracy and expertise of the people undertaking that analysis. The experts filling out the cross-impact matrix are “expected to possess insights which rather should be the results of an analysis” (Weimer-Jehle, 2006:337). This illustrates the classic catch-22, where input depends on output, rendering the analysis ineffective through *circle-logic*, or internal causal feedback. In short, populating the matrix for the CIA is especially susceptible to various forms of bias.

System dynamics (SD) can address some of the limitations of CIA mentioned above. SD, as the name suggests, is a tool that accounts for how the components of systems and their linkages *change with time* (i.e., are dynamic). Unlike CIA, which can be carried out using simple spreadsheets in Excel, system dynamics analysis requires using more sophisticated software packages. The SD models presented in this work use the STELLA (Systems Thinking Experiential Learning Laboratory with Animation) Professional software by *isee systems, Inc.* v1.7.1.

It should be noted that both CIA (combined with network analysis) and SD need not be treated as mutually exclusive when addressing the SDGs; they may appear to be dissimilar but, in reality, complement each other. It is recommended, for instance, first to carry out CIA and network analysis to map how the SDGs interact. Using both tools also forces decision makers to at least semi-quantify the strength and centrality of each component within the SDG network as well as the strength of the linkages among the goals. The results of that analysis are critical to developing robust and meaningful SD models. In system thinking lingo, they help develop so-called *mental models* of how the SDGs interact and outline hypotheses of their interaction dynamics.

Systems dynamics is a relatively recent branch of systems science that originated with the work of Dr. Jay Forrester at the Massachusetts Institute of Technology in the 1950s and 1960s. It represents a milestone in the overall evolution in the application of systems thinking and the development of tools to address complex issues in a wide range of disciplines such as engineering, business, economics, health, planning, management, and so forth. In the most simplistic sense, system dynamics studies “how systems change over time” (Ford, 2010). The System Dynamics Society (2016) defines system dynamics as a computer-aided approach to policy analysis and design. It can be applied to dynamic problems arising in complex social, managerial, economic, or ecological systems — literally any dynamic systems characterized by interdependence, mutual interaction, feedback, and causality. In general, SD has unique characteristics that warrant its use in modeling the interaction of the SDGs:

- It is a method that can be used to study how systems continuously change over time due to possible changes in and relationships among components and changes in the overall direction of systems, allowing for both qualitative and quantitative modeling.
- It requires an unambiguous formulation, a mapping, and an iterative approach to model the issue(s) at stake.
- SD models are defined by closed boundaries (causally-closed models) where endogenous components, those originating from within, predominantly dictate the behavior of the systems. Models are designed to be self-contained regarding cause-and-effect inside their boundaries so that no external (exogenous) influence needs to be explicitly considered. In other words, SD models are designed to contain the system components that “are important to explain [their] dynamic behavior” (Richardson & Andersen, 2010; Vennix, 1996), including their internal rules.
- Non-linearities in the system are included in the form of first-order differential equations.
- Information feedback mechanisms in the system can be included in the form of interconnected closed loops and circular causality, allowing for reinforcing and balancing trends; this can help in explaining the counter-intuitive forms of behavior of some systems.
- The method emphasizes that the structure of systems (i.e., their components, mutual interactions, and environmental interactions) affect their continuous behavior. Various dynamic patterns can be simulated by combining feedback loops to model different behavioral patterns of system changes such as growth, decay, overshoot, oscillations, equilibrium, randomness, and chaos. As the structure of a system changes, so does its behavior.

- More emphasis is placed on the structure of a system (its aggregated nature) than on trying to figure out the details of individual components.

A technical description of SD modeling can be found in Appendix B (Zelinka and Amadei 2019b), and the numerous publications referenced throughout. In their research, the authors provide a detailed methodology for constructing the model, determining the equations, and combining the individual structures into a more complex model. That SD interconnection model discussed in that paper was built as a generic structure that can be applied to many areas within sustainable development, specifically the techno-environmental systems discussed in Section 0 but also to socio-political systems discussed in Section 4.2.

In general, system dynamics modeling necessitates following an iterative roadmap consisting of several interconnected steps. Figure 12 shows a roadmap proposed by Ford (2010) consisting of eight steps: problem familiarization (step 1); problem definition (step 2); model formulation by constructing causal loop diagrams (step 3) and then stock-and-flow diagrams (step 4); parameter estimation (step 5); simulation to explain the problem being addressed (step 6); and simulation analysis consisting of a sensitivity analysis (step 7) and a policy analysis (step 8).

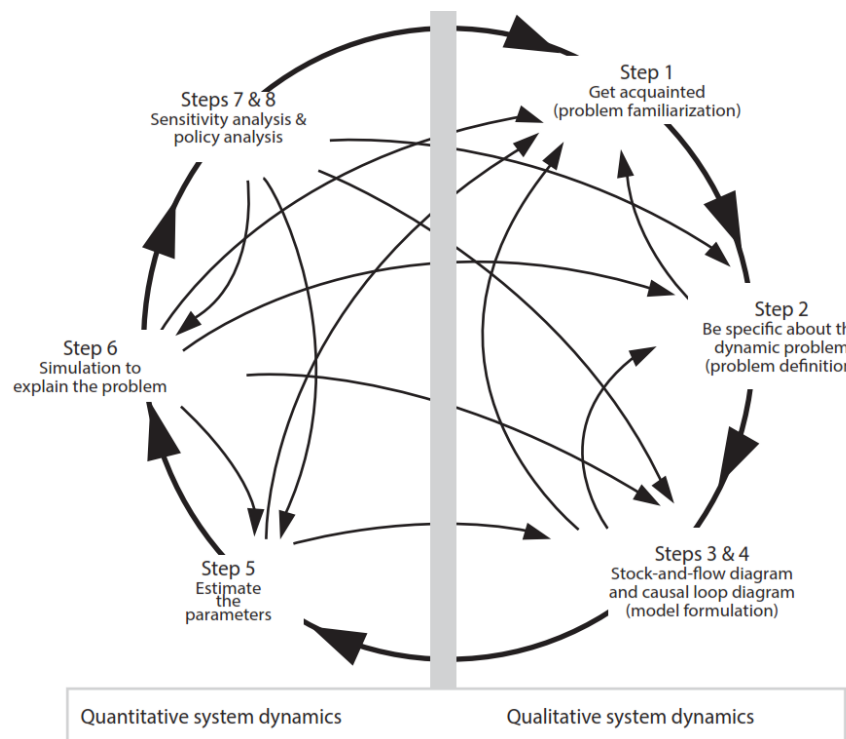


Figure 12. Road map for system dynamics modeling (Ford, 2010)

Figure 12 also shows that the SD modeling process is divided into qualitative and quantitative modeling. Steps 1–4 can be interpreted as the qualitative and conceptual components of SD modeling. The other steps emphasize the quantitative dimension of that modeling. Whether qualitative or quantitative modeling is used depends mostly on the purpose of the system analysis; the availability of data and information about the system components; and the participating audience (Wolstenholme 1999). However, a qualitative understanding of the issue being modeled is required before any quantitative modeling can be done; it serves to validate the model preemptively.

### **3.3. Qualitative social systems approach**

In anthropocentric systems within sustainable development, social scientists are as fundamental to understanding the problem as engineers are to implement possible solutions; however, although there is considerable overlap among the disciplines, there is little transdisciplinary collaboration. A qualitative social systems approach complements the quantitative systems modeling tools introduced in the previous section. Because those tools are quantitatively oriented, they can be used to run advanced analyses, but they cannot be used to inform the underlying structure and theories of the models. Quantitative methods are primarily the domain of the technical and applied sciences, while social scientists are experts in qualitative approaches. The goal of this section is to introduce a hybrid approach that can be used to combine approaches from both groups into a standardized methodology.

#### **3.3.1. Qualitative structural data analysis**

Science is mostly based on reductionist (linear) thinking, in that it breaks down complex problems into more manageable pieces. This makes for highly detailed and specialized knowledge, but it does not usually account for the effects of and interactions with other areas and disciplines. Thus, traditional scientific methods are constrained by silos of thought. To try and build bridges between information in various disciplines and turn these connections into a full-system view of their real-world effects, Zelinka and Amadei (2018a) introduced *qualitative structural data analysis* (QSDA; see Appendix F). This technique codes and converts text from peer-reviewed publications into causal-loop diagrams (CLDs), stock-and-flow diagrams, and eventually full system dynamics models.

In QSDA, the underlying structure of the text is extracted and graphically represented. The quality and validity of the model are highly dependent on the quality and structure of the text. For that reason, QSDA is best for academic peer-reviewed articles and reports from reliable and reputable journals and institutions. The information is as reliable as can be expected, and the structure of the text goes through many edits before it is published and released. Furthermore, the literature reviews for articles are the most effective locations from which to source text; they are

based on dozens of other peer-reviewed articles on the same topic. So long as the knowledge of the text is directly sourced and backed-up by reliable research, the analysis will also be valid; by this logic, the more references that back up text, the better.

The process of analysis involves mining the relevant literature to identify critical structural variables of an issue; for example, the rule of law is an essential variable in the issue of corruption. The variables and their interactions are coded and attached to specific references and locations in those sources. The simplest structure (i.e., the effect of one variable on another or two variables and a single interconnection arrow) of the text is coded. As many publications are coded in this fashion, a picture starts to emerge. The same variables will appear in multiple works, enabling the disjointed parts of the whole to connect like a puzzle.

Coding (textual analysis) is fundamental to this method; it tells the researcher which variables are important, their relationships with other variables, and the underlying structure, and guides the overall construction of the model. The coding system does not just find what is being said, but also how it is being said—the specific choice of words. In general, certain words or phrases strongly indicate the existence of individual variables and hint at their relationships to other variables. For example: “greater than” usually implies a positive correlation between two variables; “indirect” means that a variable impacts another variable through intermediaries or the existence of a hidden causal chain (A affects C through B), while “direct” infers a relationship without intermediate variables (A affects B); or phrases such as “in the presence of” or “under certain circumstances” imply a moderating relationship (A time B), as opposed to a mediating one (A adds to B). The structure of the sentence determines the structure of the systems map – nouns are the variables and verbs describe their interactions – so if the structure of the sentences in the articles can be deduced, so can the structure of the system.

Let’s illustrate this concept with a verbatim excerpt from Kolstad and Wiig (2009). The sections of text in bold were directly coded into variables; the sections of the text that are italicized represent the causal relationships between variables; and the italicized bold text indicates both variables and casual relationships. The follow text is an example the application of QSDA. The text below was broken down into individual pieces and transcoded into Table 9 that was then used to generate the example CLD in Figure 13.

As our focus is on transparency, let us discuss this in more detail. Firstly, **transparency** *has a direct impact on* **detection (the probability of getting caught)**. The more

transparent the cost structure of the oil company is, the more difficult it is for the bureaucrat to distort information and the easier it is to be caught doing so. **When information is sparse, it is difficult to reveal whether a bureaucrat is corrupt or not.** Secondly, transparency might also have indirect impacts on the other explanatory factors of corruption referred to above. **Transparency might, for instance, have an indirect impact on law enforcement.** Under **non-transparent circumstances proof is more difficult to generate** and **corrupt officials are able to buy their way out of punishment.** Transparency might also have an impact on the bribe size. On the one side, a lack of transparency may lead to a higher bribe as corrupt officials have greater bargaining power when information is sparse. On the other hand, a lack of transparency reduces the expected costs of being corrupt and might therefore decrease the bribe the bureaucrat requires for being corrupt.

Table 9. Breaking down Kolstad and Wiig (2009) using QSDA; the left column is exactly the text as found in Kolstad and Wiig (2009); in the right column explanations of the text are signified with (E), (V) stands for a variable, and (R) is a causal relationship between variables;  $\rightarrow+$  is a positive relationship,  $\rightarrow-$  is a negative relationship, and  $\rightarrow+/-$  can be both depending on the context

<u>Verbatim Text</u>	<u>QSDA Interpretation</u>
<b>transparency</b>	transparency (V)
<b>detection (the probability of getting caught)</b>	detection (risk) = risk of detection (V)
<b>transparency has a direct impact on detection (the probability of getting caught)</b>	transparency $\rightarrow+$ risk of detection (R)
<b>information is sparse</b>	access to information (V)
<b>to reveal</b>	<p>reveal is similar to the word detection (E)</p> <p>it also signifies a relationship because it is a verb; even though it's not directly attached to a noun (i.e., a general variable) it is understood that law enforcement is the responsible party that does the revealing (E)</p> <p>enforcement power <math>\rightarrow+</math> risk of detection (V) (R)</p>
<b>it is difficult to reveal whether a bureaucrat is corrupt or not</b>	<p>information (V) is used by law enforcement (V) to reveal corruption (bribery, V) (E)</p> <p>it is also used to improve the overall anti-corruption effectiveness (V) in the government, which improves transparency (V) (E)</p> <p>as enforcement power increases the risk of detection increases (E)</p> <p>enforcement power <math>\rightarrow+</math> risk of detection</p>



<p><b>When information is sparse, it is difficult to reveal whether a bureaucrat is corrupt or not.</b></p>	<p>In short, information is crucial to detecting bribery through two separate causal pathways (E)  access to information →+ anti-corruption effectiveness →+ transparency →+ risk of detection →- bribe size (R)  access to information → + enforcement power →+ risk of detection →- bribe size (R)</p>
<p><b>law enforcement</b></p>	<p>enforcement power (V)</p>
<p><b>Transparency might, for instance, have an indirect impact on law enforcement</b></p>	<p>“might” can imply an indirect connection or a relationship that is positive or negative (E)  “indirect impact” means transparency affects enforcement power through, at least, one other variable (E)  transparency →+/- (one or more variables) →+/- enforcement power (R)</p>
<p><i>proof</i></p>	<p>as the CLD grows some variables could become causal chains by themselves; proof is information that law enforcement uses to increase the chances of corrupt officials from being caught (E) (V)  access to information →+ enforcement power →+ risk of detection (R)</p>
<p><i>is more difficult to generate</i></p>	<p>signifies a negative relationship between two variables (E)  (V) →- (V) (R)</p>
<p><b>corrupt officials</b></p>	<p>corruption (not shown) (V)</p>
<p><i>are able to</i></p>	<p>can signify a positive relationship between two variables  (V) →+ (V) (R)</p>
<p><b>buy</b></p>	<p>bribe size (V)</p>
<p><b>punishment</b></p>	<p>enforcement power (V)</p>
<p><b>buy their way out of punishment</b></p>	<p>as the CLD grows some variables could become causal chains by themselves; the larger the bribe, the lower the chances law enforcement will address the corruption (because they are bought-off), which lowers the effectiveness of law enforcement (E)  bribe size →- enforcement power (R) (V)</p>
<p><b>Under non-transparent circumstances proof is more difficult to generate and corrupt officials are able to buy their way out of punishment.</b></p>	<p>a lack of transparency makes it more difficult for law enforcement to find proof, lowering the risk of detecting corruption (E)  without proof it will be easier for corrupt officials to amass financial capital that in turn can then be used to create larger bribes (E)  larger bribes mean corrupt officials can pay-off law enforcement more effectively, reducing law enforcement (E)  access to information →+ enforcement power →+ risk of detection →- bribe size →- enforcement power (R)</p>

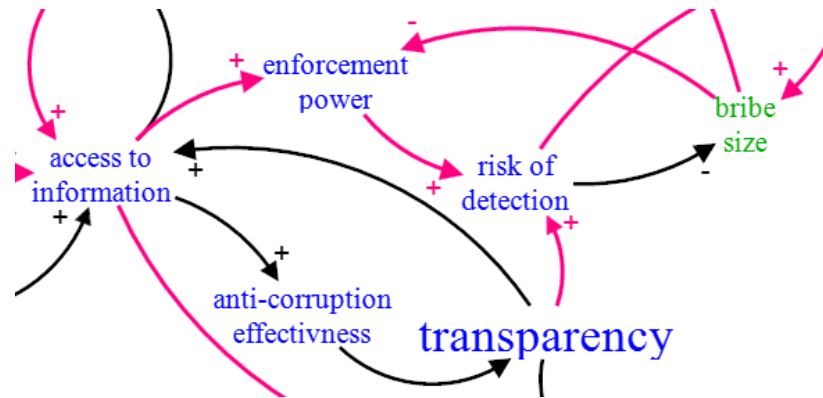


Figure 13. A subset of the CLD for Kolstad and Wiig (2009)

Nearly every word from the text selection in Kolstad and Wiig can be broken down using QSDA, but to avoid redundancy and save space, only three sentences were analyzed. The remainder of the text serves to back up the text that was and would produce the same results. Expanding QSDA to other parts of the document as well as other articles will yield a more complete CLD as depicted in the literature.

Each variable, type of variable (direct versus indirect and moderating versus mediating), relationships among variables, and direction of those relationships (positive or negative) is captured in QSDA. Eventually, an SD model can be constructed that encompasses the entire literature synthesis and all the articles analyzed within Figure 13. The main difference between a stock-and-flow diagram and a full SD model is the inclusion (in the latter) of initial conditions and equations, which will be left to future work.

### 3.3.2. NVivo QDA software

QSDA is heavily influenced by qualitative data analysis (QDA), which is “the range of processes and procedures whereby we move from the qualitative data that have been collected into some form of explanation, understanding or interpretation of the people and situations we are investigating” (Gibbs and Taylor 2010). *NVivo 12* by *QSR International* was the software utilized for the QSDAs used in this paper, and although it was not initially designed for addressing such needs, NVivo proved to be sufficient for the task at hand. Nominally, the coding mechanisms between QDA and QSDA are the same, but instead of being used to interpret and understand qualitative information, the way QDA is (Bernard and Ryan 2010), QSDA is used to identify structurally and reliably source variables, relationships, and more complicated causal mechanisms. The variables become the converters, stocks, and flows that constitute CLDs, stock-and-flow diagrams, and SD models; the relationships become the interconnections;

and the causal mechanisms – the rentier, repression, and modernization effects discussed in Section 2.3.3 – become large structures around which the rest of the model is built.

In any system dynamics model, there are three types of variables: flows, stocks, and converters (Figure 14). Stocks, represented by rectangular boxes, are net accumulations of something at one point in time and represent state variables that define the current state of the systems. Flows appear as pipelines, with a faucet controlling the flow, and refer to processes that cause change over time (dynamic) of information or materials; they are control variables that create change in the systems and affect stocks. Converters, shown as a name or a circle-and-name, transform (convert) information from one stock-and-flow path to another. For example, greenhouse gases (GHG) are emitted per year (flow) and accumulate in the atmosphere (stock). Each person uses electricity that in turn generates GHGs; electricity and GHGs are two stock-and-flow paths connected by at least one converter. The *variables* (e.g., GHG emissions, electricity, etc.) are called *nodes* in NVivo. While manually coding the literature, each variable type is noted, and when the stock-and-flow diagram is constructed, the variables are assigned their appropriate variable type.

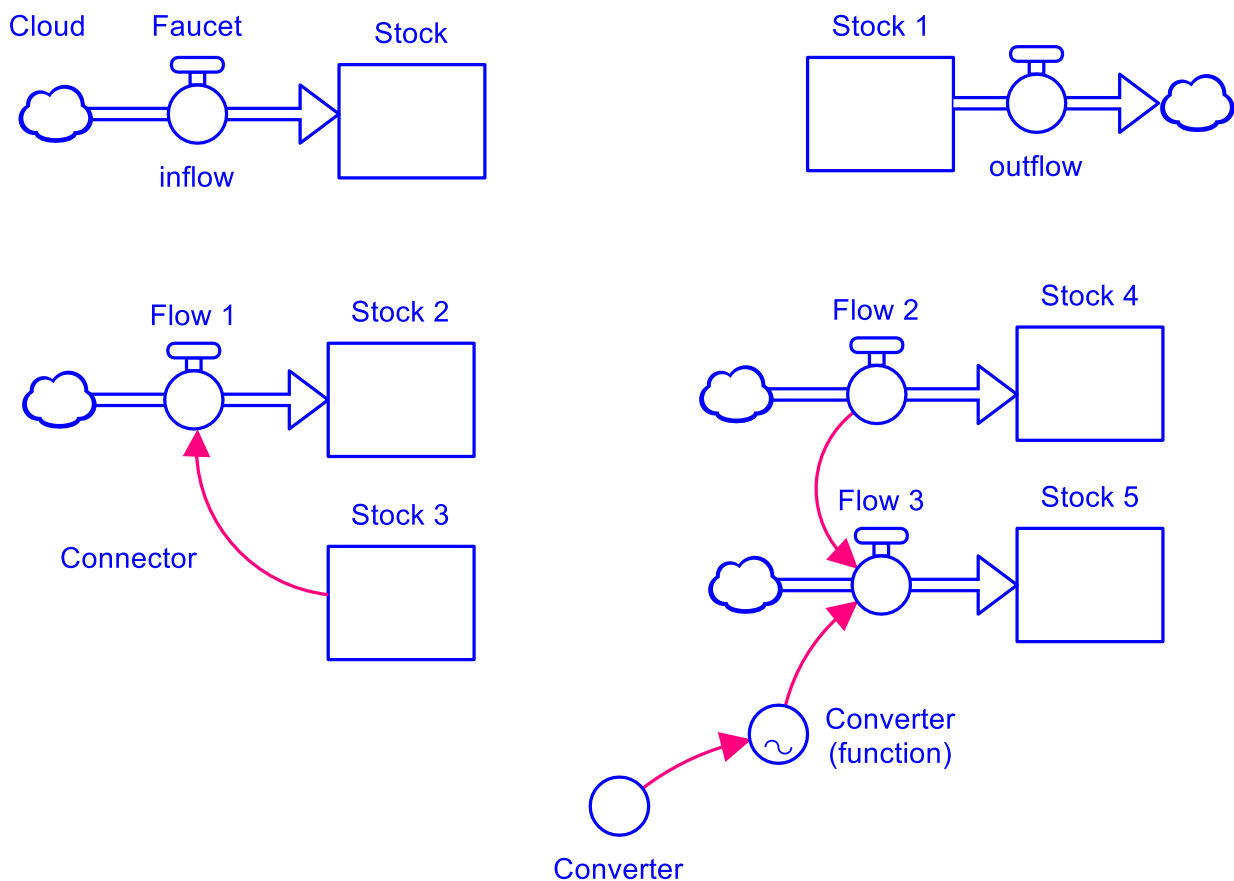


Figure 14. System dynamics modeling structures

NVivo uses the term *relationships* to signify the interconnections between two variables. Interconnections can either negatively or positively affect another variable. Once the five larger causal mechanisms discussed in Section 2.3.3 (group formation, spending, taxation, repression, and modernization effects) were classified, the necessary variables were identified, and those variables were connected with relationships as-needed. *Cases* in NVivo represent units of observation, which in QSDA are causal mechanisms and other vital structures. They are composed of individual nodes, relationships, or groups of nodes and relationships. Cases can group multiple sources that relate to the same structure or mechanism and help to organize them for when it comes time to construct the stock-and-flow diagram and then the SD model.

Once all of the variables, interconnections, and causal mechanisms (e.g., rentier effect) in the literature are identified and appropriately coded in NVivo, the information is, as objectively as possible, incorporated into STELLA (Systems Thinking Experiential Learning Laboratory with Animation) Professional (version 1.8.1), a system dynamics modeling software by *isee systems, Inc.* The components of the QSDA are added into a single stock-and-flow diagram that encompassed all five primary causal mechanisms.

### **3.3.3. Mathematical approach**

Many methodologies employed in the social sciences are regression-based, and therefore they can only represent linear approximations of causation. As such, they “are probably useful [only as] descriptions of the relationships among various variables, but they often cannot properly be used for causal inferences because they omit variables, [and] fail to deal with selection bias and endogeneity” (Goodin et al. 2010). That being said, regression analysis produces results generally “good enough” for use in the first iteration of the system’s representation. Goodin et al. (2010) aptly explain why they are good enough for most CLDs:

Regression analysis, much more than correlation analysis, provides a seductive technology for exploring causality. Its asymmetry with a dependent variable, depends on at least one independent variable, *lends itself to a discussion of causes (independent variables) and effects (dependent variables)*, whereas correlation (even partial correlation) analysis is essentially symmetric. Indeed, path analysis uses diagrams which look just like causal arrows between variables. Econometricians and statisticians provide theorems which show that if the regression model satisfies certain conditions, then the regression coefficients will be an unbiased estimate of the impact of the

independent variables or the dependent variables. *Regression analysis also provides the capacity to predict that if there is a one-unit change in some independent variable, then there will be a change in the dependent variable equal to the value of the independent variable's regression coefficient.*

More detailed system maps will need to differentiate specific underlying structures, such as non-linearities, thresholds, time-delays, collinearity, direction and reverse causality, direct versus indirect influences, moderating versus mediating variables, and, most importantly, static versus dynamic variables (Benson and Marlin 2017; Goodin et al. 2010; Hong 2015; Sterman 2000). This more detailed resolution necessitates employing more advanced analyses, as regression-based methods will not suffice. Ideal articles will use some of these advanced methodologies and statistical techniques, but regression analyses are still considered good enough for most situations.

This is a potential leverage point for both engineers and applied scientists to interact with social scientists. Many of these advanced techniques involve an understanding of areas in which engineers focus, of which *structural equation modeling (SEM)* is just one example of a technique. Broadly SEM is used to identify latent variables and general indirect effects that cannot be directly measured and can also aid in defining causal chains (Goodin et al. 2010). Also, *time-series analysis* is useful for identifying dynamic political processes such as partisanship, macroeconomic conditions, ideologies, public opinion, and foreign policy (Goodin et al. 2010), as well as general historical trends. *Factor analysis* analyzes the interactions of variables as well as their relative strengths compared to one another (Denis 2016; Goodin et al. 2010); this is useful for systems models, which rely heavily on the interactions among variables.

Méndez-Giraldo et al. (2017) also include *fuzzy logic*, which is an approach that can convert discrete to continuous variables and vice versa. Fuzzy logic can be used to bridge qualitative and quantitative data using statistical approaches and disciplinary knowledge. They can provide ways to transcode from the social science literature to quantitative systems models and vice versa. For example, a possible variable might determine if people are either cold or warm based on the ambient temperature being above or below a certain point, say 72.0°F (22.2°C); this implies a bivariate variable. Realistically, however, different people feel colder or warmer at different temperatures. Fuzzy logic mathematically allows for this by creating objective distributions with an associated mathematical function. (Some elementary fuzzy logic was employed for the SDG model earlier regarding insecure versus secure states for each SDG in Appendix B.)

It would be mutually beneficial for these groups of researchers and scholars to work together to produce science in this form. Any transdisciplinary collaboration will enable ever more complex, yet accurate, models to be constructed to analyzed complex social issues like corruption. Analyses revealing complex underlying structures and mechanisms will improve the efficiency (moderating effect) of the entire process.

### **3.4. Input data**

Like all models, system dynamics models are only as valid as the data that is input into it; garbage in, garbage out. If the quality of the input data is poor, the results could be unreliable and untrustworthy. Care must be taken so that data is pulled from reliable sources, which come in three types: quantitative, qualitative, and semi-quantitative. Spreadsheet-based (Excel) and SD (Stella) models require either semi-quantitative or quantitative input data, but causal-loop and stock-and-flow diagrams accept only qualitative data. Due to the breadth of topics covered in this dissertation all three types of data are used.

Many tools, especially system dynamics, for modeling complex systems require real-world numerical data of a situation to simulate it accurately. *Quantitative* data are numerical and a function for the equations within the model's variables. They can be regularly measured; for example, 65 degrees Celsius at 4:32 pm or 15 atm of pressure. *Qualitative* data are generally open-ended, less straightforward, if not impossible, to measure quantitatively, and usually involve abstract topics. Examples include descriptions of their feelings during or perception of a particular event. Qualitative data is usually generated when the research covers more social and political topics (e.g., corruption, migration, and conflict), and other related areas.

Semi-quantitative is usually numerical and representative of qualitative data as is the case with the cross-impact matrix of the SDGs in Section 4.1.1. In this case, the semi-quantitative data is a scale ranging from -3 to 3 representing the direction and magnitude of a specific interconnection between two SDGs in the cross-impact matrix based on qualitative understanding. Another example involves the Intergovernmental Panel on Climate Change (IPCC) that uses a scale *exceptionally unlikely* to *virtually certain* to denote the probability from 0-100% that humans are primarily responsible for the rapidly changing climate – *exceptionally unlikely* is less than 1% and *virtually certain* is greater than 99%. The qualifiers are attributed to numerical representations. Semi-quantitative data are easier to find or generate, and they require less cleaning to input into a numerical model than real-world quantitative data. It can be generated at any scale and is an effective way to bring in relevant stakeholders. Unfortunately, it is less precise than quantitative data and is best used to help understand the general picture of a problem and its solution.

The institutional capacity sensitivity analysis in Section 4.1.2 can accept both quantitative and semi-quantitative data. Surveys were the basis of the data, and they consisted of quantitative and qualitative information; the qualitative information was converted into semi-quantitative data to work with the SD model. The SDG cross-impact analysis, the SDG SD model (both in Section 4.1.1), and the Change-of-State SD model (Section 4.1.3) are semi-quantitative; and the socio-political issues in Section 4.2 are all qualitative.

SD models can accept most kinds of data so long as they are formatted and in one of the acceptable file types. The only real requirement for the input data for SD models is that the input data is also dynamic (i.e., in relation to and dependent on time). For example, if SD is used to model the interactions between population growth with natural resources use and environmental degradation, a necessary input dataset would be birth and death rates among others. Birth and death rates are a function of time, so it meets the primary requirement of data and can be input into the model. Sourcing those rates from reliable sources is crucial.

#### **4. RESULTS AND DISCUSSION**

The issues introduced in Chapter 2 were analyzed and modeled using the methods described in Chapter 3. This chapter presents the results of that analysis. The techno-environmental systems presented in Section 4.2 were primarily analyzed using the quantitative methods of Section 3.2, whereas the socio-political systems presented in Section 4.2 were analyzed with the qualitative methods described in Section 3.3. Techno-environmental systems are those that primarily involve technology, infrastructure, cities, and other built engineering systems and their reciprocal effects with the natural environment. Socio-political systems are those that involve social issues, governance, corruption, human rights, and other related areas.

There are many overlaps between these two categories of systems; for example, hydropolitics look at the effects of water (environmental) on politics. Economic and financial systems (i.e., trade, aid, business, sanctions, etc.) were omitted because they are very closely related and often attached to socio-political (i.e., the political economy) systems and can be analyzed with quantitative methods. Future work will incorporate economics and finance into the other systems and sustainable development as a whole.

## 4.1. Techno-environmental systems

### 4.1.1. Interconnections among the SDGs

#### *Cross-Impact Analysis*

Let's consider a system consisting of  $N$  interacting variables. A cross-impact analysis of that system is usually presented by an  $(N \times N)$  matrix with zeroes along its diagonal and  $N^2 - N$  off-diagonal terms. The off-diagonal terms define how each variable (row) *directly* influences or impacts the other variables and how each variable (column) depends on or is sensitive to the other variables. It should be noted that the matrix is not symmetric. The strengths of the influence between two variables can be described *qualitatively* using qualifiers such as low, medium, and high, or scored *semi-quantitatively* over an appropriate scale. The selected scale is specific to the system being analyzed.

Table 10. Semi-quantitative scale of SDGs' interactions (adapted from Nilsson et al. 2017)

<b>Strength, Title</b>	<b>Explanation</b>	<b>Examples</b>
+3, Indivisible	Inextricably linked to the achievement of another goal. Accomplishing this goal will accomplish another goal by default.	Ending all forms of discrimination against women and girls is indivisible from ensuring women's full and active participation in society on par with men.
+2, Reinforcing	Aids the achievement of another goal. This goal will by default achieve a significant portion of another goal, with only a relatively small amount of additional work required to accomplish both.	Providing access to electricity reinforces water-pumping and irrigation systems. Strengthening the capacity to adapt to climate-related hazards reduces losses caused by disasters.
+1, Enabling	Creates conditions that progress another goal. This goal could be a tool to accomplish another. There is a positive, albeit small, overlap between the two goals.	Providing electricity access in rural homes enables education because it makes it possible to do homework at night with electric lighting.
0, Neutral	No significant positive or negative interaction. The interconnections between two goals are purely indirect if they exist at all. The positive and negative impacts are equal.	Ensuring education for all does not significantly impact infrastructure development or conservation of ocean ecosystems.
-1, Constraining	Limits options on another goal, which makes another goal noticeably more difficult to accomplish.	Water requirements for thermoelectric power generation reduce available water for water, sanitation, and hygiene (WASH).
-2, Counteracting	Clashes with another goal. Unless direct actions and efforts are taken by people, this goal will make it significantly more difficult for another to be achieved.	When a population consumes more resources, economic growth can counteract waste reduction and climate mitigation and degrade the environment.



Strength, Title	Explanation	Examples
-3, Canceling	Makes it impossible to reach another goal. Nothing can be done to have these two goals coexist.	Fully ensuring public transparency and democratic accountability cannot be combined with national security goals.

Figure 15 shows an example of a cross-impact matrix (CIM) for the N = 17 SDGs where semi-quantitative scores have been assigned to describe the strength between interacting SDGs, two at a time. Using the scale proposed by Nilsson (2017) and shown in Table 10, the scores were assumed to range from -3 (most dependent and least influential) to +3 (least dependent and most influential). Negative values depict an SDG that either constrains, counteracts, or cancels another goal, broadly defined as *limiting*; the opposite occurs for positive values, which either enable, reinforce, or are indivisible from another goal and are generally defined as *enhancing*. Interactions are 0 when there are no discernable effects and are called *neutral*. Values were assigned for each one of the 272 off-diagonal terms of the double-causality matrix of Figure 15, although -3 never appeared in the analysis.

Goal	Goal 01	Goal 02	Goal 03	Goal 04	Goal 05	Goal 06	Goal 07	Goal 08	Goal 09	Goal 10	Goal 11	Goal 12	Goal 13	Goal 14	Goal 15	Goal 16	Goal 17	Total	Description	Influence	Dependence	Influence Ratio	Net Influence	Priority Index
Goal 01	0	-1	-1	-1	-1	-1	-1	-1	1	3	-1	-1	1	0	0	3	2	1	Poverty	1	37	0.03	-36	0.01
Goal 02	3	0	3	2	2	0	-1	1	0	3	-1	-1	-1	-1	3	0	0	12	Food Security	12	28	0.43	-16	0.20
Goal 03	3	1	0	2	2	1	-1	2	-1	3	1	0	0	1	0	0	0	14	Health	14	28	0.50	-14	0.22
Goal 04	2	2	2	0	2	2	1	2	2	3	2	2	0	2	1	2	2	29	Education	29	21	1.38	8	0.48
Goal 05	3	3	2	2	0	-1	-1	3	0	3	2	-1	0	0	2	3	1	21	Gender Equality	21	23	0.91	-2	0.36
Goal 06	3	3	3	2	2	0	1	3	1	3	3	1	1	2	3	0	0	31	WASH	31	16	1.94	15	0.60
Goal 07	3	1	3	2	0	2	0	3	3	3	3	-1	-1	-2	-2	0	2	19	Energy	19	8	2.38	11	0.61
Goal 08	3	2	2	3	3	2	2	0	2	-1	2	3	-2	-2	-2	0	2	19	Economy	19	26	0.73	-7	0.30
Goal 09	2	2	2	1	0	2	3	3	0	-1	3	-1	-1	0	-2	2	2	17	Infrastructure	17	17	1.00	0	0.38
Goal 10	3	2	2	0	3	-2	-2	3	0	0	-2	-2	-1	-1	-2	0	1	2	Inequality	2	30	0.07	-28	0.07
Goal 11	1	1	2	1	3	3	2	1	3	1	0	2	-1	0	1	0	1	21	Cities	21	18	1.17	3	0.42
Goal 12	2	2	1	2	1	1	2	3	2	3	2	0	-1	-1	-1	0	0	18	Consumption	18	4	4.50	14	0.87
Goal 13	2	1	-1	0	1	-1	-2	-1	-1	2	-2	-1	0	3	2	0	0	2	Climate Change	2	2	1.00	0	0.38
Goal 14	-1	1	1	0	0	1	1	-1	1	-1	1	1	0	0	2	0	0	6	Ocean	6	9	0.67	-3	0.32
Goal 15	2	3	2	0	0	2	-1	-1	-1	0	0	-1	3	3	0	0	0	11	Land	11	10	1.10	1	0.40
Goal 16	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	0	3	44	Governance	44	13	3.38	31	0.88
Goal 17	3	2	2	2	2	2	2	3	2	3	2	2	3	3	3	3	0	39	Partnerships	39	16	2.44	23	0.71
Total	37	28	28	21	23	16	8	26	17	30	18	4	2	9	10	13	16	306						

Figure 15. Double-causality matrix with influence, dependence, and priority index

Several remarks can be made about the double-causality matrix. First, the values must only represent the *direct* impact of one SDG on another, otherwise indirect effects will be double-counted. Second, it should be noted that the values in the CIM depend on the context in and scale at which the cross-impact analysis of the SDGs is conducted. For instance, the CIM of Figure 14 was constructed for an *average-sized country of average population*

and at an average level of human development. This country does not exist, but the goal was to generate a cross-impact analysis of the SDGs for a *hypothetical average country*.

Using the total influence and dependence scores from Figure 15, three indices were calculated for each SDG and are listed on the right side of Figure 15. The first index, the net influence (NI), was calculated as the difference between influence and dependence. The NI shows the absolute power of a goal. The larger the NI, the more “power” that goal has when influencing the other goals. The second index is the *influence (I)-to-dependence (D) ratio* (IR = I/D). This index focuses more on the efficiency of a goal than on its power. Finally, the third index, defined as the *priority index* (PI), is a proportionally weighted average of the IR and NI relative to the smallest and largest values for each set of goals.

The total dependence and influence values were plotted on a single dependence (x) vs. influence (y) graph as shown on Figure 16. The diagonal line separates the goals that are more dependent (above the line) from those that are more influential (below the line). The average influence and dependence value for all SDGs is 18.2 and is represented by a star on the line near infrastructure; a higher average value would indicate a more stable (determined) system (Arcade et al. 1999). The graph can then help to categorize the variables (goals). According to Arcade et al. (1999), the categories include:

- *influential variables (goals)* with low dependence and high influence; e.g., SDG 06 (WASH), SDG 16 (Governance), and SDG 17 (Partnerships);
- *excluded variables (goals)* with low influence and dependence; e.g., SDG 13 (Climate Change), SDG 14 (Oceans), and SDG 15 (Land);
- *dependent variables (goals)* with high dependence and low influence; e.g., SDG 01 (Poverty), SDG 02 (Food Security), SDG 03 (Health), and SDG 10 (Inequality); and
- *regulating variables (goals)* that lie near the center of the graph, e.g., SDG 04 (Education), SDG 05 (Gender Equality), SDG 08 (Economy), SDG 09 (Infrastructure), and SDG 11 (Cities).

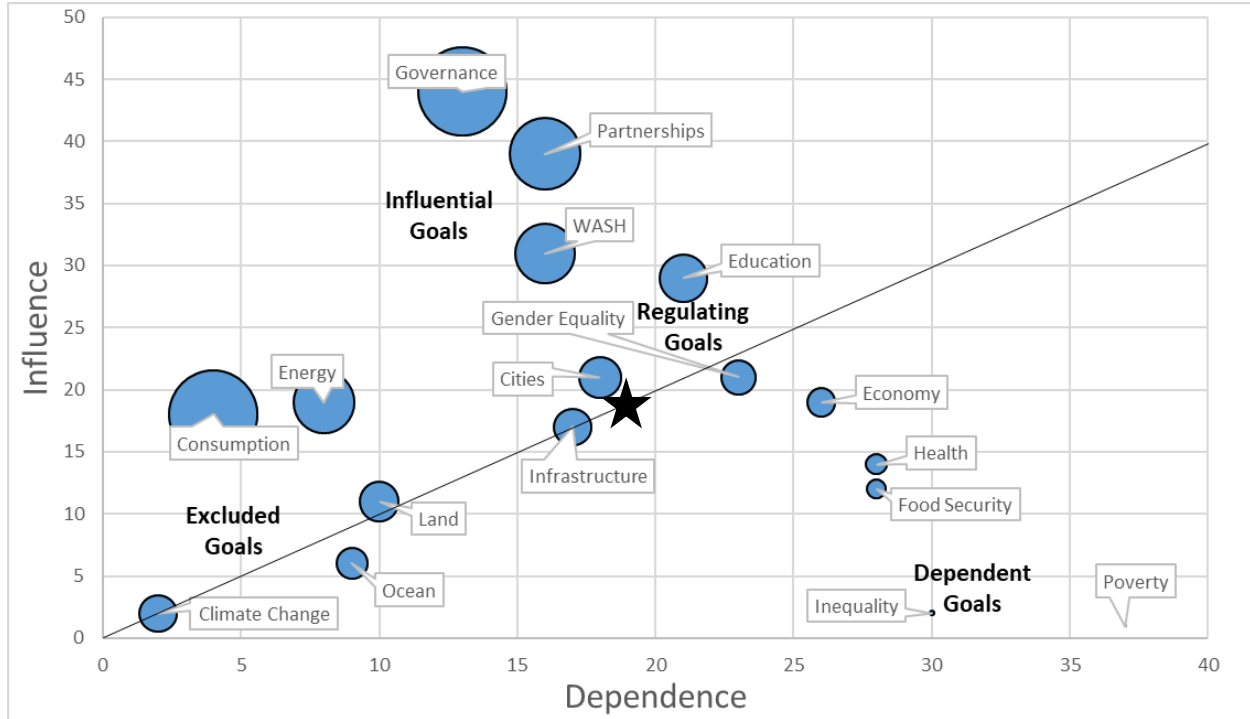


Figure 16. Influence and dependence graph with prioritization bubbles

A user-friendly interface was created in Excel (Figure 17) to hide the backend equations and reduce the learning curve required to analyze the SDGs. A user-interface enables those without an understanding of system dynamics to run complex simulations using system dynamics modeling. It has all the components mentioned in this section – the cross-impact input matrix, efficiency versus strength focus, prioritization index, and the graphical representation – but it also includes the allocation of resources for the SDGs by their primary involvement in a pillar of sustainability. The interface is useful for exploring the general allocation among political, economic, social, and environmental factors.

Once the values of the cross-impact matrix are agreed on, the results (i.e., the priority index based on the net influence and the influence ratio) can be presented in the form of a chart such as in Figure 18. The pillars of sustainable development (economic, social, political, and environmental) are shown as four shaded boxes. (The infrastructure/technical pillar was omitted for simplicity.) Each SDG falls into one of those pillars, although they can and usually do cross-cut multiple pillars. The goal of Figure 18 is to make the technical results easily understandable by decision makers. Besides the four pillars, poverty (Goal 01) and [economic] inequalities (Goal 10) represent the desired overarching goals to which the other goals strive to contribute. These two goals are placed into the fifth shaded box on top (desired socio-economic results) of Figure 18. Poverty eradication is the ultimate social outcome while

reducing inequalities is the desired economic outcome of the SDGs and is closely associated with poverty. Using the cross-impact matrix in Figure 15 (Section 3.2.1), a network analysis (Section 3.2.2) can be run. The results can be seen in Figure 19. (A more detailed methodology and analysis can be found in Zelinka and Amadei [2019a], presented in Appendix A.)

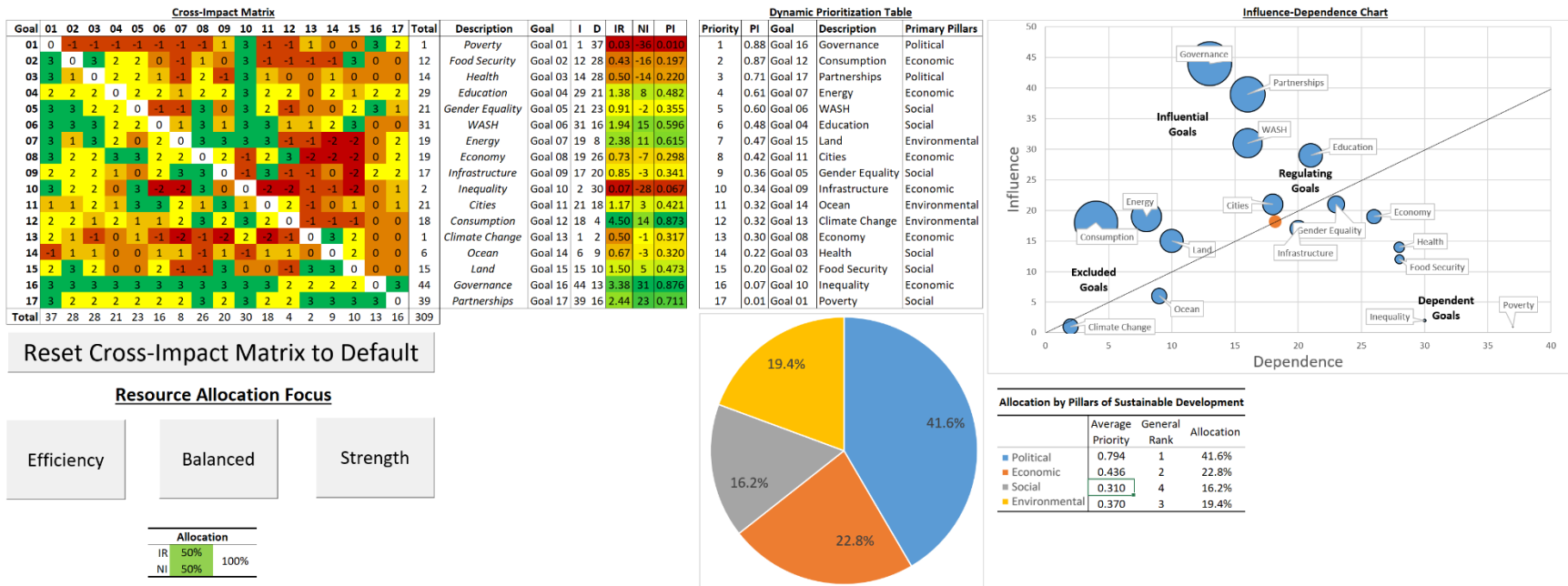


Figure 17. Cross-impact analysis user-friendly interface

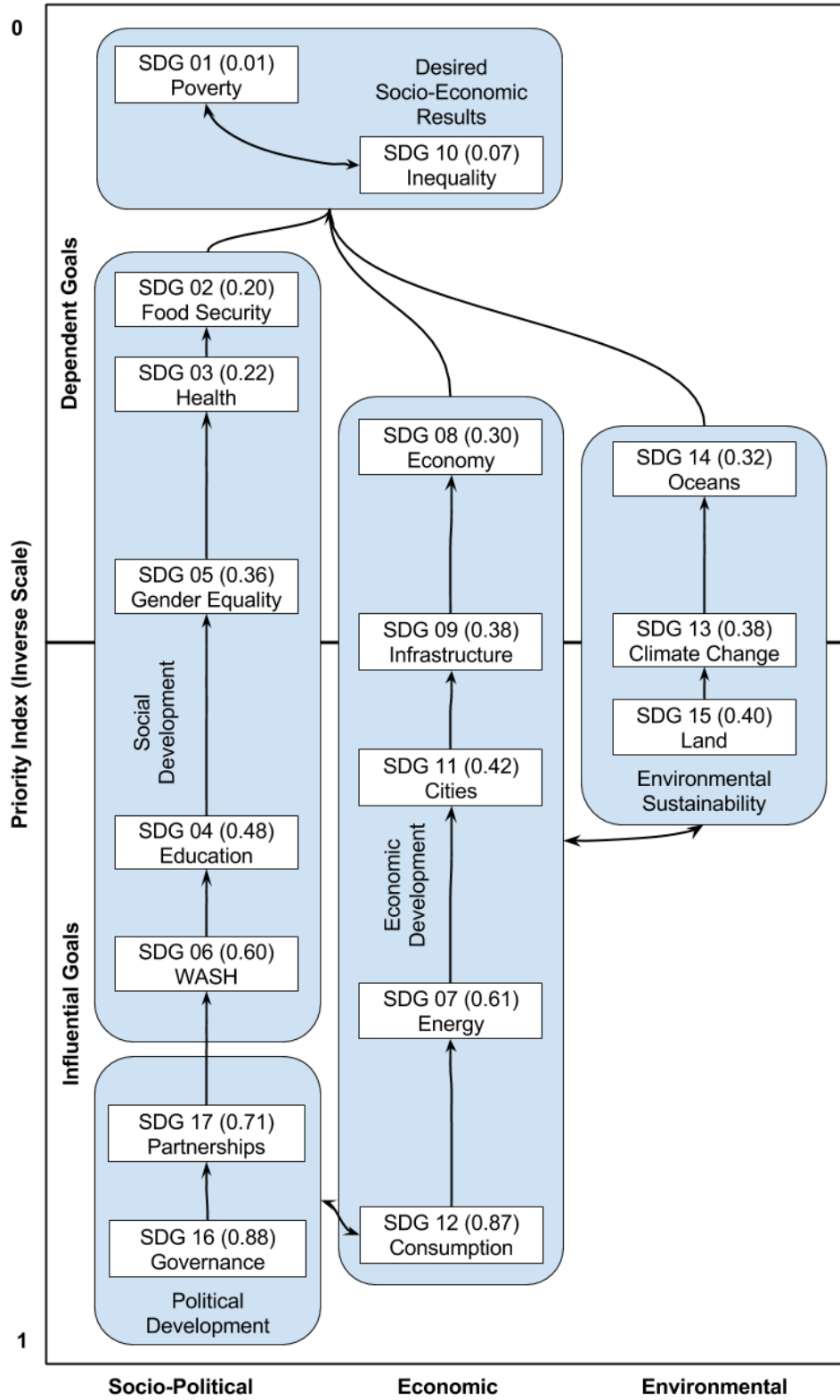


Figure 18. Flowchart of SDG prioritization

Figure 19 shows a directed, valued network representation of Figure 15 where each node size depends on the value of the priority index (PI) calculated in the cross-impact analysis. The thickness of the links in Figure 19 represents the strengths of the SDG interactions.

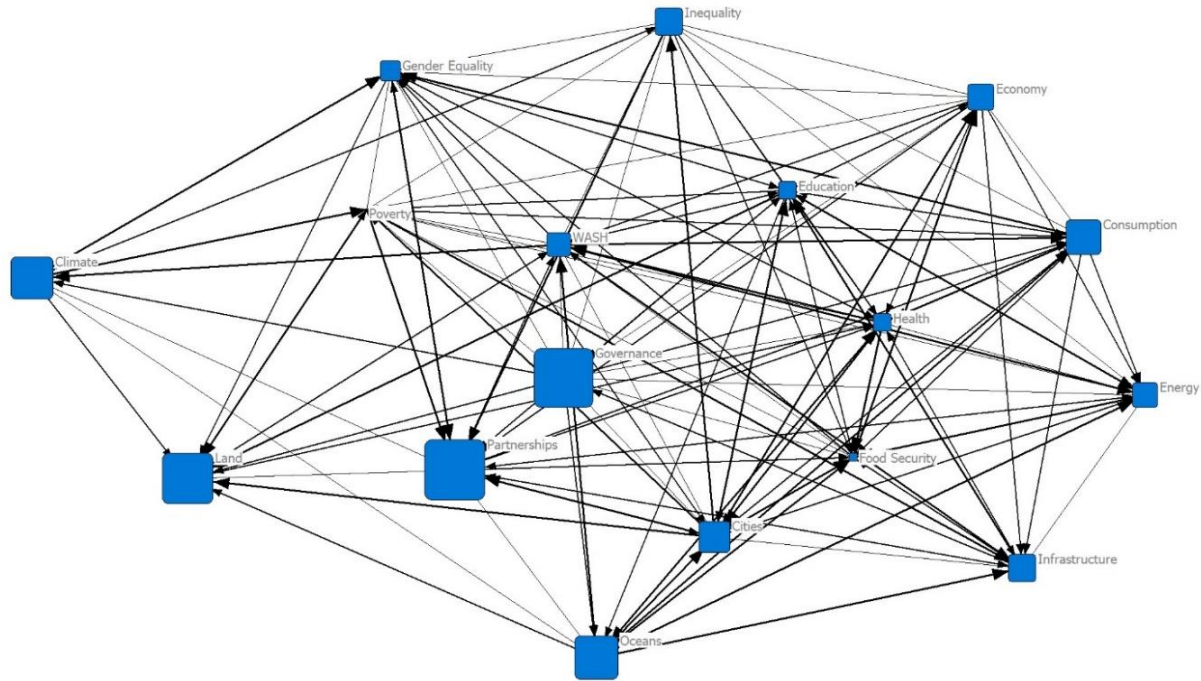


Figure 19. Network diagram map of the SDGs

Several remarks can be made about using network analysis in analyzing the SDG network. First, the network analysis presented above can be repeated at the target level, which would help decision makers to understand better how the SDGs interact with one another. Secondly, Figure 19 is only one possible representation of the SDG network among many. As discussed further by Borgatti et al. (2013), the nodes in the network graph do not have to be placed at random. Other graph layouts can be generated by using the centrality values as a priority. Likewise, *multidimensional scaling* (MDS) can be used to graphically represent the nodes so that the “distances between the points [nodes] correspond in a predetermined way to the proximities among objects in the data” (Borgatti et al. 2013). The closeness of the distance between two nodes could be used to represent how similar, or dissimilar, they are to one another. Third, the centrality of the SDGs is very high, which we expect to hold in most scenarios due to the high degree of overlap among the SDGs. Most SDGs have some form of direct connection (one degree of separation) with the other SDGs (Le Blanc, 2015; Nilsson, 2017; Nilsson et al., 2017). Those that don’t are indirectly connected with, at most, only two degrees separating them from any other SDG. This indicates that the SDG network is tight, and tighter networks are more impacted by fewer effects than looser networks.

Finally, like the cross-impact analysis, network analysis should only be used to understand the interactions across a network strategically. It pays less attention to the *nature* and *dynamic* of those interactions, which can be handled better by quantitative and hard-system tools such as system dynamics. Network analysis provides information about the network as a whole, but errors and problems could arise as the analysis becomes more precise, especially when decisions are made about intervening at the SDG level.

### *System Dynamics*

An earlier version of the model discussed above was initially presented at the *United Nations' Multi-Stakeholder Forum on Science, Technology, and Innovation for the SDGs* held in New York on 14–16 May 2017. This forum focused on just six of the 17 SDGs: SDG 01 (Poverty Eradication), SDG 02 (Food Security), SDG 03 (Health), SDG 05 (Gender Equality), SDG 09 (Infrastructure), and SDG 14 (Oceans). That forum created an incentive for developing a system dynamics (SD) analysis of the SDGs. The SD model presented herein can be extended further to include all SDGs in the future, as well as a more detailed and complex model representing sustainable development beyond just the SDGs.

The SD model uses the cross-impact analysis presented above, digitizes, and embeds it within the model. Thus, the same logic that controls the cross-impact analysis controls the SD model. The paper by Zelinka and Amadei (2019b) goes over the SDG interconnections SD model in Appendix B. This model was initially built to identify the value proposition of accounting for the SDGs interconnections instead of considering them individually as independent of each other. The results of that analysis are telling.

Figure 20 represents the variation of the SDGs over time using a traditional siloed and reductionist thinking approach. In dividing a system into smaller and more manageable parts, any analysis will miss the combined effects of their interactions with one another. Figure 21 shows the variations of the SDGs considering their interactions. The thicker blue line in the graphs represents poverty. The other five curves represent improving conditions in various SDGs, but poverty eradication is the primary goal. Since the overall effects of the interactions are positive, Figure 21 shows a faster improvement of (i.e., decline in) poverty. If the effects of the interactions are negative, however, the interactions could (counterintuitively) worsen poverty. It all depends on context.



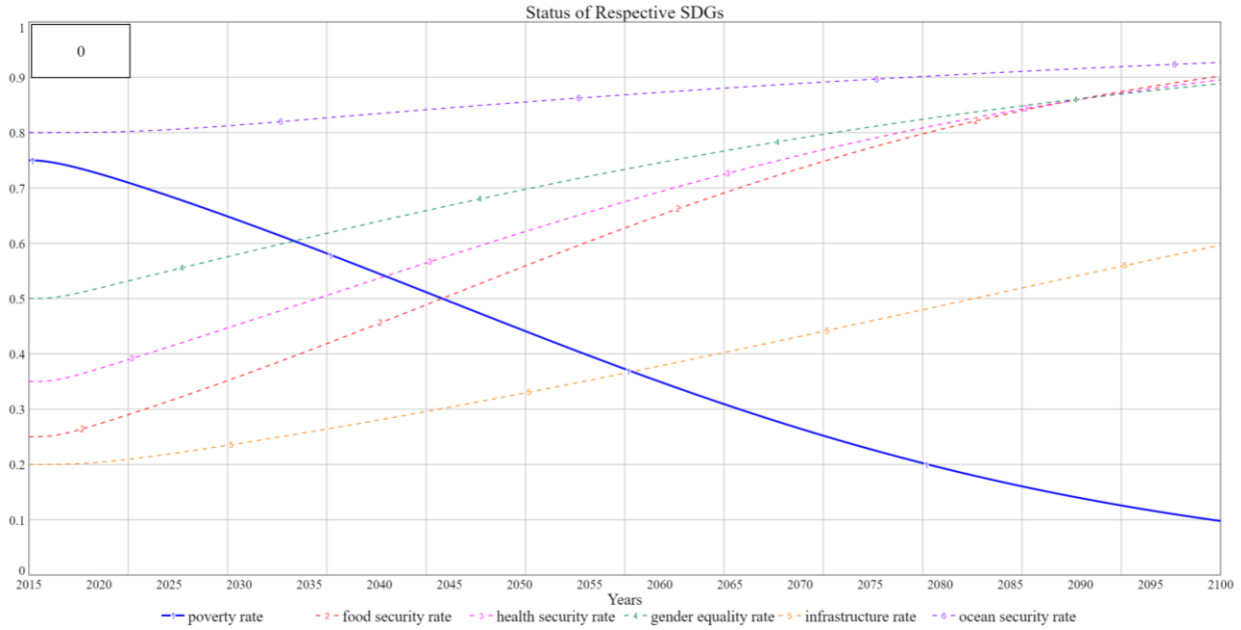


Figure 20. SDGs’ effect on poverty without accounting for their interconnections over time (silos)

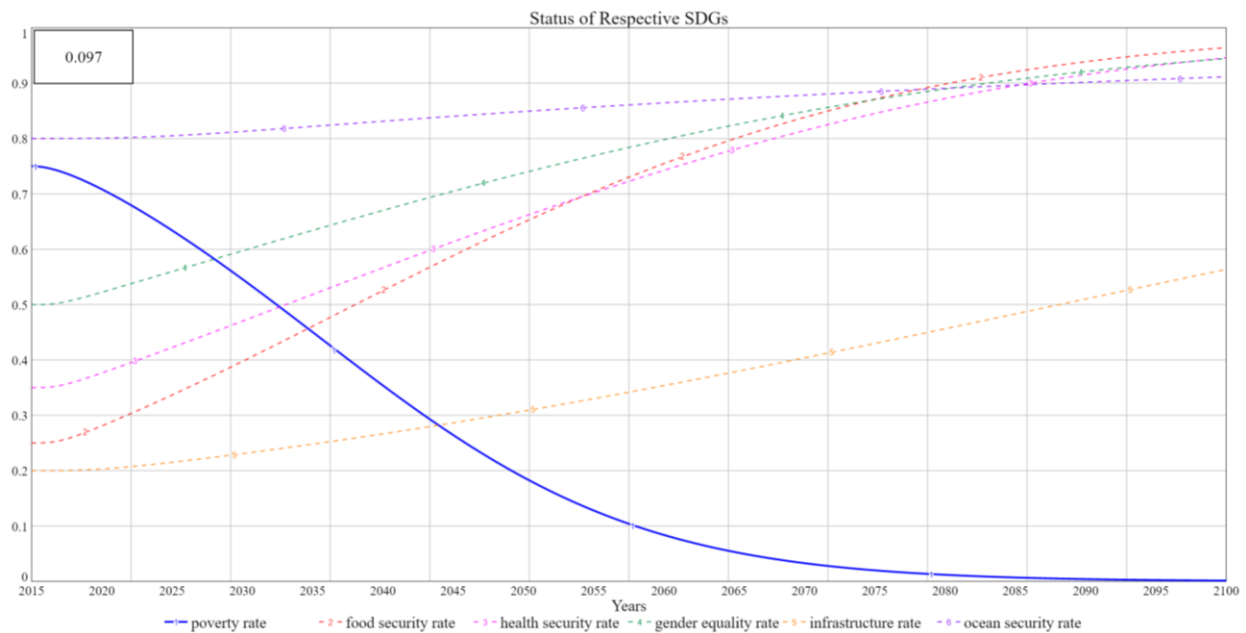


Figure 21. SDGs’ effect on poverty while accounting for their interconnections (systems)

**4.1.2. Institutional capacity sensitivity analysis**

The primary purpose of this section is to illustrate how sensitivity analysis coupled with SD modeling can help understand the variability among interacting sectors over time. In this context, a sector is any unique and relatively mutually exclusive area that interacts with other sectors within the same system (e.g., an individual SDG among the entire SDG framework as was depicted previously in the SDG interconnection model from Section 4.1.1). This concept and model can be expanded to other areas – so long as context involves multiple interacting sectors – such as those in

an economy and of the WELFC nexus (i.e., water, energy, land, food, and climate from Sector 2.2.1). In this section, the model is expanded to include community development using the community capacity assessment (CCA) framework. The CCA treats a community as having multiple interacting capacities (i.e., the sectors), or the ability to supply various services crucial to the WELFC nexus and the community's overall development (see Amadei and Zelinka 2018). In CCA there are eight capacities: service, institutional, human resources, technical resources, economic/financial, energy, environmental, and social/cultural.

In collaboration with Suleiman Halasah, a Jordanian researcher from the Ben-Gurion University of the Negev and the Arava Institute for Environmental Studies, a model was constructed to analyze communities in the West Bank using CCA (the paper is forthcoming). His earlier work (also forthcoming; Halasah et al. 2018) determined that for a set of 14 communities in the West Bank institutional capacity (IC) was the weakest link, meaning that it inhibited the overall development of those communities more than the effects of the seven other capacities. IC being the weakest link is not surprising as political and governance factors – which institutions are functionally synonymous – are significant barriers to progress in the developing world (see Section 2.3, Appendix E; Blackburn et al. 2006; d'Agostino et al. 2016; Dimant and Tosato 2017; among many others in the corruption and economic development literatures). Although the focus of that work was on the success of household-scale off-grid greywater treatment systems, it is a proxy for development for those communities, specifically, and global development, broadly.

IC measures the availability and quality of governance institutions and identifies the type of organizational structure needed for a given technology. Governance institutions also include the organization's laws, processes, or procedures that are necessary for a given technology to succeed in a community (Ahmad 2004), as well as the body of legislation and associated regulation, regulatory standards and codes, administrative authority, administrative process, and stable and good governance (Amadei and Zelinka 2018). IC can be thought of as the political pillar of sustainable development and is closely aligned with SDG 16 regarding governance.

Because IC was determined to be the weakest link it functions as a leverage point – the most efficient location to cause system-wide improvement in the community and an opportunity to most efficiently make [positive] changes. Weak IC (i.e., poor governance) leads to the ineffective provisioning of services. By improving a community's IC, its technical and management capabilities can also improve because of the positive relationships between these areas. Developing community capacity requires not just the existence of institutions, but for those institutions to be able to

maintain the improved performance levels that have been developed into the future, especially when external assistance is withdrawn (Lusthaus et al. 1999). As a leverage point, IC was the best capacity to model and became the focus of the sensitivity analysis in this section. The environmental and the social/cultural capacities were omitted because they were insignificant for the communities and there was not enough data to sufficiently analyze them.

To measure the effect of IC on community development, four scenarios were devised (Table 11). Exact values for the parameters will be in the forthcoming paper and are omitted from this dissertation. The first two scenarios are virtually identical to the SDG interconnection model in the previous section (Figure 20 and Figure 21) – one graph showing no interactions among the sectors and a second that includes those interactions, Scenario A and B in Figure 22 and Figure 23, respectively. Scenarios C and D are Scenario B with the inclusion of the sensitivity analysis. Scenario C varies the IC change rate (i.e., the rate at which IC changes per year, analogous to the growth rate of a population) that signifies investing directly in improving IC only without consideration for other capacities and interconnections. Scenario C is a relatively reductionist approach for addressing community development, as it can be thought of throwing money at a problem and hoping it helps. Scenario D varies the interconnection values for IC and is comparable focusing on the policies for the community (i.e., the synergies from IC to the other capacities). These interconnections can be thought of as strong synergies, partnerships/collaborations, spill-over effects, and broad but targeted policy interventions. The interconnection from IC to the energy capacity, for example, is focusing on energy policy. The same can be said for the other interconnections. It is a much more systems-oriented approach by addressing leverage points that requires a deeper understanding of the community or communities being modeled.

Table 11. Overview of the four scenarios

	<b>reductionist (linear) approach</b>	<b>systems approach</b>
<b>comparative analysis</b>	<i>Scenario A</i> interconnection values are zero; change rate values are default	<i>Scenario B</i> interconnection values are default; change rate values are default
<b>sensitivity analysis</b>	<i>Scenario C</i> interconnection values are default; change rate for IC varies; all other changes rates are default	<i>Scenario D</i> interconnection values for IC vary; all other interconnection values are default; all change rate values are default

The results for Scenario A (Figure 22) and Scenario B (Figure 23) exhibit a similar pattern as with the SDGs (Figure 20 that has no interconnections and Figure 21 that includes those interactions). Scenario A shows that the capacities improve at about the same rate (their change rates were all the same). Scenario B shows that they improve at different rates due to the effect of the varying the interconnection values of IC on the other capacities. Energy

capacity and economic/financial capacity exhibited the most significant changes comparably as a result of varying the IC interconnection values, implying that they were most sensitive to institutional factors within the communities. This makes sense because energy and economic factors are heavily influenced by government policies outside the community (exogenous), while human resource and technical resource capacities are primarily affected by internal factors (endogenous), hence their nearly identical trajectories in Figure 23.

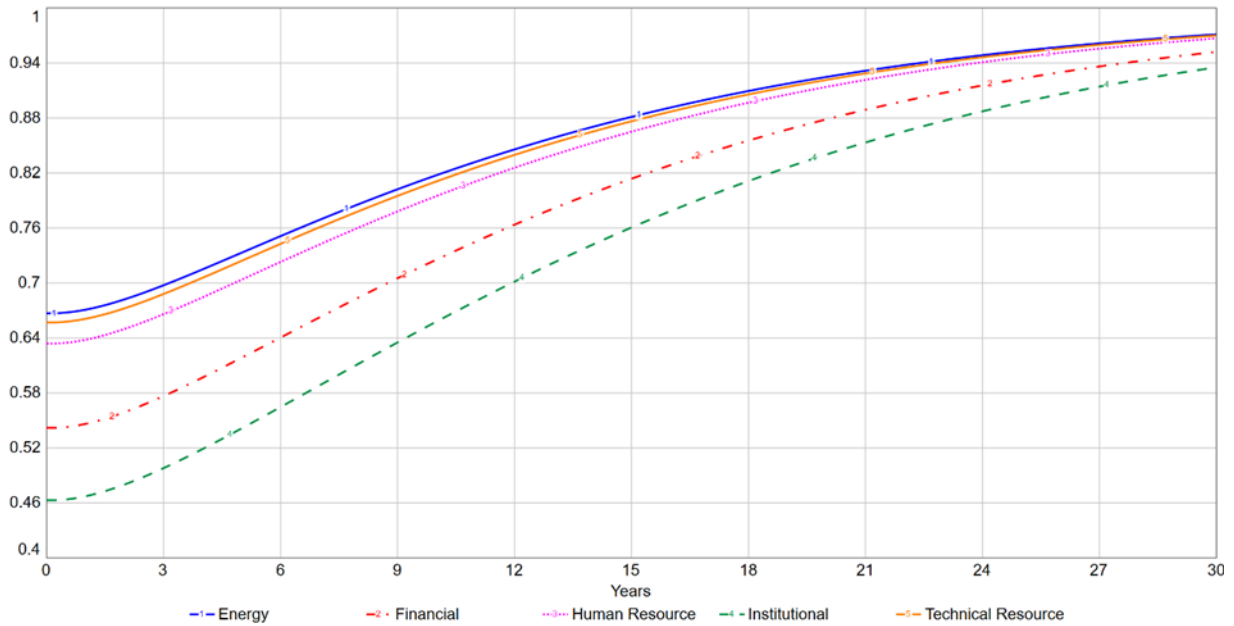


Figure 22. Scenario A: Capacity factors; x-axis represents simulation time; y-axis represents capacity from 0-1

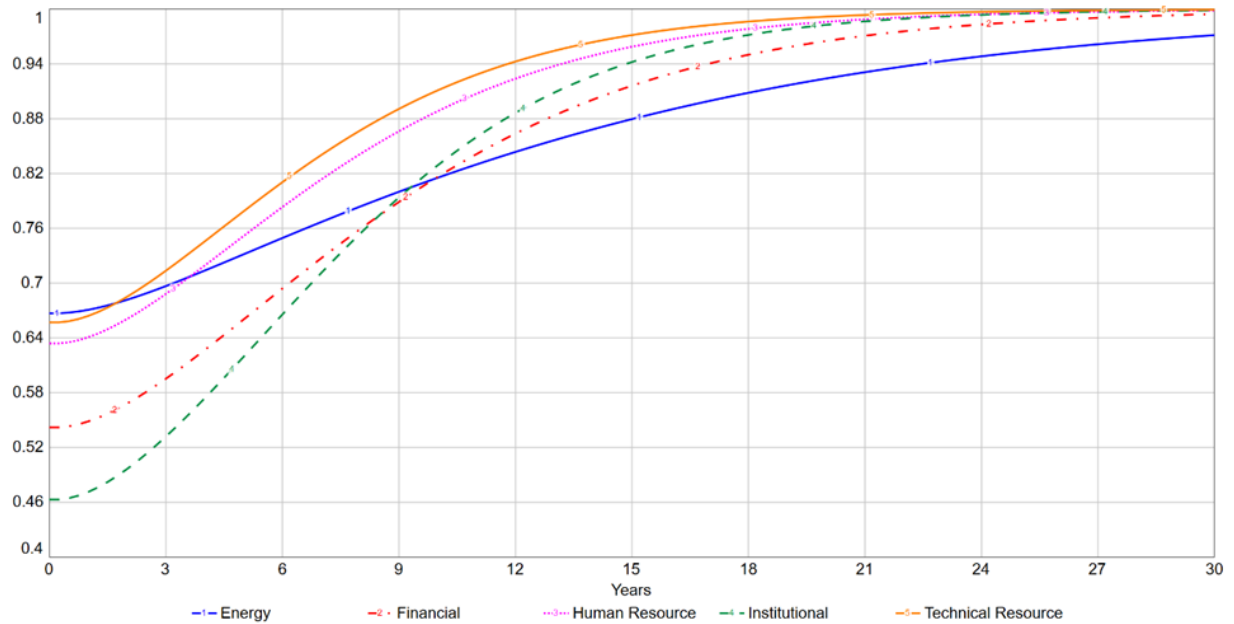


Figure 23. Scenario B: Capacity factors; x-axis represents simulation time; y-axis represents capacity from 0-1

The results for Scenario C are seen in Figure 24, Figure 25, Figure 26, and Figure 27 and Scenario D are seen in Figure 28, Figure 29, Figure 30, and Figure 31 on the following page. Scenario C and D are sensitivity analysis, which means they are presented with confidence intervals (CI), that describe the range of all total possibilities over time among all the simulations. In each graph three separate CIs, along with the mean, are shown: one band for 33% of all values, another for 67% of all values, and the last which includes all possibilities.

Scenario C alters the change rate for IC and as a result, exhibits only a minor variation in the outcomes of the other capacities. Directly addressing IC will not have a significant effect on the other capacities regardless of the outcome of IC (i.e., the effect of IC will be mostly independent and siloed from the rest of the community). Thus, altering the change rate of IC, or any other capacity for that matter, is not a systems-oriented approach as it does not focus on the interconnections from IC to the other capacities (like Scenario D). The effects in Scenario D are much more pronounced than in Scenario C. This means that focusing on the interconnections (i.e., policies) can function as a more efficient and sometimes cheaper alternative to directly focusing on improving the overall IC. The variation is more extensive, both positively and negatively, which implies that even though policies can have a more significant positive effect they can have larger adverse effect on the community. Thus, care must be taken to strategize effective policies, which will require a deeper understanding of the specific community's needs. Without context and knowledge of the community, policies can do more harm than good. The main implication of these findings is that using a systems approach by focusing on the interconnection among capacities (Scenario D) is potentially a more effective leverage point since it can elicit a more significant impact than just focusing on the nominal change rate of IC (Scenario C).

Even with the simple comparison between Scenarios A and B, SD modeling enables a visual representation of the complex interactions of a system (usually in a graphical format) beyond most other methods or tools. Someone with little or no knowledge of systems or a specific topic (capacity factor analysis, wastewater treatment systems, and the West Bank, in this case) will be able to make more informed decisions more quickly on these complex issues. Scenarios C and D take this comparison (Scenario A and B) one step further by adding randomness into the simulations with sensitivity analyses. This randomness, which is inherent to anthropocentric systems and ubiquitous across sustainable development, is a proxy to chaotic systems. The sensitivity analyses in each scenario is a way to include possible unknowns. With complex systems, the unknowns are known, but for chaotic systems, they are not. Including randomness expands the model's capabilities from complex systems to chaotic systems.

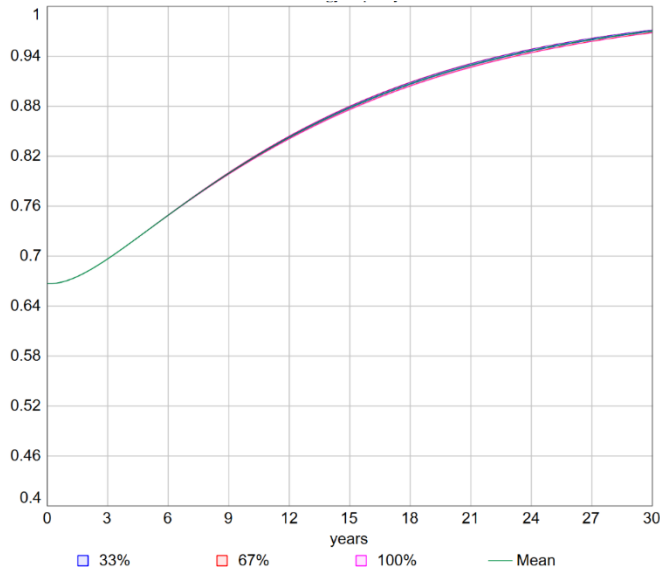


Figure 24. Scenario C: energy capacity; x-axis is time; y-axis is capacity

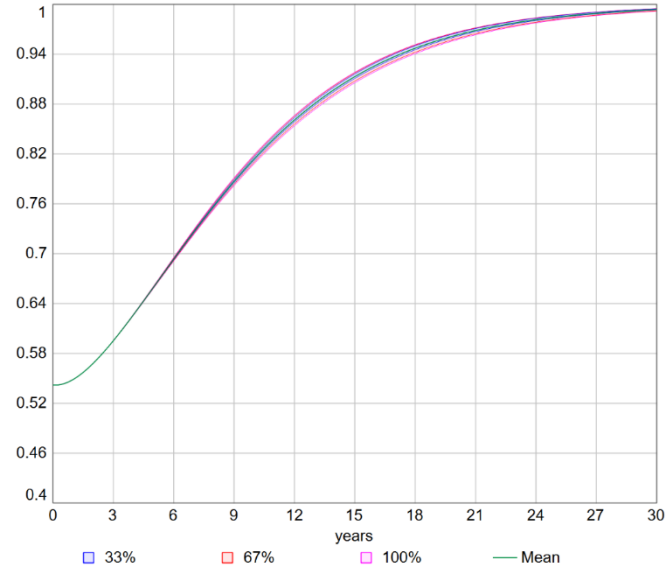


Figure 25. Scenario C: financial capacity; x-axis is time; y-axis is capacity

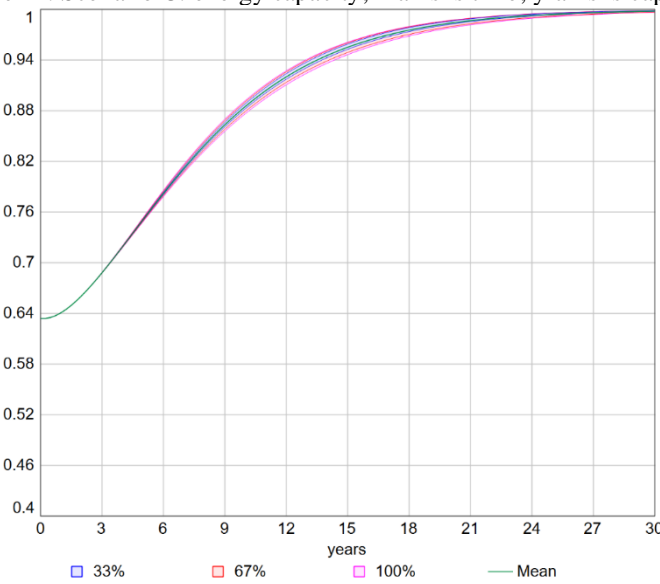


Figure 26. Scenario C: human capacity; x-axis is time; y-axis is capacity

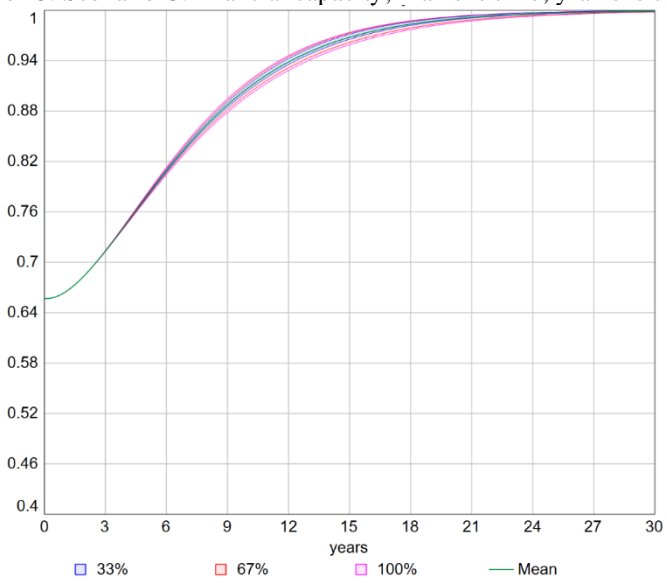


Figure 27. Scenario C: technical capacity; x-axis is time; y-axis is capacity

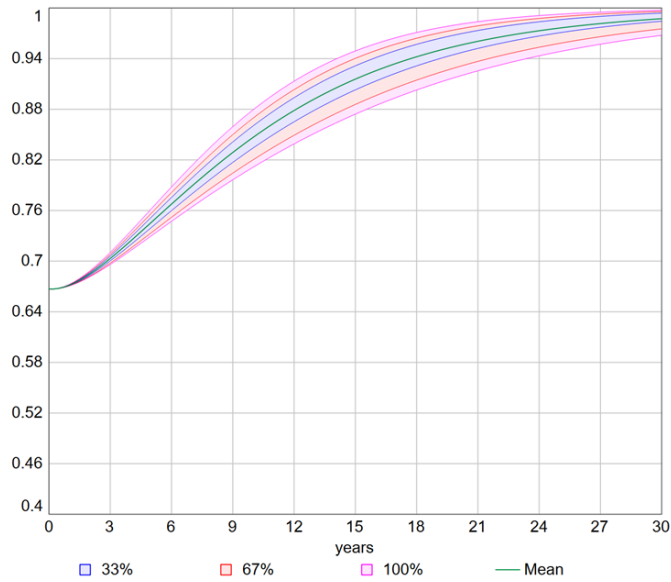


Figure 28. Scenario D: energy capacity; x-axis is time; y-axis is capacity

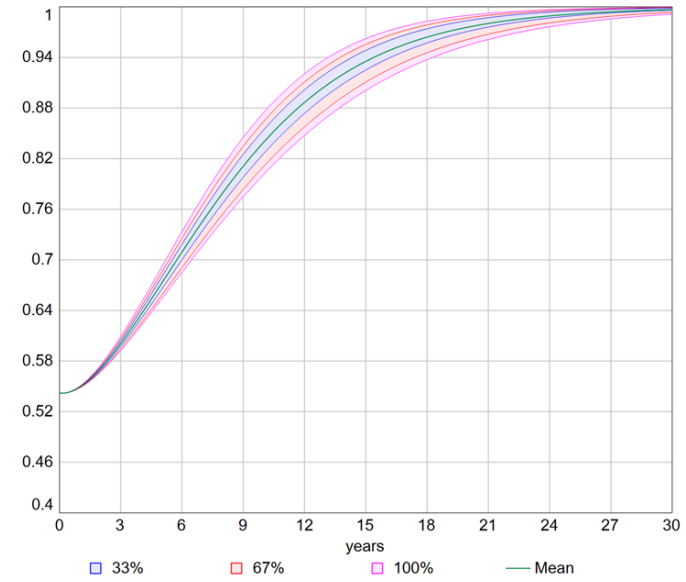


Figure 29. Scenario D: financial capacity; x-axis is time; y-axis is capacity

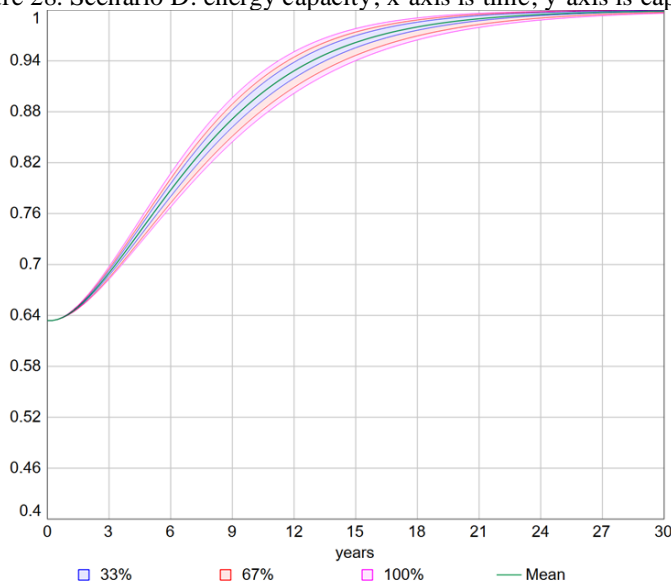


Figure 30. Scenario D: human capacity; x-axis is time; y-axis is capacity

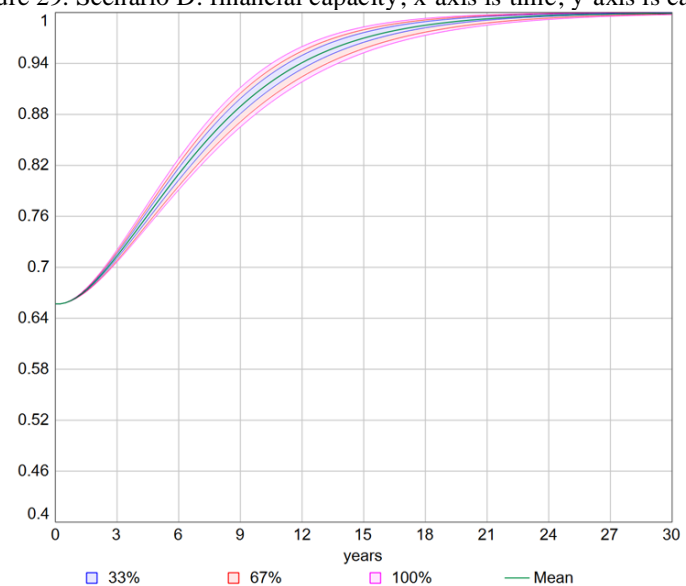


Figure 31. Scenario D: technical capacity; x-axis is time; y-axis is capacity

### 4.1.3. Change-of-State archetype

This section builds on the archetypes that were discussed in Section 3.1.2 by introducing a new archetype, one specifically designed for use in system dynamics when modeling anthropocentric systems. This archetype, also called *logistic growth*, is based on S-shaped growth and appears throughout multiple fields of science. It has been used to model: (i) epidemics (susceptible-infected-recovered epidemiological model, also called SIR); (ii) innovation diffusion (logistic innovation diffusion model); and (iii) the market penetration of products (Bass diffusion model; (Sterman 2000). In short, S-shaped growth occurs when a group is acquiring something that they did not have before. As a generic “state A” turns into “state B,” “state B” exhibits an S-shaped pattern of growth. For instance, in epidemiology, this pattern appears when a potentially susceptible population becomes infected with an illness. In market innovation, it occurs when a population adopts a product or service. Finally, in population dynamics, it happens when population growth occurs under the constraints of an ecological carrying capacity. This change-of-state archetype was first devised to simulate how an individual sector changes over time (e.g., an economic sector, an individual SDG, or a sector – like water - in the WELF nexus) due to the allocation of resources or from other some outside intervention.

Logistic growth can be applied to various aspects of international development and aid and can model the dynamics of the Sustainable Development Goals (SDGs). The logistic growth behavior can be applied to all SDGs and their targets since they can be interpreted as going from not being adopted to being adopted (or implemented). In general, growth is initially slow after an SDG is first implemented, because it takes time (delay) to inform relevant agencies, propose projects, etc. Eventually, work toward addressing the SDG (project implementation phase) will reach its fastest rate (inflection point), at which point it will start to slow due to constraints such as “the last-mile problem,” an issue especially pervasive in sustainable development. It refers to the difficulty in reaching those last few people at the end of the line due to, for instance, their geographical remoteness and lack of access to capital (Balcik et al. 2008; Chambers 1983; Minten et al. 2013). The last mile problem is similar to the effect of saturation of products in a market and can be modeled the same way. Logistic growth also appears in human security (equality, safety, income, health, education, etc.), urban migration (urbanization), and resource availability, as in the WELF nexus (water security, energy security, land security, and food security), all of which are also represented by their own goal(s) and target(s) in the SDGs.



On the concept of logistic growth, a basic systems model can be constructed. (A detailed methodology exists in Appendix E – A Modified S-Shaped Growth Behavior to Model Complex Anthropocentric Systems). It is composed of two stocks connected with a biflow. This biflow represents the migration between two states of being. These states can be rural-to-urban migration, land-use change as land is developed, or the adoption of an idea like democracy. The generic terms for the two states are secure and insecure: people can either be food secure or insecure, impoverished or income secure, water secure or water insecure, etc. Most sectors in sustainable development are split between states. There is a general rate of change between the two states, and other external factors can affect why people migrate between the two states. The literature refers to this process as diffusion, so the general model can be called the insecure–secure diffusion model, but sustainable development deems the term “change-of-state” more appropriate (Figure 32).

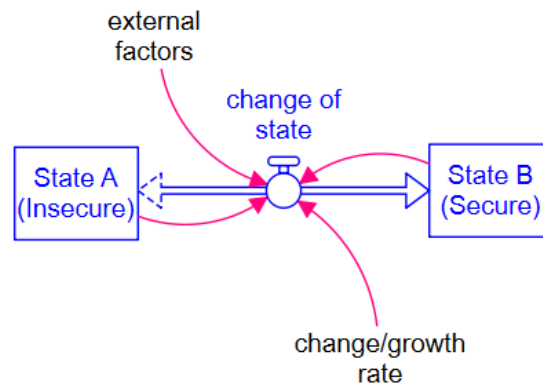


Figure 32. Insecure–secure diffusion (or change-of-state) system dynamics archetype

Figure 32 represents the simplest version of the change-of-state archetype, the **two-chambered form**. It is particularly useful when there are only two states, or when the model simulates more abstract concepts. For more complex and real-world situations, the change-of-state archetype needs to be expanded to include other versions of the archetype, each of which is designed for different uses.

Another version of the change-of-state archetype is the **extended linear form**. It is similar to the two-chambered version and can incorporate multiple states. For example, the extended linear form can be used to measure the income distributions of countries. The World Bank classifies countries into four groups: low-income, low middle-income, upper-middle-income, and high-income. To develop the extended linear form, the two-chamber model is expanded to depict these four groups, with one stock (i.e., the current income level or state) for each country group. A low-income country must first become low middle-income before it can graduate to higher income levels; it cannot

jump levels. For this reason, it must be linear. The structure of the archetype in this example would contain four groups of countries in each of those four income levels, with three biflows connecting them. The linear form can be slightly altered (converting biflows to uniflows) to model population dynamics and demographics, where each stock represents an age group.

A particular case of an extended linear form is represented in Figure 33 and consists of a **three-chambered triangular form**. This triangular form is useful for analyzing more complex urbanization processes by including a peri-urban group (i.e., suburbs, urban periphery, and low-to-medium density areas outside the city-prime). People in these areas can freely move to the other two: rural to urban and peri-urban; urban to rural and peri-urban, and peri-urban to rural and urban.

Although not described in this work, the triangular form can theoretically be expanded to a **four-chambered square form**, a five-chambered pentagonal form, etc., which could be useful for modeling highway networks where vehicles can only travel (flow) between exits, where they either continue or get off the highway. Essentially, this becomes a unique version of the linear form so that the ends of the line are connected to create a **circle form** (of sorts). This phenomenon will be left for others and future work to explore.

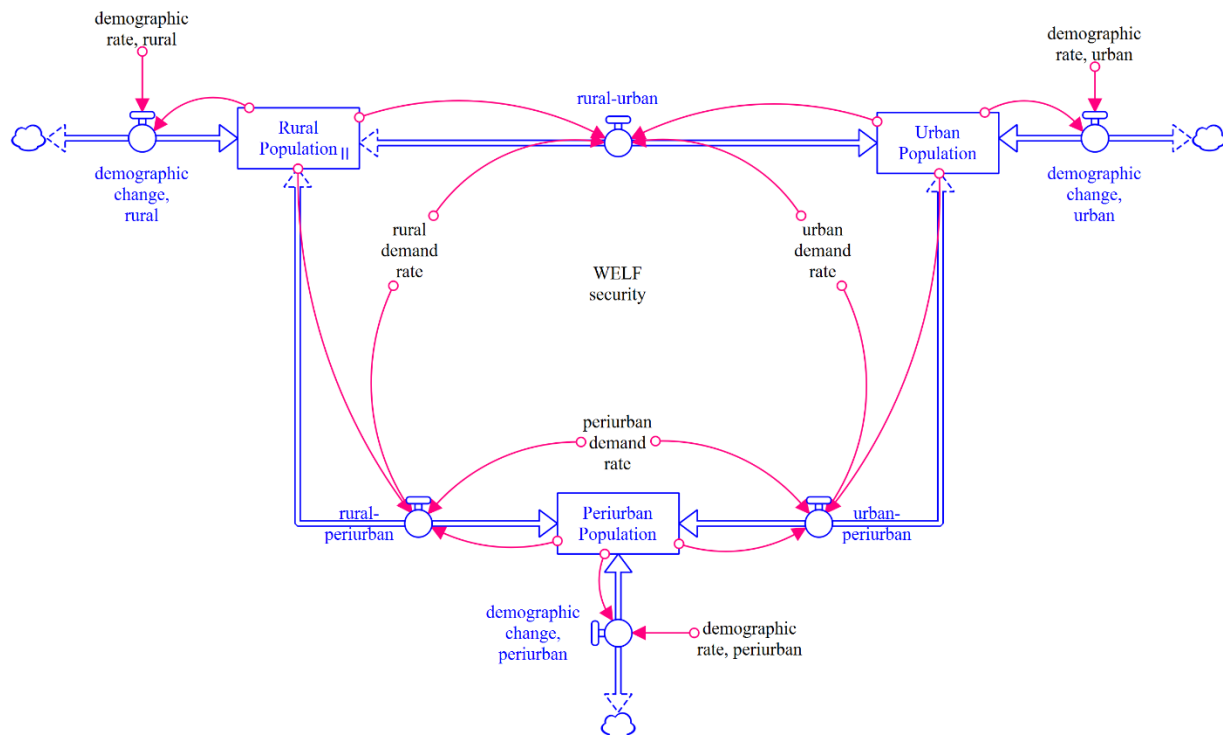


Figure 33. Three-chambered triangular form

The last type of stock-and-flow structure considered herein (although there are undoubtedly more), is shown in Figure 34. This **multi-chambered hierarchical form** is useful for modeling land-use changes or large nested systems within systems (income distributions between *and* within countries, for instance). This type can have any number of chambers, but it utilizes a central chamber from where individual “branches” emanate out. For the case of land-use change, as a population grows, land is developed for housing, which reduces the available land devoted to the environment. Since people require not only land on which to live but also land on which to grow crops and raise livestock, the various chambers are related and influence each other. For example, in order to feed a growing population, wild environmental land must be converted to agricultural land at a rate dependent on population growth. In that way, population is a driver for any two chambers connected by a biflow. Any number of chambers can be added. A fourth chamber can represent environmental degradation, which is indirectly a function of population growth due to the environmental impact of the other two chambers. If a policy is enacted that forms protected land like a national park, a fifth chamber can be included, as well.

Each chamber can be further subdivided into lower-level chambers that resemble the larger structure of Figure 34, resembling an increasingly complicated hierarchical structure. For example, developed land is realistically composed of various kinds of land use (e.g., residential, commercial, and industrial); food land can be devoted to livestock and plants; the environment can be pristine, untouched land, and national parks; and degraded land can be subject to pollution, desertification, etc. These subcategories are what make the structure hierarchical, although less complicated models probably do not require extra levels (subcategories). Residential land, for instance, can be further categorized by population density of that residential land (i.e., rural, peri-urban, and urban land use) or anything the user desires.

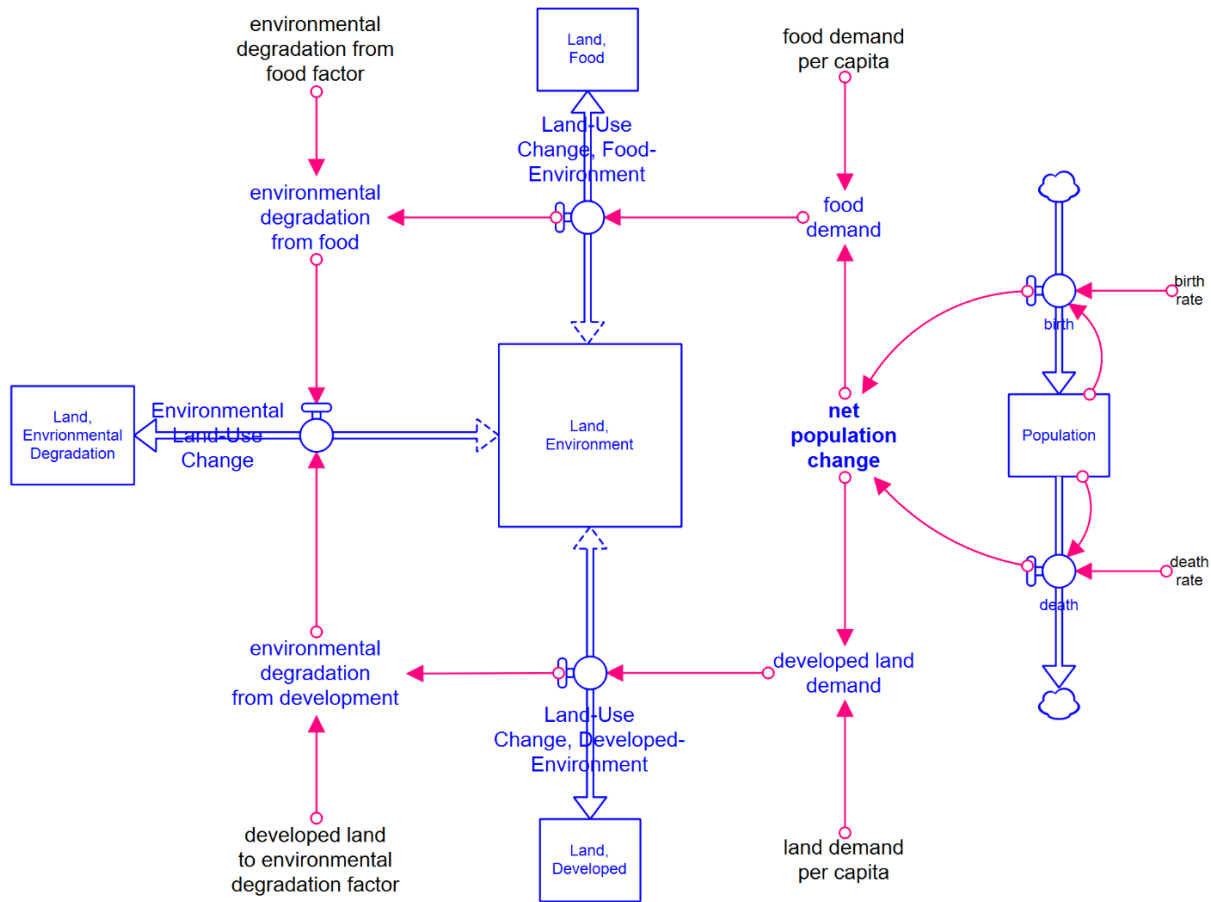


Figure 34. Hierarchical multi-chambered form

#### 4.2. Socio-political systems

Qualitative structural data analysis (QSDA; Section 3.3) was initially designed to analyze the natural resource curse. However, it was successfully applied not only to corruption's interactions with the natural resource sector (Section 4.2.1, Figure 35), but also to systems archetypes in the Palestinian-Israeli conflict (Section 4.2.2, Figure 36) and hydropolitics of the Jordan River basin (Section 4.2.3, Figure 37). As conflict and hydropolitics were included in the analysis, it became apparent that QSDA could be applied to many different issues, so, for this reason, QSDA was expanded to a standardized methodology that can be applied to most qualitative social issues. The following sections provide a proof-of-concept of QSDA using those three individual topics, although conflict and hydropolitics share much in common. Each section herein should be read alongside the associated casual-loop diagrams at the end of each section they explain one another, and they reiterate and portray the application of QSDA.

#### 4.2.1. Natural resource curse

QSDA was applied to the causal mechanisms (modernization, repression, and rentier effects) of the natural resource curse in Section 2.3.3. Figure 35 contains each mechanism in the form of a causal loop. It also includes some important stocks and flows for resources, government treasury, social interest groups, and government approval, the last of which is based on the insecure-secure model. These three mechanisms are described exactly how they appear, and the italicized words that follow are the verbatim variables in Figure 35.

The **modernization effect** reduces *socioeconomic development spending*, which then reduces *satisfaction with the government* increasing *accountability*. However, lower spending decreases the rate of economic *modernization and industrialization*. An (agricultural-based) economy that is not modernizing has little *resource demand* and therefore little need for *skilled labor* lowering the demand for *education*. Less educated populations demand less accountability than more educated people.

The **repression effect** alters budget allocations among various sectors – primarily from socioeconomic areas – to *national security spending*, which enables the government to forcibly reduce opposition making it easier to engage in corrupt acts as there is also a repressed demand for accountability. The repression effect can be seen by increased spending for national security and the military, and as a result, it is most often projected through hard military power.

The **rentier effect** spends the rents generated from overexploitation of a country's natural resources through corrupt actions and “re-invests” those profits to perpetuate political corruption further. The rentier effect refers to the added capacity to be corrupt as a direct result of the rents generated from previously corrupt acts in the natural resource sector; this is accomplished through *patronage*, which bribes people with positions of power. Rents can also be used to repress *social group formation rate* that over time reduces civil society opposition. Lastly, the rents can be used to alter the *tax policy* reducing the *tax rate*, which has the side effect of reducing overall government revenue. By increases patronage, reducing taxes, and repressing opposition groups the rentier effect will reduce the demand for accountability, which will further incentivize and make it easier for government officials to engage in corrupt acts.

These combined effects (Figure 35) are what govern the natural resource curse. Corruption siphons funds generated through natural resources to perpetuate and augment political and corporate corruption. Corrupt officials are held less accountable for their actions and have less pressure to improve the institutional capacity of their government. They will want to increase their rents and, as a result, will further engage in patronage, over-exploitative

resource extraction, and destructive environmental policy. This explains why the natural resource curse is a positive feedback loop. As resource extraction increases, government officials get richer and are further incentivized to extract more resources and engage in corrupt acts.

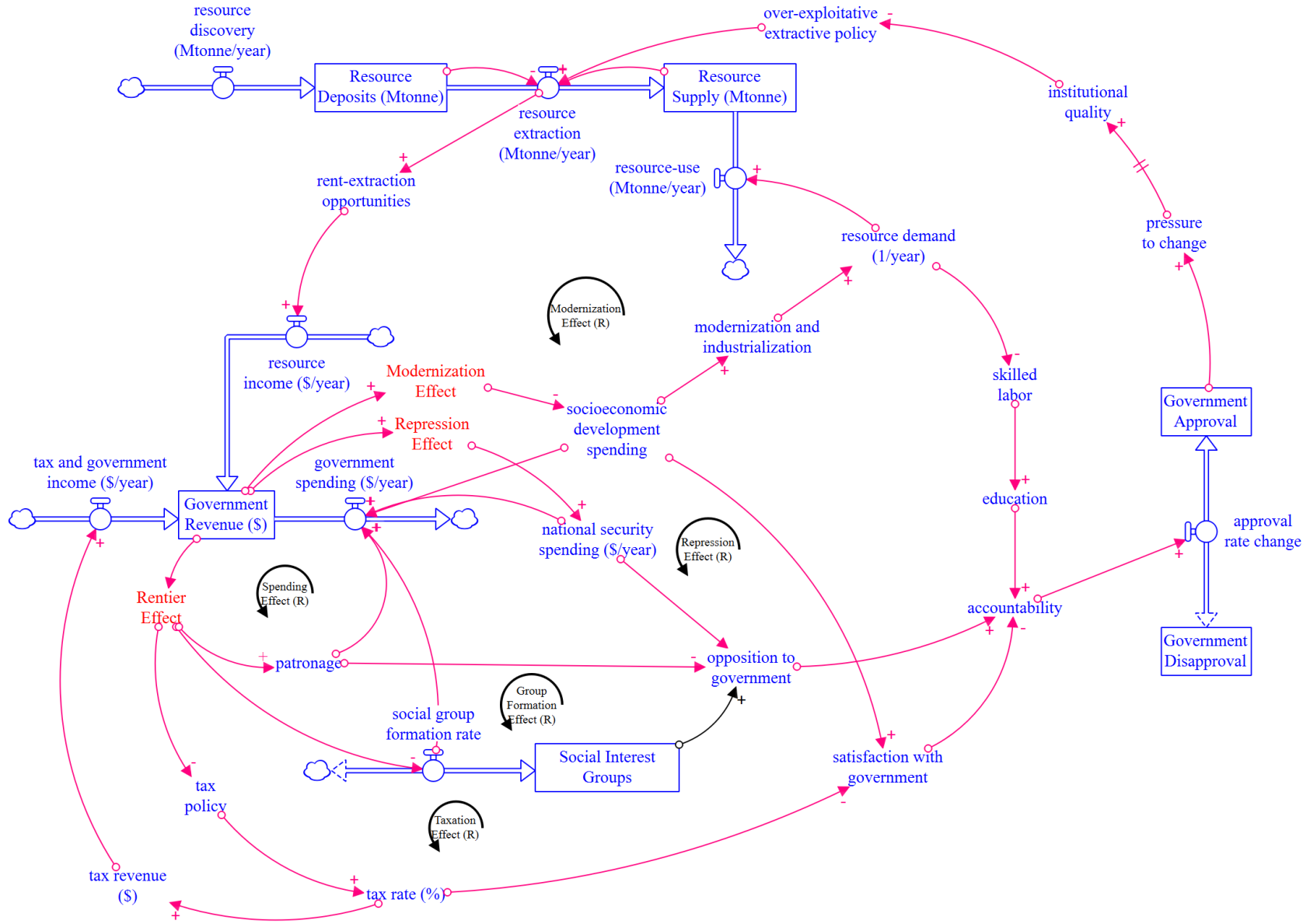


Figure 35. Stock-and-flow diagram of the natural resource curse

#### 4.2.2. Palestinian-Israeli conflict: Archetypes

Figure 36 uses QSDA with the system archetypes to represent the Palestinian-Israeli conflict (PIC) in the form of a causal-loop diagram. The italicized words that follow are the verbatim variables in Figure 36. Escalation, Conflicting/Drifting Goals, and Shifting the Burden are the three most essential archetypes that describe the PIC, especially Escalation. In **Escalation**, both sides see *consequences of conflict* leading to *humiliation and injustice* and *fear and anger*. Humiliation and injustice lead to *victimization* and *denial of aggression* against the other side, increasing the likelihood of *using military or political and economic force or power*, which further validates the *perceived threats and rights to exist*. Fear and anger, meanwhile, lead to the *justification of aggression against the other side* and *support for violence and extremist groups*. Ultimately, escalation leads to *pressure on the leaders to be tough against the other side*, eventually causing increased tensions and *attempts to undermine the other*. Eventually, violent conflict will erupt, causing *oppression, losses, and occupation*, further continuing the cycle of escalation.

In conflict, there are often multiple viewpoints, even on the same side. **Conflicting Goals** of various groups on one side cause a positive feedback loop. When one's own side cannot agree, it becomes more difficult to come to a peaceful solution or end the conflict.

**Shifting the Burden** connects *attempts to undermine the other side* to *victimization*. In conflict, this can be done through propaganda or other forms of influence that portray the enemy in ways that anger your population and call them to action. It can increase the political capital necessary to go to war, for example.

**Long-term peace efforts**, while not an archetype, are important and connect international factors to the conflict. The international community can be pressured to step in if the conflict becomes more violent and the losses mount when the conflict effectively passes a threshold of international involvement. The United Nations Peacekeeping Operations (UNPKO) serve this purpose. Also, sustained war weariness can cause domestic groups to overcome the violence and finally negotiate. Other countries can threaten sanctions, enact embargos, and apply other geo-economic tools, or use joint military force (hard power) as a geopolitical tool.



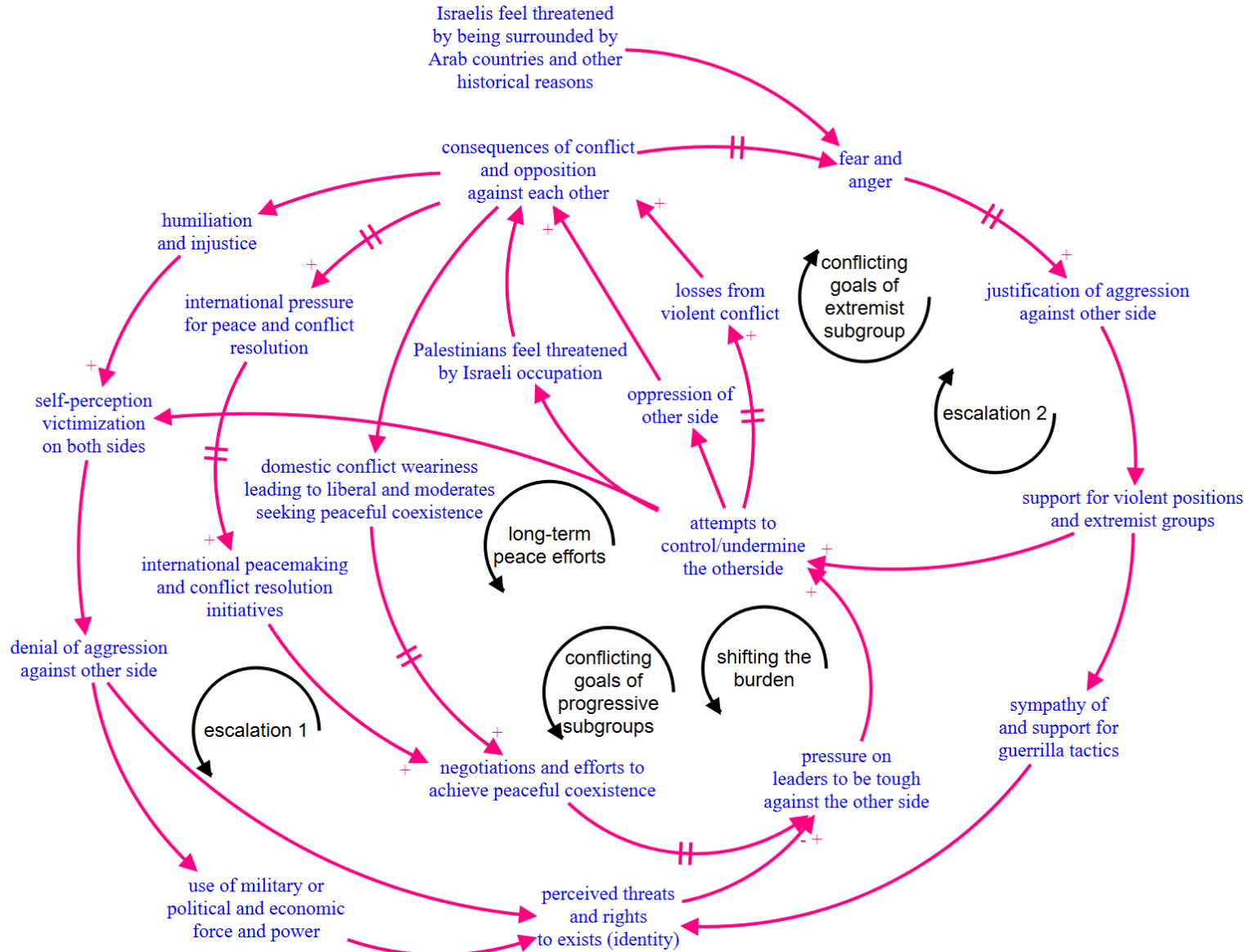


Figure 36. Causal-loop diagram of the Palestinian-Israeli conflict

#### 4.2.3. Palestinian-Israeli conflict: Hydropolitical perspective

QSDA is applied to the interest-power-position and hydro-hegemon frameworks from hydropolitics in Section 2.5.3. Hydropolitics is positioned at the center of Figure 37, and it connects with a high-level view of the Palestinian-Israeli conflict as well as human development and environmental factors for in the Middle East. The effects of implementing various solutions to the conflict fall into two categories: those that increase democratization and have weak ethnoreligious influences, and those that decrease democratization and have strong ethnoreligious influences. As the asymmetry of power favors Israel (as discussed in Sections 2.4 and 2.5, the Israeli government can more easily ignore international laws and water rights thereby generally maintaining the business-as-usual. The significant power differential with Palestine means that Israel is the hydro-hegemon in the region. Because of Israel's hydropolitical hegemony, it can directly affect human development and facilitate or hinder peace. Israel is a leverage point.

There are two domestic pathways for reaching peace or perpetuating the conflict, one that leads to cooperation, accountability, and transparency, and overall good governance through the **bi-national Democracy, secular Palestine, the confederation, or the federation models**, while the other is **business-as-usual** that will most likely result in an **Israeli apartheid state** or the improbable **Palestinian Islamic state**. The crux is cooperation, and all solutions depend on and influence cooperation. With cooperation, there is trust that is built up over time, lowering tensions and the chances of violence. Trust is essential for negotiations.

*Transboundary water governance* can play a crucial role in how the solutions play out. Any transboundary issues (international water management, pollution, etc.) require high levels of trust, so by adequately managing water that spans international borders, trust should theoretically be built, if that cooperation can be maintained. In doing so, *water withdrawals* decrease. Depending on the specific policies in a water governance regime, more available water (from fewer water withdrawals) can affect *economic growth and development*. If there are positive effects on the economy, people might *increase their consumption habits*, possibly improving the economy, which would disincentivize the continued proper management of transboundary water resources. This process, in short, is the Tragedy of the Commons. The water governance system must ensure that the Tragedy of the Commons does not occur. With improving levels of economic development, better *water treatment infrastructure* (including desalination) can be built and maintained, but the consumption habits will probably increase *industrial and water polluting activities*. If this economic development can be sustainable, it will eventually alter population growth patterns nationally.

Unique to Israel is its *demographic policy*, which directly affects population growth patterns for specific demographics in Israel and is usually a function of religiosity (i.e., Haredi Orthodox Jews have much higher population growth rates than secular Jews). The demographic policy aims to maintain the Jewish majority, which today represents about 75% of the population, versus the minority Arab population, which is currently less than 21%. Improving water infrastructure, increasing consumptive habits, and changing populations all affect *climate change and environmental degradation*, as they all strain water resources; this causes an increased **interest** in maintaining water resources. Depending on the **geographic position** and relative **power**, interest in dwindling water resources augments the likelihood of a water-induced event (i.e., conflict and violence) from happening. Many structural factors determine how that event unfolds and whether it leads to cooperation or conflict. For instance, *international involvement* can act as a dominant (endogenous and exogenous) factor that can cause variability in the system; most of the other factors focus on domestic (endogenous) factors. International involvement is influenced by factors both inside and outside the system.

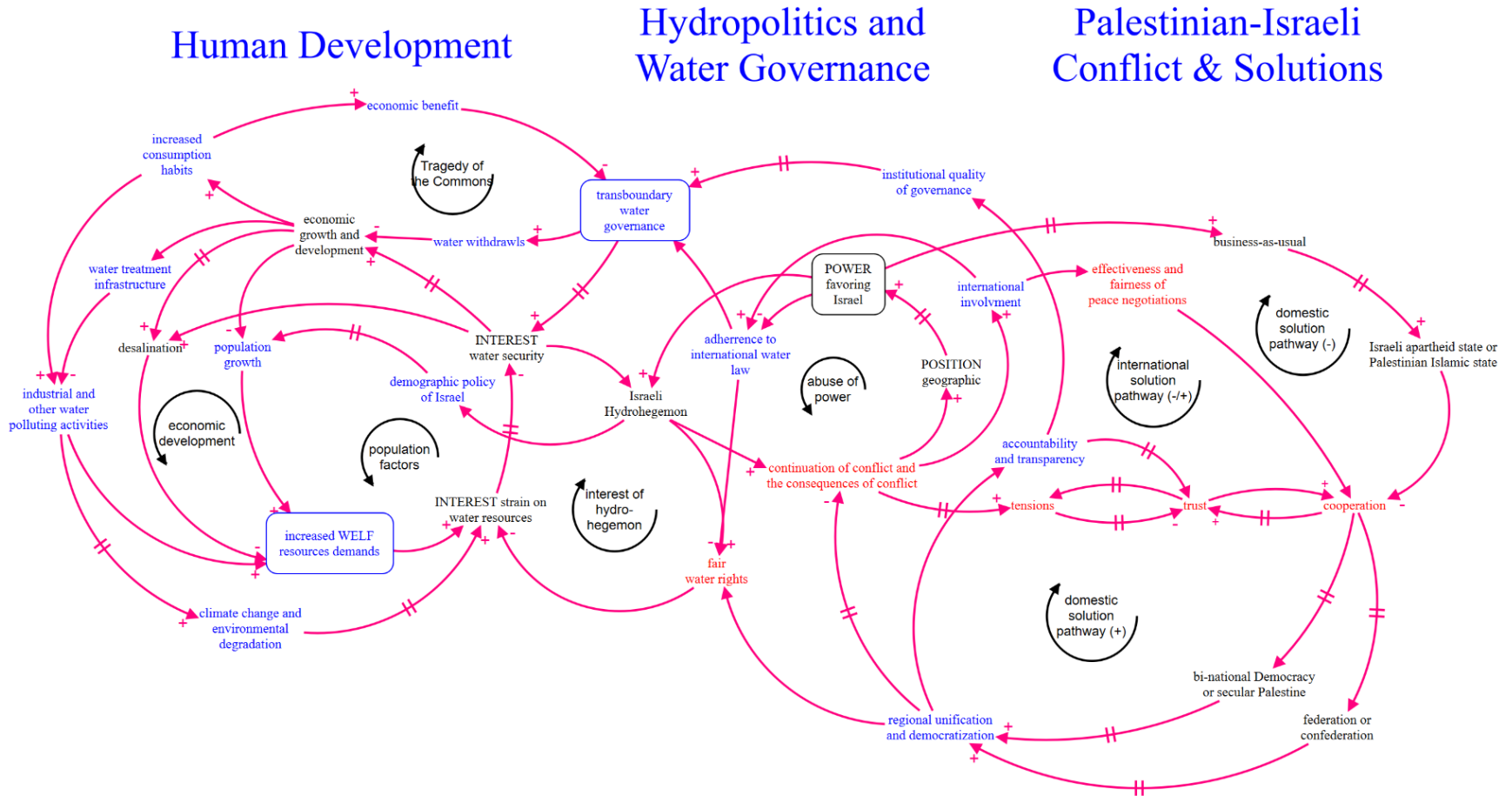


Figure 37. Causal-loop diagram of hydropolitics

## 5. CONCLUSIONS

The goal of this work was to analyze the complex issues inherent to sustainable development (Chapter 2) that transcend multiple disciplines using systems-based tools and methods (Chapter 3). The systems approach yields insights beyond what traditional linear thinking is capable, aggregating knowledge from many fields to produce a nearly complete picture of an issue (Chapter 3.4). This approach requires and advocates for transdisciplinary collaboration and to adopt a systems thinking mindset among a diverse group of researchers from both the technical and hard sciences and the social sciences. The methods employed by engineers and technical scientists (primarily quantitative) generally differ from those utilized by social scientists (generally qualitative): the systems approach proposed herein used quantitative (Section 3.2) and qualitative (Section 3.3) methods. Parts of the quantitative and qualitative methods were coupled to produce a hybrid methodology (Section 3.3.1) that can serve as a tool to be used by all scientists and engineers, regardless of their background and focus. The focus of this hybrid methodology is to standardize the process through which the qualitative understanding (the realm of social scientists) of a complex issue can be utilized to produce a valid quantitative model (the realm of technical scientists and engineers). In doing so, the results can be more representative of the real-world issue so that decision-makers can craft better strategies for progressing sustainable development (the realm of policymakers, NGOs, IGOs, and governments).

### 5.1. Main contributions and limitations of systems approaches

Sustainable development is an applied discipline (similar to engineering, a.k.a. the applied sciences), but one with a particular goal in mind: to improve the well-being of every human without degrading the environment and exceeding Earth's ecological capacity. That goal is technically attainable and needs to be the main driving force for humanity, but "most people in our modern society, and especially our large social institutions, subscribe to the concepts of an outdated worldview, a perception of reality inadequate for dealing with our overpopulated, globally interconnected world" (Capra and Luisi 2016). Linear thinking – that outdated worldview dominating scientific reasoning over the last 500 years – is no longer sufficient to solve contemporary complex, ill-defined, and messy problems, namely rapid population growth, conflict, environmental degradation, and climate change among others. In a letter published in the *New York Times* (1946), Albert Einstein wrote that "a new type of thinking is essential if [humanity] is to survive and move toward higher levels." The letter was meant to address the challenges of the newly invented atomic weapons, but the quote fits any complex issue today. Systems thinking is that new type of thinking, and with more work like that which was presented in this paper, this thinking can drive the sustainability goals of the

future and preserve human life for all generations to come. Systems provide the overall approach for genuinely understanding and effectively strategizing for complex global challenges.

The capacity for systems approaches, namely system dynamics (SD), to understand these large-scale complex issues is also a limitation. SD was primarily designed for macro-scale issues, so when the scale of challenges becomes smaller (i.e., more local), the importance of context grows while the accuracy and precision (and therefore effectiveness) of SD modeling will frequently diminish. SD excels at understanding and modeling the strategy-level (the overall system) trends and connections and causal feedback mechanisms in the overall system, but other tools and methods, such as agent-based modeling, should be used at smaller scales.

At smaller scales, the influence of various issues and errors in the model or data can become more extreme, but at larger scales (or scope) where system dynamics operate, the overall effect of something is distributed evenly over the entire system. I.e., the propagation of errors is naturally mitigated in system dynamics – but not eliminated. For example, if one village in a region were significantly more prosperous than its neighbors for whatever reason than looking solely at that village would invalidate the model's use for other villages; when all villages in the region are included the effect of that "outlier" village is less pronounced in the results. However, at the scales that systems operate, the needs the region supersede the needs of any individual village; that implies that the utility of the region is maximized at the potential expense of one or a minority. Nested models operating at smaller scales can be constructed and added to the model that *could* improve the effectiveness of the SD models at smaller scales, but doing so would considerably increase the model's complexity, increasing the potential for error, the propagation of any error, time and effort, and computational power requirements. Essentially, SD forces the researcher to balance the trade-offs between the needs to understand the overall picture of the system and its general trends with the scale and precision of the model and its input data. Furthermore, the data that informs system dynamics models are more accurate and available at larger-scales, but that is not something unique to SD modeling but because systems operate at these larger scale data is more readily available. Nations might keep track of specific pieces of data like GDP per capita, but rural villages might not. With that being said, causal-loop and stock-and-flow diagrams can be applied at smaller scales because they do not rely on difficult to acquire quantitative information but doing so would yield a less precision general view of an issue.

Many times, all that is needed is a general understanding of complex issues to make strategies to address them. Systems can help to frame a problem to produce a map of the problem. Systems can be used to clearly explain complex systems in a simple manner to decision makers and for training and education purposes. Training people to think in systems can reduce unintended consequences in their decision making. Instead of being reactionary to problems, humanity can avoid them from ever happening at all.

Just with any other method or tool, SD should be used for the right situation. When a large-scale view of a complex issue is all that is required, merely looking at it from a systems perspective can be incredibly insightful. Simple causal-loop diagrams can further aid in understand and producing effective strategies for solving problems. SD modeling can be used to produce more informative and quantitative results if needed. In other situations, other tools exist for modeling complex systems notably network analysis and agent-based modeling, among others. Many challenges that sustainable development endeavors to solve are aptly suited for SD, but there are many situations when other tools can be used to complement SD. In summary, pick the tool that is right for the job. SD is that tool when a complete systems view is needed, but general trends and quantitative models will suffice and often at larger scales, although not necessarily.

Systems thinking is a perspective that can be used in all areas of one's life. It is simply a different way of looking at the world that can overcome many of the problems caused by linear thinking. Systems thinking and approaches should be seriously advocated for within academia and governance institutions first as those are the places that are the best leverage points for change in our society. Governance is where many of those global-scale problems are the best addressed. Furthermore, governments and economic institutions are many times (but not all) the only entities with the power and capital do leverage any real effect (top-down approach), not including some massive multinational corporations. Civil society and grassroots movements (bottom-up approach) are essential, but without governments facilitating the process by creating legislation and providing resources many of the problems described throughout this dissertation would be too complex and pervasive for civil society to address alone.

Academia is where new insight and knowledge is generated and provides the intellectual foundation for solving complex issues. In academia, systems approaches should be leveraged to improve interdisciplinary collaboration among the many disciplines that sustainable development challenges span. No one field has the expertise

and tools to understand and address problems like conflict, megacities, environmental degradation, climate change, and so on it requires transdisciplinary collaboration among all fields.

## **5.2. Transdisciplinary collaboration and academic synergies**

The base systems approach (Sections 3.1 and 3.2) and the new QSDA (Section 3.3) method proposed in this dissertation represent the first truly analytical and standardized way to understand and model complex transdisciplinary issues in sustainable development. Section 3.1 applies the general systems thought-process to all the issues described in Chapter 2. Section 3.2 applies quantitative systems tools to some areas and challenges that are more familiar to engineers and technical scientists (see Section 2.1.3 on the SDGs and Section 2.2 on the nexus approach and urbanization). Section 3.3 is designed more for social issues, to enable social scientists to apply more quantitative methods to traditionally qualitative issues such as those in Sections 2.3, 2.4, and 2.5. Note that all methods can be applied to many aspects of an issue to varying extents.

Socio-political issues in sustainable development and anthropocentric systems such as corruption, conflict, and hydropolitics are mostly the focus of the social sciences, with most of the literature emanating specifically from political science and economics (Jancsics 2014). Although many of the issues overlap among many fields within the social sciences, there is relatively little collaborative work among them (Jancsics 2014; Torsello and Venard 2016) and even less collaboration with the technical sciences and engineering. For example, only a few articles use system dynamics to analyze corruption (see Méndez-Giraldo et al., 2017; Soto Torres et al., 2007; Ullah et al., 2012; Ullah & Arthanari, 2011). Jancsics (2014), a sociologist, notices this deficiency in the corruption literature and the social sciences in general; he describes the “lack of interdisciplinary communication about [complex socio-political issues], such that models developed by different academic disciplines are often isolated from each other.”

This homogenous approach to complex issues is inherently reductionist (i.e., siloed), and although it is a useful method for very focused issues, it is not valid for disciplinarily heterogenous challenges. Collaboration is the key to understanding the complexity of a problem that is fundamentally interconnected with many other areas and problems; it is not a new idea but has received little attention (Morris 2001) until recently. System sciences can bring together various fragmented parts through a transdisciplinary and collaborative approach. Social science methodologies, generally, tend to emphasize individual relationships and avoid the big picture. Although they are proficient at detailing individual factors and nuance to identify fundamental and underlying mechanisms (Denis 2016; Dent 2001; Goodin et al. 2010; Hong 2015), they can be subject to tunnel vision. Engineering methods can fill in data



gaps and present a set of quantitative tools and modeling techniques that social scientists might not often use in their work. Engineering, generally, is apt at understanding the big picture but misses nuance and specific theories when understanding social issues. Thus, to tackle sustainable development, both areas are needed in a complimentary manner.

The weaknesses in the social sciences, engineering, and system dynamics can be overcome, at least partially, through collaboration by focusing on the strengths of each. Indeed, a collaborative system is greater than the sum of its parts; emergent properties and methodologies arise from transdisciplinary collaboration and associated synergy, which can provide high-resolution details at a large scale to reveal how many mechanisms interact with one another, explore reverse causality, and detect indirect influences and effects. Perhaps most importantly, a systems approach can make complex and ill-defined social issues understandable to non-social-scientists, namely policy and decision makers. In short, this work argues that not only should the disciplines work together, but that the complexity and transdisciplinary nature of complex sustainable development issues require it.

It is the hope that a systems approach can improve the overall understanding of the issues described throughout this work and others similar issues. With new insights and better and more efficient evidence-based strategies, more and stronger partnerships can be formed among researchers, decision makers, development entities, and the people for whom these issues affect most. Transdisciplinary collaboration is the main leverage point for significantly furthering the mission of sustainable development to improve human well-being.

### **5.3. Agenda-2100: The Integrated Global Development Goals**

The deep historical background for the need for sustainable development was discussed in Section 2.1. The rest of chapter 2 introduced five key representative issues affecting global sustainable development – the SDGs, urban migration and population growth, corruption, conflict, and hydropolitics – from recent decades to the present day. Chapters 3 and 4 presented contemporary tools and novel methods that can and must be applied to those issues. Those four chapters represent the past and present of sustainable development from about 1300 through literally today. This last section looks into the future through 2100 – the top box of Figure 2 involving 800 years of global development.

The world will not accomplish all the 169 SDG targets, nor the 17 goals by 2030, so when Agenda-2030 comes to an end, humankind will need a new guiding set of global development principles – a new Agenda with a new time horizon. Some goals might be accomplished by some countries, but it is assured that not all countries will

meet all the goals. The SDGs are global in scale, and as such, if all people of the world cannot enjoy high levels of human development, there is more work to be done. The SDGs do not represent the first attempt at guiding global sustainable development, and they should not be the last. The end of Agenda-2030 will provide an opportunity to design a brand-new set of goals.

Using the systems approaches and tools presented herein, the third iteration of global development goals could be created in a more structured way, avoiding much of the confusion surrounding the implementation and analysis of the SDGs. The argument is that since political consensus, not academic consensus, influenced the design of the SDGs, the interconnections were not understood or accounted for in their creation. Relevant researchers were not sufficiently involved in devising the methodologies of the SDGs, so they were forced to learn how to understand those interactions after-the-fact.

The theoretical third set of goals past 2030, perhaps the Integrated Global Development Goals (IGDGs), should be carefully designed so that their interactions are understood from their outset and systematic measurement systems are based on specific, readily available indicators. Every goal should have a clear explanation of why it was included, a detailed explanation as to how it fits into the more complex system, measurement mechanisms and indicators detailing its progress, and a description of how to acquire the necessary data for those measurements and indicators. An advanced version of the SDG interconnection model detailed in Section 4.1.1 is one possible tool that could be used to simulate the goals' dynamic interactions based on those indicators. An interconnection model can simulate how the IGDGs interact before they are released, reducing any possible confusion during their implementation and monitoring phase.

Ideally, each country, city, or governing body will have a set of goals, based on the overall IGDGs, that are customized to their needs. Goals that don't pertain to a particular context and/or scale would not be included. For example, a high-income country might focus on reducing inequalities as opposed to raising the few remaining people below the poverty line out of it, or a landlocked country might not need to consider ocean fisheries in its development strategies. A resource-poor country should have additional environmental sustainability-oriented goals, as environmental sustainability is vital to their economy, development plans, and human health. A country that is modernizing could focus on energy efficiency and energy generated from renewable sources to bypass fossil fuel development. Developed countries are more responsible for climate change, and as a result, they would receive a

significant allocation of responsibility to address it when the goals are crafted. In short, the iGDGs need to be customized for each unique context and spatial scale.

The iGDGs must also be flexible, adaptive, and dynamic to adapt to a rapidly changing world. The world is chaotic, and it is impossible to truly see what will happen in the future. The goals should be built to account for shocks and unforeseen externalities. For example, another global economic depression might shift the goals to mitigating economic impact, protecting vulnerable groups, and alleviating ripple effects from the depression; thus, the iGDGs could act as economic buffers.

Lastly, because of the slow yet dynamic interactions of many global development processes, the iGDGs should be more long-term; concluding in 2100, hence Agenda-2100, seems appropriate. This time-frame would be sufficiently long to allow for slow-moving societal change to occur and roughly coincides with peak human population. For example, some sustainable processes take a generation (roughly 20 years) or more to see change (e.g., education, climate change, human rights, large infrastructure projects), but the MGDs and SDGs each lasted only 15 years – not even a generation – which is not long enough to see the effects or to adequately plan for long-term implementation strategies. This limitation can lead to problems associated with the systems archetypes, namely Drifting/Conflicting Goals, Fixes That Backfire, and Shifting the Burden. As the world becomes more complex over time, it will become exceedingly difficult to project what will happen into the future. The horizon will only go so far until chaotic variability becomes overwhelming to models and human understanding. Thus, while appropriate, pursuing these goals through 2100 would be a stretch, which is why adjustments will have to be made along the way. The iGDGs need to be a dynamic framework to account for shocks and randomness in the global system and the inherent chaos of the anthroposphere.

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## **Appendix A – A Systems Approach for Modeling Interactions Among the Sustainable Development Goals Part 1: Cross-Impact Network Analysis**

### **Abstract**

This paper advocates for a systems approach to analyzing the SDGs, categorized as an anthropocentric network. Cross-impact analysis, a semi-qualitative, soft-systems approach, is used to explore the connections among the SDGs. This approach can better capture the science underlying the SDGs' interactions in a generic manner compared to existing methods. The suggested approach enables users to: (i) get a better qualitative and quantitative understanding of how the SDGs interact; (ii) detect emerging patterns resulting from those interactions; (iii) use context-specific information about direct impacts to identify indirect effects; and (iv) identify leverage points hidden within the SDGs. The paper also discusses how network analysis complements cross-impact analysis as a mathematical approach to understanding patterns of interactions among the SDGs. The term *cross-impact network analysis* is proposed to describe the synergy between these two analytical methods. This paper is the first of two papers systematically analyzing the interactions between the SDGs.

**Keywords:** Sustainable Development Goals, Systems Approach, Systems Thinking, Interactions, Cross-Impact Analysis, Network Analysis, Soft System

## 1. Introduction

### 1.1. The Sustainable Development Goals

In 2015, the United Nations introduced the Sustainable Development Goals (SDGs) as a new 15-year long roadmap for worldwide sustainable development (United Nations, 2016). The 17 SDGs listed in Table A1 consist of 169 targets and 230 indicators. As described in the resolution adopted by the General Assembly on 25 September 2015, the aim of the SDG framework is to cultivate and expand humanity’s desire to “do good” while also organizing its ability to do so. The SDGs “...seek to build on the [previous] Millennium Development Goals (MDGs) and complete what they did not achieve” (United Nations General Assembly, 2015, p.1). In launching the SDGs, the General Assembly of the United Nations “recognize[d] that eradicating poverty in all its forms and dimensions (including extreme poverty) is the greatest global challenge and an indispensable requirement for sustainable development” (United Nations General Assembly, 2015, p. 1). To that end, the SDGs represent “a plan of action for people, planet, and prosperity,” which in addition to peace and partnership, define the five “P’s” of the mission of the SDGs. To accomplish that mission, there needs to be a “balance [between] the three dimensions of sustainable development: the economic, social, and environmental” (United Nations General Assembly, 2015, p. 3). It must be acknowledged that fulfilling the mission of sustainable development is indeed a daunting task, a formidable undertaking, unparalleled in human history.

Table A1. The 17 Sustainable Development Goals (adapted from Global Goals, 2016)

Goal	Title	Description
SDG 01	Poverty	End poverty in all its forms everywhere
SDG 02	Food Security	End hunger, achieve food security, and improved nutrition and promote sustainable agriculture
SDG 03	Health	Ensure healthy lives and promote well-being for all at all ages
SDG 04	Education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
SDG 05	Gender Equality	Achieve gender equality and empower all women and girls
SDG 06	Water and Sanitation	Ensure availability and sustainable management of water and sanitation for all
SDG 07	Energy	Ensure access to affordable, reliable, sustainable, and modern energy for all
SDG 08	Economy	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all
SDG 09	Infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation
SDG 10	Inequality	Reduce inequality within and among countries

<b>Goal</b>	<b>Title</b>	<b>Description</b>
SDG 11	Cities	Make cities and human settlements inclusive, safe, resilient, and sustainable
SDG 12	Consumption	Ensure sustainable consumption and production patterns
SDG 13	Climate	Take urgent action to combat climate change and its impacts
SDG 14	Ocean	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development
SDG 15	Land	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
SDG 16	Governance	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable, and inclusive institutions at all levels
SDG 17	Partnerships	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

It should be noted that even though there are many goals and targets, eradicating extreme poverty (SDG 01) is the ultimate goal, but only if it is accomplished in an environmentally benign way. The other goals can be understood as constraints and requirements that the goal of eradicating extreme poverty must also satisfy.

From the inception and ultimately the adoption of the SDGs, there has been an increasing interest in understanding and quantifying their interactions (Costanza et al., 2016). Multiple papers and reports have been produced by various organizations to identify important linkages among the SDGs, how the SDGs affect each other (Coopman, et al., 2016; ICSU & ISSC, 2015; Nilsson et al., 2017; Nilsson et al., 2013; Vladimirova & Le Blanc, 2016), and how to measure qualitatively or semi-quantitatively those interactions (ICSU & ISSC, 2015; Nilsson, et al., 2016; Nilsson et al., 2017; Sustainable Development Solutions Network, Schmidt-Traub et al., 2015). Other publications have looked at the interactions of the SDGs with other frameworks and international agreements such as the Paris Climate Agreement, most notably (Von Stechow et al., 2016).

## **1.2. Systems Thinking for the SDGs**

Even though it is recognized that the SDGs are interconnected, the authors are not aware of existing publications that analyze the effects of the SDG interactions in a systemic or integrated manner. However, some mathematical tools already exist in the literature that could be used for that purpose, such as (i) equations to calculate the indirect impacts (the effect due to the interconnections) from direct observations of a mathematical system (Bollen, 1987); (ii) the economic input-output and Leontief models (Moffatt & Hanley, 2001; Sachs et al., 2016; Todorov & Marinova, 2011); (iii) the MICMAC structural analysis (Arcade et al., 1999; Glenn, 2004); and (iv) the cross-impact

analysis (Weimer-Jehle, 2006, 2008; Zelinka and Amadei, 2017). These publications are great starting points, as they focus on the science of linkages, but fall short of quantifying the impact of these interactions. They serve as the scientific foundation (ICSU & ISSC, 2015) on which we build a methodology to understand the long-term trajectory and success of the SDGs with a systems perspective.

While addressing and implementing the SDGs, accounting for their effects on one another is crucial to their success. Because of their complex formulation, some goals are bound to affect others negatively or positively, whereas others may not have any direct effect, while all SDGs will affect all others through some indirect path. Furthermore, the interactions are context- and scale-specific; each country, city, or entity attempting to adhere to the SDG framework has unique characteristics and situations. For example, rural Kenya will not have the same conditions as an island-nation; a city will have different issues than a country; a water-poor country will struggle with problems that a water-rich community will not; political factors might constrain or further enable certain outcomes for the SDGs. Likewise, a country with strong environmental regulations might not have such large negative impacts on the environment resulting from energy-use and economic activity. The factors leading to the success or failure of implementing the SDGs are innumerable.

Current guidelines for implementing the SDGs do not account for the interconnectivity of the SDGs and most focus on only one, or a group of them. Adopting a systems mindset will enable development practitioners to understand how prioritizing certain aspects of sustainable development could influence all SDGs. For example, as discussed later in this paper, attempting to directly reduce poverty (SDG 01) is ultimately self-defeating, as poverty is dependent on virtually all other goals and areas of sustainable development (energy, sustainable consumption, reducing inequalities, environmental sustainability, good governance, etc.) not the other way around. In directly addressing poverty, the other goals are neglected and suffer as a result. Because all the other goals influence poverty, and poverty overall negatively affects the other goals, focusing on poverty is, counterintuitively, detrimental to its alleviation and is highly counteracting to the eventual goal of poverty eradication.

Thus far, we have described the need for systems thinking approaches rather than a reductionist approach when addressing the SDGs. As defined by Richmond (1994), systems thinking “is the art and science of making reliable inferences about behavior by developing an increasingly deep understanding of underlying structure” (p. 6). Another definition proposed by Sterman (2006) considers systems thinking as a new mindset with both depth and

breadth and “an iterative learning process in which we replace a reductionist, narrow, short-term, static view of the world with a holistic, broad, long-term, dynamic view, reinventing our policies and institutions accordingly” (p. 509) Systems thinking and systems tools such as cross-impact analysis (CIA) and network analysis (NA), which are considered in this paper, enable decision-makers to explore the cross-impact and interconnections across the SDGs in a more rigorous and analytical way than just using intuition.

A systems or integrated approach to the SDGs requires development practitioners to acquire a certain level of awareness and decision-making maturity. System thinking is learned, and anyone can become a systems thinker by adjusting his or her perspectives and adopting new habits. These habits are best described by the Waters Foundation (Benson & Marlin, 2017) and are listed in Table A2. Even though these habits were developed in the context of integrating systems thinking in K-12 education, they apply to a wide range of situations where the thinker is faced with complex issues associated with messy, wicked, or ill-structured problems. These habits can also be understood as thinking strategies (visual, listening and speaking, and kinesthetic) that a decision maker, such as someone who makes decisions about addressing the SDGs, might want to follow to address complex problems. Table A2 gives examples of how each habit can be used when addressing the SDGs.

Table A2. Habits of system thinkers and the SDGs (adapted from Benson and Marlin, 2017)

Habit	Description: as they pertain to the SDGs
Big Picture	A systems thinker “steps back” to examine the dynamics of a system and the interrelationships among its parts. They see the forest, rather than the details of any one tree. To understand the SDGs’ framework, analyzing all the SDGs, not just one, is required.
Change with time	Dynamic systems are made up of interdependent elements, the values of which change over time. The status of the SDGs and sustainable development are governed by elements that change over time, such as education, infrastructure, and governance.
System’s structure	Focusing on the structure of the system facilitates an understanding of the outcomes of the system (i.e., structure determines behavior). The institutions involved with the SDGs have an organizational structure that cannot be ignored when considering strategies for implementing the SDGs. The success of the SDGs is closely related to the strength of the institutions on which they rely.
Interdependencies	A systems thinker knows that the cause-effect relationships within dynamic systems are circular rather than linear. Complex cause and effect relationships include balancing feedback, in which the system is trying to reach and maintain a goal, e.g., the heating system in a house. There also may be reinforcing feedback, such that the more you start with, the more it increases over time, e.g., population. Each SDG is intimately tied to the other SDGs; thinking of the SDGs in their silos ignores the interdependences on which the SDGs are affected.
Connections	A systems thinker intentionally makes connections in order to better understand the relationships in systems. A systems thinker creates meaning by considering how new information connects to previous knowledge by adding, modifying, transferring, and synthesizing the information into a deeper understanding. Seeing how the SDGs are

Habit	Description: as they pertain to the SDGs
	connected is required to understand how they will change over time thereby affecting the strategies for their implementation.
Change perspectives	To understand how a dynamic system actually works, a systems thinker looks at the system from a variety of different angles and perspectives, perhaps in collaboration with others. Changing perspectives enables multiple alternative strategies to be considered for the implementation of the SDGs. A strategy might not work for all situations, countries, or cultures, so various perspectives are needed.
Assumptions	A systems thinker will rigorously examine assumptions in order to gain insight into a system. Insight put into action can lead to improved performance. It is crucial to understand how and why assumptions are made, beliefs are developed, and actions are taken based on perceived data to avoid incorrect assumptions. An SDG implementation strategy based on incorrect assumptions could run over budget, not have the desired outcome, create risks, or fail entirely.
Fully considers issues	A systems thinker is patient. S/he will take time to understand the system's structure and its behaviors before recommending and implementing a course of action. A systems thinker also understands that succumbing to the urge for a quick solution can create more problems in the long term. The complexity of the SDG framework requires a deep understanding of the issues to make sure an appropriate strategy is used.
Mental models	In any given situation, an individual perceives and interprets what is happening, thus creating a picture, or mental models, which are comprised of assumptions, beliefs, and values that people hold, sometimes for a lifetime. A systems thinker is aware of how these mental models influence perspectives and ultimately any actions taken. Mental models often govern how people implement the SDGs, and if those mental models are comprised of misleading or incorrect assumptions, strong biases might corrupt the strategy to implement the SDGs.
Leverage	Based on an understanding of the structure, interdependencies, and feedback within a system, a systems thinker implements the leverage action that seems most likely to produce desirable outcomes. Identifying leverage points for the SDGs will most effectively use resources to forward the mission of the SDGs; they are locations that policies should be focused.
Consequences	Before acting to change a dynamic system, a system thinker weighs the possible short-term, long-term, and unintended outcomes of the action. Without understanding possible consequences, any actions taken to improve the outcome of the SDGs might back-fire and make the situation worse.
Accumulations	Systems are made up of many elements including accumulations, i.e., amounts that can increase and decrease over time, and their rates of change. Sustainable development, and therefore the SDGs, are based on things (population, money, infrastructure, etc.) that change (flow) over time, or accumulate.
Time Delays	A systems thinker recognizes that when an action is taken within a complex, dynamic system, the outcome of the action may not be seen for some time. Implementing policies for the SDGs will take time, which will differ based on the specific policy and sector in which it will function, and the effects of those policies will take time to be felt. For example, a policy that involves constructing infrastructure takes a lot of time and investment before that infrastructure can even be used.
Successive approximations	By trying a solution and then assessing (monitoring and evaluating) the results, understanding of the issue will increase. Over time, each cycle or successive approximation, of checking results and changing actions if needed, will move the system closer to a desired goal. The desired and actual effects are not normally the same when a policy or strategy for

Habit	Description: as they pertain to the SDGs
	SDG implementation are made, so the outcomes need to be monitored. Sometimes, course corrections must be made to bring the desired and actual effects closer together.

A systems approach to addressing the SDGs is an appropriate means to account for the complexity and uncertainty to play in sustainable development at the country or other scales of interest. It can be used to:

- better understand how meeting the goals and their targets depend on context along with the capacity, vulnerability, and structure at the local, city, country, or global levels;
- explore how certain structural variables or factors influence that dynamic, including feedback mechanisms, by carrying out various parametric and sensitivity studies;
- explain existing patterns of human development at different spatial and temporal scales;
- interpret emergent properties of human development such as poverty/wealth, peace/conflict, health, resilience, and sustainability that may involve one or several goals;
- examine various perspectives of human development interventions and consider possible (intended and unintended) consequences of decision making and policies and their implications;
- identify and explore leverage or tipping points, those critical places to intervene at different scales that will most benefit human development;
- predict how countries or regions may respond to various constraints and disturbances and/or strategies of capacity development;
- monitor and evaluate the performance of development interventions and decide on how to adjust as development projects unfold, thus leading to more successful projects in the long term; and
- develop approximate but good enough sustainable development solutions that are more flexible and adaptive to change than the traditional deterministic, rigid, and ultimately inappropriate long-term solutions.

In summary, a systems approach to addressing the SDGs and their targets has the potential to provide an alternative to the deterministic decision process that has been used in development around the world over the past 50 years. This has led many people to the misguided conclusion that aid and Foreign Direct Investment have been

ineffective as suggested by William Easterly (2006), author of *White Man's Burden*, and Dambisa Moyo (2009), author of *Dead Aid*.

We present below two systems thinking tools to address the SDGs in an integrative manner: cross-impact analysis and network analysis. Together these two tools represent the first of two papers of which the second paper uses system dynamics as a modeling tool to analyze the interactions among the SDGs. This paper focuses on soft-systems approaches and forms the foundation for the hard-systems approach in the second the following paper.

The remainder of this paper is categorized into three sections. Section 2 introduces the cross-impact matrix as well as the cross-impact analysis to mathematically calculate the priority of each SDG in relation to each other as a complete system. Section 3 introduces to the network analysis as another tool to understand all the SDGs. The last section concludes by discussing the benefits and limitations of the cross-impact analysis and briefly introduces system dynamics modeling.

## **2. Cross-Impact Analysis of the SDGs**

### **2.1. Cross-Impact Analysis**

Cross-impact analysis (CIA), also called double-causality analysis, is a mathematical approach used in Futures Research studies. It originated in the mid- to late-1960s (Gordon, 2014; Gordon & Hayward, 1968) and was initially developed to analyze weakly (soft) structured systems for which theory-based computational (hard) models do not work due to the systems complexity, uncertainty, and disciplinary heterogeneity. Since its inception, cross-impact analysis has been a general soft-system method for assessing the “interrelations [among] the most important influential factors in a system by experts who evaluate [subjectively] pairs of these factors” (Weimer-Jehle, 2006, p. 336). The different methods of cross-impact analysis differ on how the interrelations are formulated (probabilistically or deterministically) and whether a qualitative, quantitative, or mixed approach is used to describe causalities (Serdar Asan & Asan, 2007).

Cross-impact analysis is particularly appropriate to tackle large-scale human societal issues such as those addressed by the SDGs. Its approach is flexible and lends itself to expert discourse, which is vital for effectively identifying the actual causes of a problem as opposed to using a mere intuitive and/or educated guess. Cross-impact analysis is a method to understand complex systems with relatively little effort in a concise and informative way. Due to its flexibility and versatility, it is apt for use in comparing multiple scenarios and finding out the most appropriate



ones based on analytical tools rather than, ideally, guesses, bias, and partisan influence. Cross-impact analysis is used in this paper to analyze the interactions of the SDGs.

Let's consider a system consisting of  $n$  interacting variables. Cross-impact analysis of that system is usually presented by a  $(n \times n)$  matrix with zeroes along its diagonal and  $n^2 - n$  off-diagonal terms. The off-diagonal terms define how each variable (row) directly influences or impacts the other variables and how each variable (column) depends on, or is sensitive to, the other variables. It should be noted that the matrix is not symmetric. The strengths of the influence between two variables can be described qualitatively using qualifiers such as high, medium, or low, or scored semi-quantitatively over an appropriate scale, say, between 0 for no influence up to 3 (or larger) for high influence. The selected scale is specific to the system being analyzed.

Figure A1 shows an example of a cross-impact matrix for the  $n = 17$  SDGs where semi-quantitative scores have been assigned to describe the strength between interacting SDGs, two at a time. Using the scale proposed by Nilsson (2017) in Table A3, the scores were assumed to range from -3 (most positive dependence) to +3 (most positive influence). Negative values depict an SDG that either constrains, counteracts, or cancels another goal, broadly defined as limiting; the opposite is true for positive values, which either enable, reinforce, or are indivisible to another goal and are generally defined as enhancing. Each of the three limiting and enhancing titles refers to the relative magnitude of those interactions. Interactions are 0 when there are no discernable effects and are called neutral. Values were assigned for each one of the 272 off-diagonal terms of the double-causality matrix of Figure 1, although -3 never appeared in our analysis.

**Table A3. Semi-quantitative scale of sustainable development goals' interactions (adapted from Nilsson et al., 2017)**

<b>Strength, Title</b>	<b>Explanation</b>	<b>Examples</b>
+3, Indivisible	Inextricably linked to the achievement of another goal. Accomplishing this goal will accomplish another goal by default.	Ending all forms of discrimination against women and girls is indivisible from ensuring women's full and effective participation.
+2, Reinforcing	Aids the achievement of another goal. This goal will by default achieve a significant portion of another goal, with only a relatively small amount of work required to further accomplish both.	Providing access to electricity reinforces water-pumping and irrigation systems. Strengthening the capacity to adapt to climate-related hazards reduces losses caused by disasters.
+1, Enabling	Creates conditions that further another goal's progress. This goal could be a tool to accomplish another. There is a positive overlap.	Providing electricity access in rural homes enables education because it makes it possible to do homework at night with electric lighting.

Strength, Title	Explanation	Examples
0, Neutral	No significant positive or negative interaction. The interconnections between two goals are purely indirect if they exist at all. The positive and negative impacts are equal.	Ensuring education for all does not interact significantly with infrastructure development or conservation of ocean ecosystems.
-1, Constraining	Limits options on another goal. This makes another goal noticeably more difficult to accomplish.	Water requirements for thermoelectric power generation reduce available water for WASH. A climate change can constrain the options for energy access.
-2, Counteracting	Clashes with another goal. Unless direct actions and efforts are taken by people, then this goal will make it significantly more difficult for another to be achieved.	When a population consumes more, economic growth can counteract waste reduction and climate mitigation and degrade the environment.
-3, Canceling	Makes it impossible to reach another goal. Nothing can be done to have these two goals coexist.	Fully ensuring public transparency and democratic accountability cannot be combined with national-security goals.

Goal	Goal 01	Goal 02	Goal 03	Goal 04	Goal 05	Goal 06	Goal 07	Goal 08	Goal 09	Goal 10	Goal 11	Goal 12	Goal 13	Goal 14	Goal 15	Goal 16	Goal 17	Total	Description	Influence	Dependence	Influence Ratio	Net Influence	Priority Index
Goal 01	0	-1	-1	-1	-1	-1	-1	-1	1	3	-1	-1	1	0	0	3	2	1	Poverty	1	37	0.03	-36	0.01
Goal 02	3	0	3	2	2	0	-1	1	0	3	-1	-1	-1	-1	3	0	0	12	Food Security	12	28	0.43	-16	0.20
Goal 03	3	1	0	2	2	1	-1	2	-1	3	1	0	0	1	0	0	0	14	Health	14	28	0.50	-14	0.22
Goal 04	2	2	2	0	2	2	1	2	2	3	2	2	0	2	1	2	2	29	Education	29	21	1.38	8	0.48
Goal 05	3	3	2	2	0	-1	-1	3	0	3	2	-1	0	0	2	3	1	21	Gender Equality	21	23	0.91	-2	0.36
Goal 06	3	3	3	2	2	0	1	3	1	3	3	1	1	2	3	0	0	31	WASH	31	16	1.94	15	0.60
Goal 07	3	1	3	2	0	2	0	3	3	3	3	-1	-1	-2	-2	0	2	19	Energy	19	8	2.38	11	0.61
Goal 08	3	2	2	3	3	2	2	0	2	-1	2	3	-2	-2	-2	0	2	19	Economy	19	26	0.73	-7	0.30
Goal 09	2	2	2	1	0	2	3	3	0	-1	3	-1	-1	0	-2	2	2	17	Infrastructure	17	17	1.00	0	0.38
Goal 10	3	2	2	0	3	-2	-2	3	0	0	-2	-2	-1	-1	-2	0	1	2	Inequality	2	30	0.07	-28	0.07
Goal 11	1	1	2	1	3	3	2	1	3	1	0	2	-1	0	1	0	1	21	Cities	21	18	1.17	3	0.42
Goal 12	2	2	1	2	1	1	2	3	2	3	2	0	-1	-1	-1	0	0	18	Consumption	18	4	4.50	14	0.87
Goal 13	2	1	-1	0	1	-1	-2	-1	-1	2	-2	-1	0	3	2	0	0	2	Climate Change	2	2	1.00	0	0.38
Goal 14	-1	1	1	0	0	1	1	-1	1	-1	1	1	0	0	2	0	0	6	Ocean	6	9	0.67	-3	0.32
Goal 15	2	3	2	0	0	2	-1	-1	-1	0	0	-1	3	3	0	0	0	11	Land	11	10	1.10	1	0.40
Goal 16	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	0	3	44	Governance	44	13	3.38	31	0.88
Goal 17	3	2	2	2	2	2	2	3	2	3	2	2	3	3	3	0	0	39	Partnerships	39	16	2.44	23	0.71
Total	37	28	28	21	23	16	8	26	17	30	18	4	2	9	10	13	16	306						

Figure A1. Double-causality matrix with influence, dependence, and priority index

Several remarks can be made about the double-causality matrix. First, the values represent the direct impact of one SDG onto another. The point of the cross-impact analysis is to map the direct effects between variables which, when analyzed further, could help to determine indirect effects among variables. As an example, let's consider two of the SDGs, the effect of the ocean (SDG 14) and gender equality (SDG 05). These two SDGs have no direct influence per se on each other, but the indirect influence is possible. For instance, cleaner oceans might

improve water and sanitation that eventually improve health and education, eventually improving human rights and gender equality.

A second remark about Figure A1 relates to the selection of the interaction scores. Metric and indicators must be developed to determine what represents a positive or negative score. Nilsson et al. (2017) developed, for instance, such metrics for SDG 02 (Food Security), SDG 03 (Health), SDG 07 (Energy), and SDG 14 (Oceans). The scores in Figure A1 were based on some of these metrics and on other publications (Coopman et al., 2016; Sustainable Development Solutions Network et al., 2015; Vladimirova & Le Blanc, 2016). They were assumed to reproduce the interaction dynamics among the SDGs representing an *average-sized country of average population and at an average level of human development*. The country doesn't exist, but our goal was to generate a cross-impact analysis of the SDGs for a hypothetical average country. This should be understood as a proof-of-concept that could be used for specific countries.

Finally, it should be noted that the scores in Figure A1 depend on the context in and scale at which the cross-impact analysis of the SDGs is conducted. The proof-of-concept could be extended to analyze the interactions of the SDGs at the global, regional, or community level. It could also be applied to any culture, socio-economic group, or groups of multiple communities.

## 2.2. Influence and Dependence across the SDGs

The total influence (impact), of each SDG on the others and the total dependence (sensitivity) of each SDG on the others, was calculated by summing the row scores and column scores of the double-causality matrix, respectively (Figure 1). The dependence and influence values were plotted on a single dependence (x) vs. influence (y) graph (Figure 2). The first diagonal shown on Figure 2 separates the goals that are more dependent (above the line) from those that are more influential (below the line). The average influence and dependence value for all SDGs is 18.2 and is represented by a star on the line near infrastructure; a higher average value would indicate a more stable (determined) system (Arcade et al., 1999). The graph can then help to separate the variables (goals) into several groups. According to Arcade et al. (1999), they include:

- *influential variables (goals)* with low dependence and high influence; e.g., SDG 06 (WASH), SDG 16 (Governance) and SDG 17 (Partnerships);

- *excluded variables (goals)* with low influence and dependence; e.g., SDG 13 (Climate Change), SDG 14 (Oceans), and SDG 15 (Land);
- *dependent variables (goals)* with high dependence and low influence; e.g., SDG 01 (Poverty), SDG 02 (Food Security), SDG 03 (Health), and SDG 10 (Inequality); and
- *regulating variables (goals)* that lie near the center of the graph, e.g. SDG 04 (Education), SDG 05 (Gender Equality), SDG 08 (Economy), SDG 09 (Infrastructure), and SDG 11 (Cities).

Because of their high influence and low dependence, influential goals are goals with high leverage; lower is the dependence, higher is the leverage. As their dependence increases, these goals become more difficult to address. On the other side of the dependence vs. influence spectrum, are the dependent variables that are the outputs of all the variable interactions. They are “strong indicators of the ‘health’ of the entire system of variables” (Ritchie-Dunham & Rabbino, 2001) and are sensitive to changes in the other variables. In Figure A2, both poverty reduction (SDG 01) and inequality reduction (SDG 10) are strongly dependent variables and are key indicators of the overall state of sustainable development at the country level. Other dependent variables such as health (SDG 03) and food security (SDG 02) are also indicators of the health of the system but have more influence on the other SDGs than poverty reduction and inequality reduction.

Goals that are clustered anywhere near the diagonal line on the graph have similar influence and dependence values meaning that these goals are not significant one way or another. A focus on these goals is much more tactical than focusing on the influential goals. They might not improve sustainable development overall, but they could improve a specific goal. For instance, if a policymaker wants to specifically spur energy and economic development, then allocating resources to infrastructure (Goal 09) makes sense.

### **2.3. Calculating and Depicting Priority**

Using the total influence and dependence scores from Figure 1, three indices were calculated for each SDG and are listed on the right side of Figure A1. The first index, the net influence (NI), was calculated as the difference between influence and dependence. The NI shows the absolute power of a goal. The larger the NI the more “power” that goal has when influencing the other goals. The second index is the *influence (I)-to-dependence (D) ratio* ( $IR = I/D$ ). It

focuses more on the efficiency of a goal. Since the net influence of a goal can be positive or negative and IR needs to be positive, the following algorithm was used to calculate IR for each goal SDGx:

	$I > 0$	$I = 0$	$I < 0$
$D < 0$	$IR = \frac{I_x}{D_x}$	$IR = 0$	
$D = 0$	$IR = 48$		
$D > 0$	$IR = \frac{I_x}{I_x +  D_x }$	$IR = \frac{1}{48} \cong 0.02$	$IR = \frac{D_x}{I_x}$

Finally, the third index defined as the *priority index* (PI) is a proportionally weighted-average of the influence ratio (IR) and net influence (NI) relative to the smallest and largest values for each set of goals:

$$PI = A \frac{IR_x - \min IR}{\max IR - \min IR} + B \frac{NI_x - \min NI}{\max NI - \min NI}$$

**A:** weight of influence ratio  
**B:** weight of net influence  
**min:** minimum value in set of all goals  
**max:** maximum value in set of all goals

This index ranges between 0 and 1 with small values indicating low priority goals and high values representing high priority goals. The priority index values listed in Figure A1 assumed equal weights ( $A = B = 0.5$ ) for the influence ratio and the net influence. The size of the bubbles in Figure A2 relates to the priority index value: the larger the priority index, the larger the size of the bubble. Goals with a priority index value of 0 are not shown on the dependence-influence graph.

It should be noted that the two weights A and B do not always have to be equal, however their sum must always be equal to 1. There might be circumstances, however, for which the weights A and B are not the same. For instance, if policymakers want to focus on generating as much impact as possible, then they would focus solely on the net influence and select  $B = 1$  ( $A = 0$ ). Conversely,  $A = 1$  ( $B = 0$ ) would correspond to the most efficient allocation of resources.

Dependence is to input as influence is to output. The influence ratio illustrates the efficacy of a goal. A large ratio implies that *relatively* few resources will yield a *relatively* large benefit in terms of aggregate impacts. The higher the IR, the more it helps accomplishing the other goals. The net influence NI tells the likely size of that *absolute* impact. Although similar, IR and NI tell two different pieces of information. Just because IR is large doesn't

necessarily indicate it will have a significant impact. Consumption (Goal 12) is an example: it has the largest ratio but is fourth for NI. Goal 12 will produce the highest amount of good, or utility, relative to its cost, but it will not generate the most-good in absolute terms. It will be cheaper to allocate resources with the highest relative pay-out, but if the goal is to generate the greatest overall impact, then Goal 16 or 17 would be better.

Using the IR and NI together should aid policymakers in identifying what is best for their situation, which is why the priority index was introduced in the first place. Poorer countries might elect to focus on the influence ratio, since resources are scarce, but richer countries might want to focus on a higher net influence to see positive change faster. In short, the main differences are relative vs. absolute and efficiency vs. cost for the influence ratio and net influence, respectively. Regardless, an influence ratio below one and a net influence below zero should be avoided. Only when calculable and noticeable progress is made on the more attractive goals should the dependent goals be addressed.

Both the influence ratio and net influence were used to produce a priority ranking of the SDGs as shown in Table A4. The ranking is also represented in Figure A3 where the pillars of sustainable development (economic, social, political, and environmental) are shown as four shaded boxes. Each SDG falls into one of those four pillars. Although by their very nature SDGs cross-cut multiple pillars, they are assigned to just one for ease of graphical representation. The political pillar was placed in the same column as the social pillar as they are highly interrelated, even more so than the other pillars, and sometimes are combined; this assumption was made in defining the original three economic, social, and environmental legs of sustainability (Thwink.org, 2014).

Table A4. Priority order of the SDGs

Description	Goal	IR	NI	PI
Governance	Goal 16	3.38	31	0.88
Consumption	Goal 12	4.50	14	0.87
Partnerships	Goal 17	2.44	23	0.71
Energy	Goal 07	2.38	11	0.61
WASH	Goal 06	1.94	15	0.60
Education	Goal 04	1.38	8	0.48
Cities	Goal 11	1.17	3	0.42
Land	Goal 15	1.10	1	0.40
Infrastructure	Goal 09	1.00	0	0.38
Climate Change	Goal 13	1.00	0	0.38
Gender Equality	Goal 05	0.91	-2	0.36
Ocean	Goal 14	0.67	-3	0.32
Economy	Goal 08	0.73	-7	0.30
Health	Goal 03	0.50	-14	0.22
Food Security	Goal 02	0.43	-16	0.20

Inequality	Goal 10	0.07	-28	0.07
Poverty	Goal 01	0.03	-36	0.01

Besides the four pillars, poverty (Goal 01) and [economic] inequalities (Goal 10) represent the desired overarching goals to which the other goals strive to contribute and improve. They fall in the fifth shaded box on top (desired socio-economic results) of Figure A3. Poverty eradication is the ultimate social outcome, while reducing inequalities is the desired economic outcome of the SDGs and is closely associated with poverty.

Two types of arrows are used to link the SDGs in Figure A3 – directional and concurrent. *Directional arrows* have an order and are such that salient progress is needed in a *prerequisite* goal before resources can be seriously allocated for a *subsequent* goal. For instance, SDG 04 (Education) should occur prior to SDG 05 (Gender Equality). *Concurrent arrows* on the other hand are *requisites*. SDGs, or groups of related goals, connected by concurrent arrows should be prioritized together because they are closely interrelated; there could be detrimental effects if both SDGs aren't prioritized together. Specific examples include SDG 12 (Consumption) with the political development goals of SDG 16 (Governance) and SDG 17 (Partnerships), as well as SDG 01 (Poverty) with SDG 10 (Inequalities).

Furthermore, all the economic development SDGs must be undertaken with high consideration for the environment sustainability SDGs (SDG 13 Climate, SDG 14 Oceans, and SDG 15 Land). Concurrent arrows also imply that the connecting SDGs must be considered equally when either one is prioritized. Concurrency is crucial for environmental sustainability, as the environment is important for all the goals. Inequality and poverty are highly interconnected, and both represent the desired outcome of the SDGs and thus should follow all other goals. The issues of food security, health improvement, strong governance, and so on are important, but they are requirements for and feed into poverty eradication and inequality. For this reason, SDG 01 and SDG 10 are placed at the top. Only when all the other goals have made considerable progress, will addressing poverty and inequality be effective. Food security is the last social development goal; economy is the last economic development goal; and land is the last environmental sustainability goal. These feed directly into poverty and inequality.

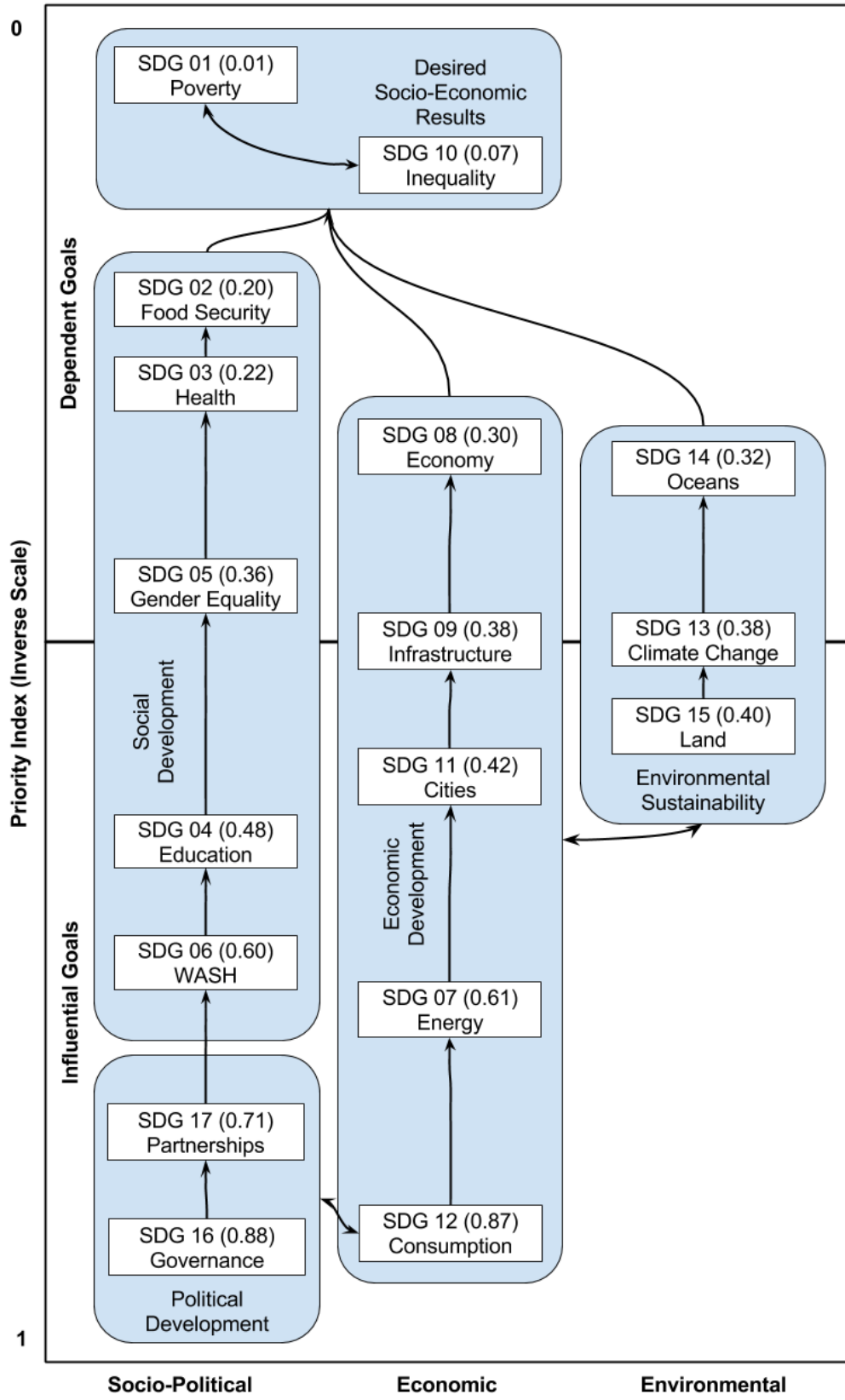


Figure A3. Flowchart of SDG prioritization



### 3. Network Analysis of the SDGs

#### 3.1. Cross-Impact Network Analysis

The cross-impact analysis helps to describe the influence and dependence of multiple interacting variables such as the SDGs. The interaction can also be represented as a network diagram or graph consisting of multiple nodes (vertices or actors) representing each SDG and links (edges or ties). In directed graphs, arrowheads pointing inward to or outward from some nodes can be added to map how the SDGs influence or depend on each other. When the strength of and the connectivity between nodes are represented by symbols of varied sizes such as lines with different thicknesses or colors, the network is defined as a valued network (Borgatti et al., 2002) or weighted network (Newman, 2010).

Network analysis complements cross-impact analysis as it provides a mathematical approach to understanding patterns of interactions among the SDGs. The term cross-impact network analysis is proposed to describe the synergist aspect of these two forms of analysis.

A network approach to the SDGs has not received much attention until recently. Le Blanc (2015) looked at the SDGs as part of a network where the interconnectivity was assumed to take place at the target level. The analysis was carried-out considering the relationships that exist between the 17 goals and their 169 targets. In the network literature, this type of analysis is referred to as a two-mode network analysis. The approach selected in this paper is slightly different as it considers how the 17 goals interact with each other, which can be described as a one-mode network analysis. It starts with the same (17 x 17) matrix considered in the cross-impact analysis (e.g., Figure 1). The matrix, also called adjacency matrix in network analysis, was input into the network analysis software UCINET which is available through *Analytic Technologies* based in Lexington, KY (Borgatti et al., 2002). Figure A4 shows a directed, valued network representation of Figure 1 where each node size depends on the value of the priority index (PI) calculated in the cross-impact analysis. The thickness of the links in Figure A4 represents the strengths of the SDG interactions.

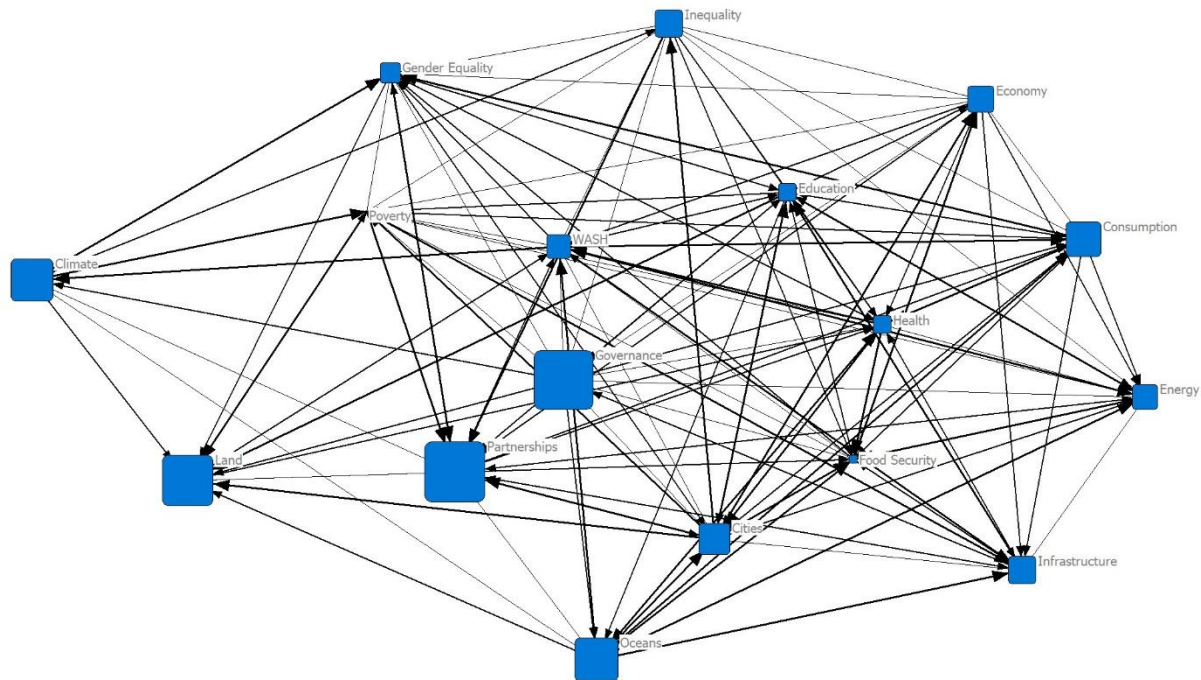


Figure A4. Network diagram map of the SDGs

Figure A4 is more than just a graphical representation on how the SDGs are interconnected. As discussed by Borgatti et al. (2013) for social networks, a graph such as Figure A4 can be used to identify the strengths, weaknesses, and patterns of interaction; identify potential attractors; make predictions; assess the network resilience; map assets and forms of vulnerabilities; conduct simulations; and plan interventions that leverage or strengthen existing network connections. Borgatti et al. (2013) reviews some of the measures and properties that can be inferred from directed graphs such as Figure A4 at the network-level (cohesion, shape), the node-level (different forms of centrality, betweenness), and the link-level (cohesion, equivalence).

*Centrality* represents a family of concepts that help indicate the significance of the contribution that a node makes on the network as a whole. Centrality can be understood as the extent to which a specific actor in a network is important. An actor with high centrality could be considered a hub or connected to many other actors. It translates into having high influence in the cross-impact analysis. Among the many measures of centrality, the simplest one is the *degree centrality* which is the number of actors each other actor connects (Borgatti et al., 2013). Since the network of the 17 SDGs is directed and valued, the centrality of each node of the network (each SDG) needs to be broken down into *outdegree centrality* and *indegree centrality* (Borgatti et al., 2013). The outdegree centrality (sum of values of outgoing links) and indegree centrality (sum of values of ingoing links) of the SDGs are respectively equal to the row sums (total influence) and column sums (total dependence) of the adjacency matrix in Figure A1.

### 3.2. Remarks

Several remarks can be made about using network analysis in analyzing the SDG network. First, networks are usually classified in the literature into different groups such as social networks, technological networks, biological networks, and information networks (Newman, 2010). The network shown in Figure A4 does not fall into any of these categories, however. Although not technically a social network, the SDG network is intimately tied to human social interactions at varying scales. For that reason, we refer to it as an *anthropocentric network*, i.e., a network whose main actors are directly and strongly influenced by complex human socio-economic-political interactions but are themselves not humans.

Second, the network analysis presented above can be repeated at the SDG target level. This could help in understanding better how the SDGs interact with each other. The same could also be done at the indicator level.

Third, like the cross-impact analysis, network analysis should only be used to strategically understand the interactions across a network. It pays less attention on the *nature* and *dynamic* of those interactions which can be handled better both qualitatively and quantitatively by hard system tools such as system dynamics. Network analysis provides information indicative of the network as a whole, but errors and problems could arise as the analysis becomes more precise, especially when decisions are made about intervening at the SDG level.

Fourth, for the numerical example considered in Figure 1, the centrality of the SDGs is very high, which we expect to hold in most scenarios. Most SDGs have some form of direct connection (one degree of separation) with the other SDGs (Le Blanc, 2015; Nilsson, 2017; Nilsson et al., 2017). Those that don't are indirectly connected with at most only two degrees separating them from any other SDG. This indicates that the SDG network is tight, and tighter networks are more impacted by fewer effects than looser networks.

Finally, Figure A4 is one possible representation of the SDG network among many others. As discussed further by (Borgatti et al., 2013), the nodes in Figure A4 do not have to be placed at random. Other graph layouts can be generated by using the centrality values as a priority. Likewise, multidimensional scaling (MDS) can be used to graphically represent the nodes so that the “distances between the points [nodes] correspond in a predetermined way to the proximities among objects in the data” (Borgatti et al., 2013). Essentially, the closeness of the distance between two nodes could be used to represent how similar, or dissimilar, they are to one another.

#### 4. Conclusion

This paper advocates for a systems approach to analyzing the SDG framework, which we categorize as an anthropocentric network. It describes a method combining cross-impact analysis with network analysis to aid decision makers to understand the complex interplay of the SDGs from a systems perspective. Cross-impact network analysis is a powerful tool that simplifies the process to prioritize the SDGs by relying on an analytical method rather than pure educated guesses and intuition. It illuminates hidden properties and emergent patterns that can be used to identify leverage points where policy can be applied most effectively to progress sustainable development and successfully implement the SDGs. This technique is but one way that the SDGs can be viewed and examined as an integrated system or network, but other hard system approaches are required to extract a deeper understanding.

We examine below two limitations of cross-impact analysis, the possibility of human-induced errors and its static nature. Cross-impact analysis is entirely based on human input, and ideally, expert judgement. The cross-impact matrix, which is the fundamental core of cross-impact analysis, “demand[s] the estimation of at least one of the following quantities by the judging experts: conditional probabilities or joint probabilities of event pairs, or the marginal probability of events. To be able to do these estimations properly, the experts not only need to know which interrelations exist in a system, but they also have to recognize” (Weimer-Jehle, 2006, p. 337) the possible results of these impacts. Essentially, the quality of the analysis depends on the accuracy and expertise of the person or people undertaking that analysis. The experts filling out the matrix are “expected to possess insights which rather should be the results of an analysis (Weimer-Jehle, 2006, p. 337).” This is the classic *Catch-22*, where input depends on output, seemingly rendering the analysis ineffective through *circle-logic*.

Cross-impact analysis should not be used to provide specific or detailed information about a system to begin with. So, as long as people understand that limitation, it is a relatively insignificant issue to the analysis itself. Cross-impact analysis is a soft system tool. Hence, specific numbers, equations, and quantitative data are not always necessary. Cross-impact analysis is to be used for grasping the strategic view of the system (see first systems-thinker habit in Table 2), and not to describe systems in detail. This brings us back to the problem of relying on the judgement of experts as imperfect humans. The structure and purpose of cross-impact analysis provides a possible mechanism to aid in this. Experts have deep understanding over specific elements within a system, and when many experts come together any deficiencies are hopefully smoothed out, and inaccurate or overly biased information holds less weight

when many experts are involved. It is much like smoothing algorithms used for filling data gaps. In short, cross-impact analysis relies on academic consensus. If most experts determine one outcome, then the minority view should not significantly skew the overall outcome, leaving the analysis valid.

This limitation is also a strength. Expert consensus allows cross-impact analysis to be built with relative ease depending on the desired detail of the output. In many cases, a qualitative approach is sufficient, but a semi-quantitative or quantitative approach is needed. Technically, a qualitative approach does not need external data beyond the expertise of those that fill it out, which makes it a relatively simple and straightforward approach compared to others, but it also tells less about the system. A qualitative approach is best for many situations if, for instance, the systems merely needs to be described to the stakeholders or policymakers. A semi-quantitative method (as used in this paper) is usually effective enough for most analyses of complex systems, as it requires little primary data from the system itself. Quantitative methods require a great deal of empirical data but leads to the highest accuracy and is usually reserved for more detail modeling approaches like system dynamics modeling. As the amount of data increases so does the possibility and propagation of errors. Regardless of the method employed, surprising levels of insight can be gleaned from any complex system, beyond what could be learned without a systems-approaches.

The second limitation of cross-impact analysis is that it represents a snapshot of a system in time and cannot handle dynamic issues. There are many situations, however, when a static approach will suffice: when a system changes very slowly with time relative to human time-scales or when the duration over which the system operates is short. The first could be geological time-scales or long-term macroeconomic impacts. When a system changes with time, a new cross-impact analysis must be carried out at each time interval; as time affects the system overall, the magnitude and direction of the interaction will also change. When that interval is long, or few intervals are desired, this is not a problem, but the effort quickly proves counter-productive to the analysis when many intervals are needed.

Since cross-impact analysis pays less attention on the *nature* and *dynamic* of interactions in a system, it needs to be supplemented with hard systems tools if the dynamic needs to be addressed. This point is addressed in our second paper (Part 2). It focuses on how to use system dynamics modeling (hard-systems approach) to model the interactions among the SDGs based on the soft-systems approach presented in this work. The idea is that once cross-impact analysis has reached its limits, it can be supplemented by the system dynamics analysis which automates much of the work in creating the analysis, generating background equations, and calculating the interactions. System dynamics

can be used not just for the SDGs but for a wide range of complex systems and applications (Azar, 2012) like in the areas of business and innovation (Shafiei & Hakaki, 2018); telecommunication mobile networks in Kenya (Omamo, Rodriguez, & Muliaro, 2018); e-waste (Nikabadi & Hajihoseinali, 2018); photovoltaic systems (Yatimi & Aroudam, 2018); or even Shakespeare (Haslett, 2012) and comic books (Wyburn & Roach, 2013) and many more – the possibilities are endless. It frees the users' time so that they can perform complex, comparative, and informative analyses on which decision makers should rely to craft policy.

## **Appendix B – A Systems Approach for Modeling Interactions Among the Sustainable Development Goals Part 2: System Dynamics**

### **Abstract**

This paper presents a methodology using system dynamics to model the time-dependent progress of each one of the 17 Sustainable Development Goals (SDGs), as well as their mutual interactions. The hard-systems approach presented herein complements a soft-systems, cross-impact analysis approach presented in part 1. To accomplish this, a modified logistic innovation-diffusion model is used to represent the progress of individual SDGs over time. Then, matrix transposition is used to model the SDGs' interactions. Combining these two techniques into one system dynamics model, we propose an analytical, quantifiable, and easily learned tool to understand the complex interplay among the SDGs as a system. The new web-based tool can be used to analyze several scenarios of the SDGs over time to understand the impact of a certain policy or economic intervention. This paper is the second of a sequence of two papers analyzing the interactions between the SDGs in a systemic manner.

**Keywords:** Sustainable Development Goals, Systems Approach, Systems Thinking, Interactions, System Dynamics, Modeling, Hard System, Interface, Scenario Analysis

## 1. Introduction

In a companion paper (Part 1), the authors advocated the need for using a systems approach, based on cross-impact analysis (CIA) combined with network analysis, to analyze the interaction among the 17 Sustainable Development Goals (SDGs). The analysis was based on the rationale that the SDGs form an *anthropocentric network* consisting of many interactions at the goal- and/or target-level. As reviewed in the companion paper, although the interactions among the SDGs have been acknowledged by many authors in the sustainable development literature (Allen et al., 2017; Coopman et al., 2016; Le Blanc, 2015; Nilsson et al., 2016; Nilsson, 2017; Nilsson et al., 2017; Nilsson et al., 2013; UN Water, 2016; United Nations Economic and Social Council, 2015; United Nations General Assembly, 2015; Vladimirova & Le Blanc, 2016; Weitz et al., 2014), little has been done to model how the SDGs influence or depend on one another.

Cross impact analysis originated in the 1960s (Gordon, 2014; Gordon & Hayward, 1968) to analyze “weak [soft] structured systems” (Weimer-Jehle, 2006, p.336) for which theory-based computational (hard) models do not work well due to system complexity and disciplinary heterogeneity. Since its inception, cross-impact analysis has been used a general method for assessing the “interrelations between the most important influential factors in a system by experts who evaluate [subjectively] pairs of these factors” (Weimer-Jehle, 2006, p.336). Cross -impact analysis is a *soft* systems approach that uses a systemic process of inquiry.

As discussed in Part 1, combining cross-impact analysis and network analysis has many advantages when analyzing the SDGs. More specifically, the approach enables decision makers to: (i) attain a better qualitative and quantitative understanding of the way the SDGs interact; (ii) detect emerging patterns resulting from those interactions; (iii) use context-specific information about direct impacts to identify indirect effects; and (iv) identify leverage points hidden within the SDGs.

Cross impact analysis also has limitations. As noted by Checkland and Poulter (2006), the limitation of a soft systems approach is that it uses an action-oriented learning process for learning to address problem areas and not the content of the problems. The second limitation of cross-impact network analysis is that it is static; it represents a snapshot of a system in time and cannot handle dynamic (time-dependent) issues.

A third limitation is that cross-impact analysis is entirely based on human input, ideally, expert judgement. The cross-impact matrix, which is at the fundamental core of cross impact analysis, requires judging experts to



estimate how variables interact with each other, the degree of their interactions, and the possible results of their impacts (Weimer-Jehle, 2006). Essentially, the quality of the analysis depends on the accuracy and expertise of the people undertaking that analysis. The experts filling out the cross-impact matrix are “expected to possess insights which rather should be the results of an analysis (Weimer-Jehle, 2006, p.337).” This is the classic *Catch-22*, where input depends on output, rendering the analysis ineffective through *circle-logic*.

We present below an alternative *hard* systems approach to analyze the interactions among the SDGs which helps address the limitations mentioned above. The approach uses system dynamics which, as the name suggests, accounts for how the components of systems and their linkages change with time. Furthermore, it takes under consideration the components of a system in addition to following a systemic process of inquiry. Unlike cross-impact analysis that can be carried out using simple tables in Excel, system dynamics analysis requires using more sophisticated software packages. The system dynamics (SD) models presented in this paper use the STELLA (Systems Thinking Experiential Learning Laboratory with Animation) Professional software by *isee systems, Inc.* v1.2.1.

It should be noted that both cross-impact analysis (combined with network analysis) and system dynamics are not mutually exclusive from each other when addressing the SDGs; they may appear to be dissimilar but, in reality, complement each other. It is recommended, for instance, to first carry out cross-impact analysis and network analysis to map how the SDGs interact. They also force decision makers to, at least, semi-quantify the strength and centrality of each component within the SDG network as well as the strength of the linkages among the goals. The results of that analysis are critical to developing robust and meaningful SD models. In system thinking lingo, they help develop so-called *mental models* of how the SDGs interact and outline hypotheses of their interaction dynamics.

An earlier version of the model discussed herein was originally presented at the *United Nations’ Multi-Stakeholder Forum on Science, Technology and Innovation for the SDGs* held in New York on 14-16 May 2017, which focused on six of the 17 SDGs, namely, SDG 01 (Poverty Eradication), SDG 02 (Food Security), SDG 03 (Health), SDG 05 (Gender Equality), SDG 09 (Infrastructure), and SDG 14 (Oceans). That presentation served as a catalyst for this paper. The model presented herein can be extended further to include all SDGs in the future as well as a more detailed and complex model representing sustainable development in general.

The rest of the paper is organized as follows: section 2 presents an overview of system dynamics modeling by discussing its definition, major components, causal-loop diagrams, and stock-and-flow diagrams; section 3

describes a system dynamics archetype based on the logistic, innovation diffusion model; section 4 details how to connect many structures together using a nested cross-impact matrix, first mentioned in part 1 of this series, as well as an overview of a user-friendly interface; we conclude in section 5 with a discussion of the benefits and limitations of system dynamics modeling and future work.

## **2. An Overview of System Dynamics Modeling**

### **2.1. Definition**

Systems dynamics is a relatively recent branch of systems science that originated with the work of Dr. Jay Forrester at the Massachusetts Institute of Technology in the 1950s and 1960s. It represents a milestone in the overall evolution in the application of systems thinking and the development of tools to address complex issues in a wide range of disciplines such as engineering, business, economics, health, planning, management, etc. A simple way to see system dynamics is that it studies “how systems change over time” (Ford, 2010). The System Dynamics Society (2016) defines system dynamics as a computer-aided approach to policy analysis and design. It applies to dynamic problems arising in complex social, managerial, economic, or ecological systems — literally any dynamic systems characterized by interdependence, mutual interaction, feedback, and causality.

Since its inception, system dynamics has accrued popularity in various STEM and social science fields. It can be used for a wide range of complex systems and applications (Azar, 2012), for example. in the areas of business and innovation (Shafiei & Hakaki, 2018); telecommunication mobile networks in Kenya (Omamo et al., 2018); e-waste (Nikabadi & Hajihoseinali, 2018); photovoltaic systems (Yatimi & Aroudam, 2018); or even Shakespeare (Haslett, 2012) and comic books (Wyburn & Roach, 2013) and many more – the possibilities are endless. Landmark books, among many others, that have promoted the applications of system dynamics include those by: Sterman (2000) on business dynamics; Ford (2010) on modeling environmental/ecological processes; and Amadei (2015) which involves application of systems thinking and SD to community development. In general, systems dynamics has unique characteristics that warrant its use in modeling the interaction of the SDGs.

- It is a method that can be used to study how systems continuously change over time due to possible changes in and relationships among components and changes in the overall direction of systems allowing for both qualitative and quantitative modeling.
- It requires a clear formulation, a mapping, and an iterative approach to model the issue(s) at stake.

- SD models are defined by closed boundaries (causally-closed models) where endogenous components, those originating from within, predominantly dictate the behavior of the systems. Models are designed to be self-contained in terms of cause-and-effect inside their boundaries so that no external (exogeneous) influence needs to be explicitly considered. In other words, SD models are designed to contain the components that “are important to explain [their] dynamic behavior” (Richardson & Andersen, 2010; Vennix, 1996) of systems including their internal rules.
- Non-linearities in the system are included in the form of first order differential equations.
- Information feedback mechanisms in the system can be included in the form of interconnected closed loops and circular causality allowing for reinforcing and balancing trends. This can help in explaining the counter-intuitive forms of behavior of some systems.
- The method emphasizes that the structure of systems (i.e., their components, mutual interactions, and environmental interactions) affects their continuous behavior. Combining feedback loops, various dynamic patterns can be simulated and used to model different behavioral patterns of system changes such as growth, decay, overshoot, oscillations, equilibrium, randomness, and chaos. As the structure of a system changes, so does its behavior.
- More emphasis is placed on the structure of a system (its aggregated nature) than on trying to figure out the details of individual components.

A main characteristic of SD modeling is that it captures the feedback mechanisms inherent to complex systems using two types of cause-and-effect circular causations: reinforcing and balancing feedback loops. *Reinforcing (R)* loops are used to model self-reinforcing, feedback processes that have potential to cause permanent growth or eventual collapse. Reinforcing loops are prevented from perpetual growth or decline with *balancing (B)* loops, which create self-correcting processes leading to stability and equilibrium. In addition to these two basic components, delays may be added to model the effect of time in linking causes and effects or any adjustment processes.

As described in the system dynamics literature, various combinations of loops and delays can be created to model the behavior patterns of complex systems and unique repetitive patterns called archetypes. The models can be represented in an object-oriented form of causal-loop diagrams or stock-and-flow diagrams. *Causal loop-diagrams*

show how elements of a feedback mechanism interact in a causal manner. They are useful in mapping, inferring, and visualizing what contributes to growth, decline, delay, or stability, and are mostly used at the *strategy-level*. They show trends and connections and causal feedback mechanisms in a system. They are *not* used to conduct numerical simulations of systems. On the other hand, *stock-and-flow diagrams*, as discussed below, consist of combinations of several building blocks. They help visualize flow, accumulation, delay, and dissipation processes (*qualitative*). They also allow for numerical (*quantitative*) simulations and parametric or sensitivity studies and can therefore be used at the *operation-level*.

In general, both causal-loop and stock-and-flow diagrams are useful tools for: (i) depicting how parts of a system interact and create patterns of behavior; (ii) communicating the dynamic of systems with others; and (iii) designing and planning interventions to address issues faced by the system. Only stock-and-flow diagrams are used in this paper.

## 2.2. Stock-and-flow diagrams

All stock-and-flow diagrams that are used in system dynamics software packages such as STELLA consist of several of the components shown in Figure B1 (Richmond, 1994). *Stocks*, represented by rectangular boxes, are net accumulations of something at one point in time. Possible SDG-related accumulations include: currency for GDP in economic systems; people as population; CO<sub>2</sub> as an indicator for climate change; and volume of water per person for a village, town, city, or country. Stocks are *state variables*: they define the current state of a system.

*Flows*, represented in the form of pipelines (with a faucet controlling the flow), refer to processes that cause *change over time* of information or materials (number of births per year, inflation rate, flow of a river, cash flow, carbon emission and sequestration, rate of cutting or planting trees, etc.). Flow (flux or rate), in turn, results in changes (dynamic behavior) in the stock accumulations and in the entire system. Flows are *control variables*; they create change in the state of a system. Flow can be a *uniflow* or a *biflow* – a uniflow flows one direction, while a biflow flows in both. Flows can be connected to stocks and convertors through connectors (visualized by thin arrows). Flows could be attached on both ends, one end, or neither end to a stock. When one or neither end is connected, a *cloud* is shown, which represents an infinite source or sink outside the boundaries of the model.

*Convertors*, represented by just a name or a circle-and-name, convert or transform information from a stock-and-flow path to another path. For example, if the population growth (a stock) requires a related growth in food

production (another stock) then a convertor can be used to link the two. For each living person, a certain quantity of food is required, and a convertor will be included to carry out this calculation. Converters can be described in a functional form that depends on time or a connected variable. In this case a “~” appears inside the converter.

*Connectors*, represented by arrows, connect the various components and variables and transmit information throughout the model. Multiple variables can be connected to a single variable, or vice versa. Connections include stock-to-flow, flow-to-flow, or between converters. The tail of the arrow represents the cause, or dependent variable, and the head represents the effect, or independent variable.

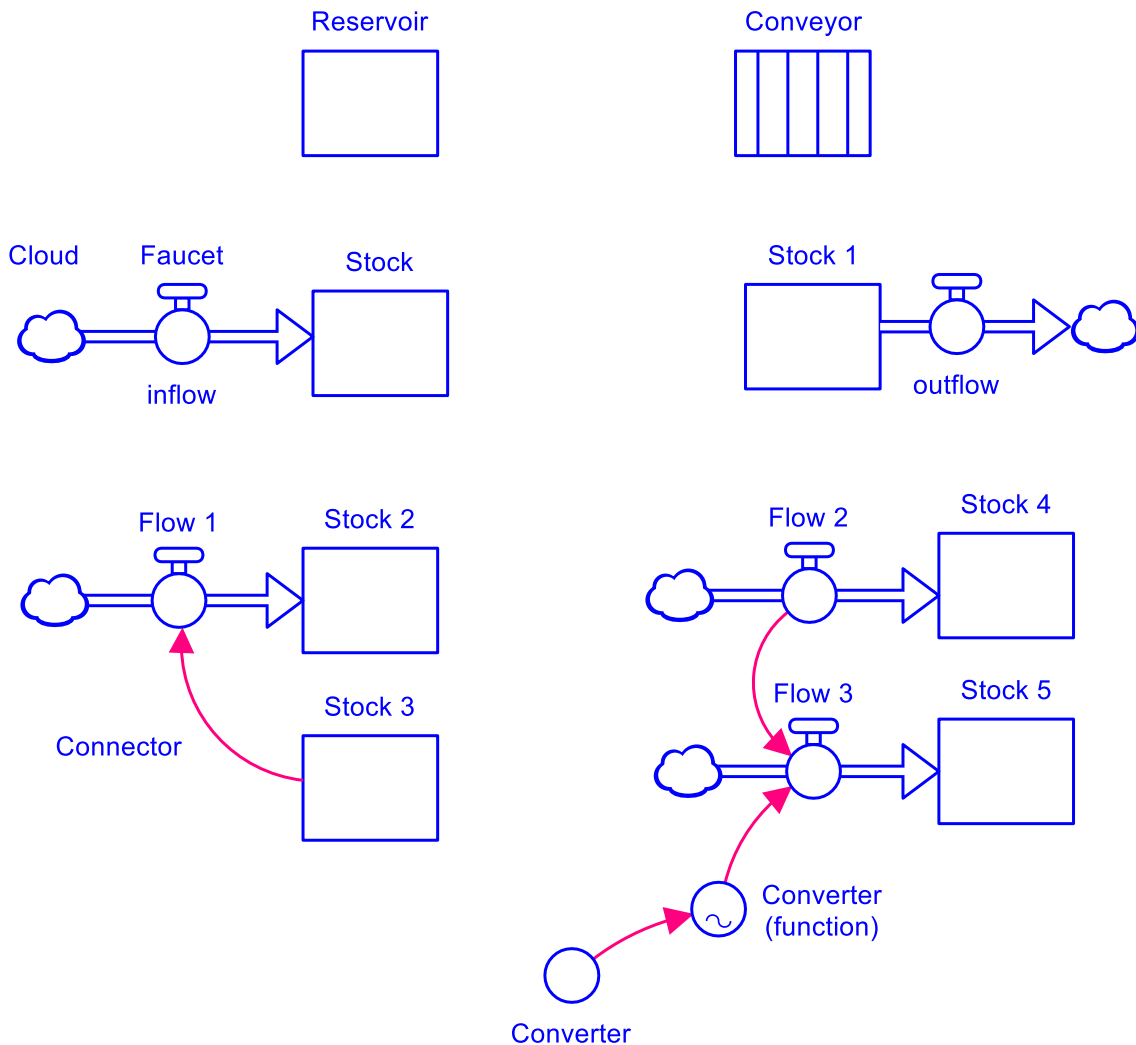


Figure B1. System dynamics modeling structures

Figure B2 shows an example of a simple stock-and-flow model that uses the main elements described above to represent the dynamics of exponential population change (growth or decay). In this basic example, the population is aggregated into one total population and does not account for various demographics.

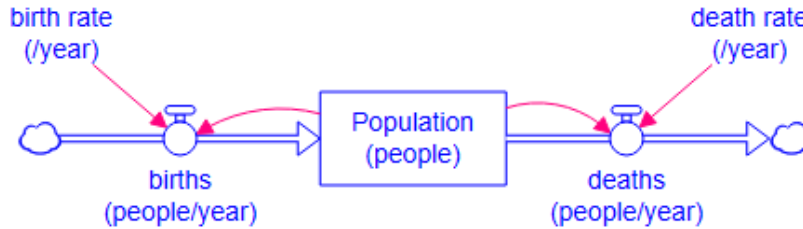


Figure B2. Simple population model

### 2.3. System dynamics modeling

Modeling a problem with system dynamics necessitates following a road map consisting of several interconnected steps. Figure B3 shows a road map proposed by (Ford, 2010) consisting of eight steps: problem familiarization (step 1); problem definition (step 2); model formulation by constructing causal loop diagrams (step 3) and then stock-and-flow diagrams (step 4); parameter estimation (step 5); simulation to explain the problem being addressed (step 6); and simulation analysis consisting of a sensitivity analysis (step 7) and a policy analysis (step 8).

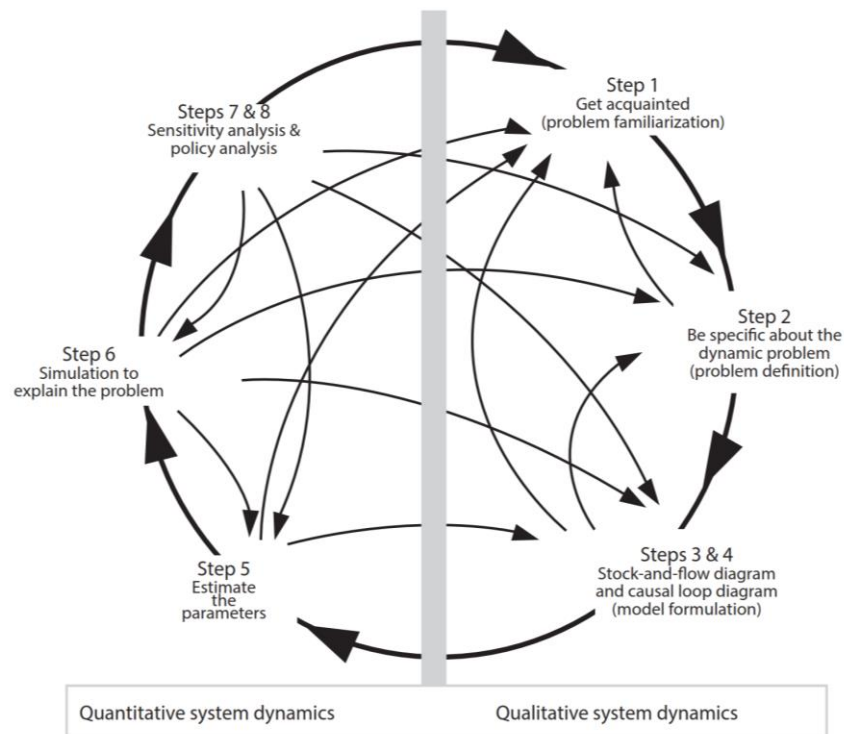


Figure B3. Road map for system dynamics modeling

Figure 3 shows that SD modeling follows a cyclical and iterative process. The first two steps suggested by Ford (2010) are about defining the problem being addressed and developing an initial *mental model*, a so-called *reference mode of behavior* (Ford, 2010) and proposing dynamic hypotheses for the problem. Modelers need to pay special attention to these two steps as they define: what is being modeled; why it is modeled; who is involved in the

modeling; the where and when of the modeling (i.e., the context and scale, respectively, physical and temporal); and how the modeling is undertaken.

Figure B3 also shows that the SD modeling process is divided into qualitative and quantitative modeling. Steps 1-4 can be interpreted as the qualitative and conceptual components of SD modeling. The other activities emphasize the quantitative dimension of that modeling. Whether qualitative or quantitative modeling is used depends largely the purpose of the system analysis, the availability of data and information about the system components, and the participating audience (Wolstenholme, 1999).

### **3. Base Model Archetype: S-Shaped Growth**

The SDGs are not static and progress, hopefully forward, over time. In this paper, we use system dynamics to model their individual progress and interactions with a logistic, S-shaped, growth archetype. This type of growth appears throughout multiple fields of science and is used to model epidemics (susceptible-infected-recovered epidemiological model, also called SIR), innovation diffusion (logistic innovation diffusion model), and market penetration of products (Bass diffusion model) (Sterman, 2000).

S-shaped growth can be described when a group is acquiring something that they didn't have before. As state A turns into state B, state B shows an S-shaped pattern of growth. For epidemics that is a potentially susceptible population becoming infected with an illness; for innovation in markets that is a population adopting a product or service; for population dynamics that is population growth under the constraints of an ecological carrying capacity.

The same logistic growth archetype can be applied to each SDG since the SDGs can be seen as going from non-being adopted to being adopted or implemented. Growth is initially slow after an SDG is first implemented because it takes time (delay) to inform relevant agencies, propose projects, etc. Eventually, work towards addressing the SDG will reach its fastest rate (inflection point), at which point it will start to slow, which results from constraints such as “the last-mile problem,” an issue especially pervasive in sustainable development (Balcik et al., 2008; Chambers, 1983; Minten et al., 2013). It refers to the difficulty in reaching those last few people at the end of the supply line due to their geographical remoteness, for instance.

### 3.1. The logistic innovation diffusion model

Of the three S-shaped growth models mentioned above, the logistic innovation diffusion model (IDM) was selected to model the dynamic of the SDGs and their interaction. Modifications to the original IDM were made to capture that dynamic.

In the fields of marketing and management science, the innovation diffusion model is used to represent the adopting rate of new products and technologies in a market by people who in turn are affected by internal and external forces. Internal forces represent word-of-mouth (positive feedback) from people that have already adopted the product and the difficulty in a new product being adopted in the absence of people that have already done so (negative feedback). Essentially, the IDM was designed to model market penetration and has been used for mobile phones (Swinerd & McNaught, 2014) and many products including refrigerators, record players, TVs, air conditioners and many more (Kumar et al., 2015). External forces represent external influences on the current adopters, such as advertisements from the media. Figure B4 shows a generic IDM stock-and-flow diagram consisting of a uni-directional flow from *potential adopters* to *current adopters*. The *adopting rate* depends on a *transfer rate* and external factors.

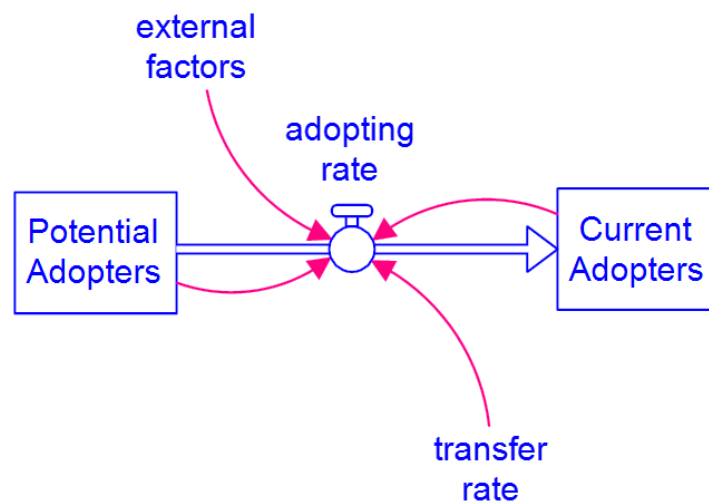


Figure B4. General innovation diffusion model

In general, the dynamic shown in Figure B4 yields a positively-skewed normal distribution (bell-shaped) for the adopting rate and a logistic S-shaped growth curve for the current adopters. Once a technology or product is adopted, a person cannot un-adopt it, unless a new, superior, and similar-functioning product is released. For this reason, the IDM is uni-directional. Internal factors are illustrated by the arrow (uniflow) from potential adopters to



current adopters. External factors are whatever the user’s specific context requires. The adopting rate may represent, for instance, market saturation and word-of-mouth. The transfer rate is a user-entered value (like population growth rate), that describes how a product or service is adopted by the population.

The generic IDM model depicted in Figure B4 was modified to generate the diagram in Figure B5 which now allows for flow in both directions (from potential adopters to adopters and from adopters to potential adopters). The terms “potential adopters” and “adopters” used in IDM no longer apply and are replaced by *State A (Insecure)* and *State B (Secure)*, respectively to be able to depict non-linearity and feedbacks more accurately. The bi-flow model of Figure B5 more accurately depicts what is happening in sustainable development. As an example, when addressing poverty, people can escape poverty, but they can also fall back into poverty any number of times. It is also similar to the confidence model used by Featherston and Doolan (2013) where a person could gain confidence in something (board of director’s in their case) or lose confidence in something. Instead of confidence we use a *secure state*, or desired state, which for SDG 01 is “no poverty.” Similarly, losing confidence is akin to being impoverished, which is the *insecure state*, or undesired state. The change of state is a function of the size of the *Insecure State* and the *Secure State* (poor versus non-poor population), the effect of the interactions of the other SDGs (explained later), and the effect of outside influences.

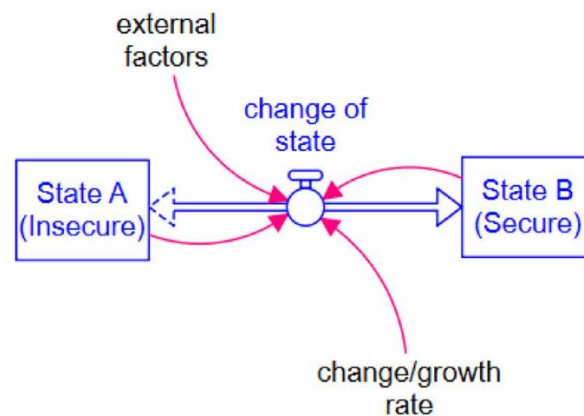


Figure B5. Insecure-secure diffusion model

It might be helpful to think of what is happening in Figure B5 as analogous to a see-saw. Instead of two populations, consider two closed chambers filled with a finite liquid. The *change of state* is like a pump that moves the liquid in a pipe between the two chambers; the speed at which this liquid moves between chambers is controlled by the relative amount of liquid in each chamber and the pipe size and friction, referred to as internal factors represented by arrows from the stocks to the *change of state* biflow. If there is more liquid in one chamber, that side

is “heavier” and causes more liquid to flow from the other chamber to that chamber. This phenomenon is known as a positive feedback loop. The external factors might enable or balance this feedback loop. If the external factors are greater than the push and pull of the internal factors, then the flow will happen in the opposite direction.

Instead of a liquid, it is a population going between an insecure state and a secure state due to various internal and external factors. Because we are presenting a generic methodology, the names for each stock – a current *Insecure State* and a desired *Secure State* – are placeholders representing whatever the user’s situation requires. We chose those names to signify a transition from one state to another. For each one of the SDGs considered in this paper (the six mentioned earlier), we define insecure and secure states as described in Table B1. When certain conditions are met, the state of the SDG begins to change from insecure to secure, signifying progress towards the implementation of that specific SDG.

Our S-shaped growth method requires a binomial variable: an SDG has either been accomplished or it hasn’t. Until the progress of an SDG passes a predefine threshold it has not been accomplished and mathematically is zero. On completion, it becomes 1. The definitions are left purposely broad because they are dependent on the user’s specific case.

Table B1. SDG-specific secure and insecure state qualitative definitions

<b>SDG</b>	<b>Insecure State</b>	<b>Secure State</b>
SDG 01 Poverty	Below international poverty line (USD\$2/day)	Above international poverty line (USD\$2/day)
SDG 02 Food Security	Lacks access to the proper quantity of calories/nutrients	Has access to the proper quantity of calories/nutrients
SDG 03 Health	General poor health	General good health
SDG 09 Gender Equality	General gender inequality	General gender equal
SDG 11 Infrastructure	Lacks access to basic infrastructure services	Access to basic infrastructure services
SDG 14 Oceans	More than a certain percentage of fishers are overexploited, and pollution is problematic.	Most fisheries are not overexploited, and pollution is minimal

#### 4. A System Dynamics Model of the SDGs: Putting It All Together

SD models are often best explained in a story-form. We will start with an operational-level explanation of poverty, as an example for all individual SDGs, by building on the insecure-secure diffusion model introduced in the previous section and illustrated in Figure B5. Then, we discuss the methodology selected to account for the interactions between SDGs using a simple matrix inversion technique.

In system dynamics modeling it is assumed that the system's structure determines its behavior and since all SDGs are assumed to behave the same way (from unsecured to secured states), all SDG modules can have the same structure. Hence, for clarity sake, we will only depict the modular structure for SDG 01 (poverty); the only difference between the SDG 01 module and the others is the specific input data and names of the module variables. To generalize the methodology to all 17 SDGs: (i) repeat the SDG 01 module an additional 16 times; (ii) connect all modules as explained later; and (iii) rename the module variables for each SDG. It is recommended that the reader follows along with the downloadable STELLA model [here](#) (select *Download Model* to download the .stmx file and *Play* or holding ctrl while [clicking here](#) to use the interface), if possible.

#### 4.1. Modeling the progress of an individual SDG

##### 4.1.1. Entry points and caps

The generic insecure-secure diffusion model of Figure B5 was repurposed for SDG 01 as shown in Figure B6. There are two types of variables to keep in mind: variables that depend on external data (e.g., expected years for completion, poverty; poverty delay; poverty interconnection factor) and variables that convert data (e.g., poverty change rate, economic mobility, and impoverished and secure population). In the user-interface section below, only variables that depend on external data will be presented to avoid any confusion and for simplicity sake.

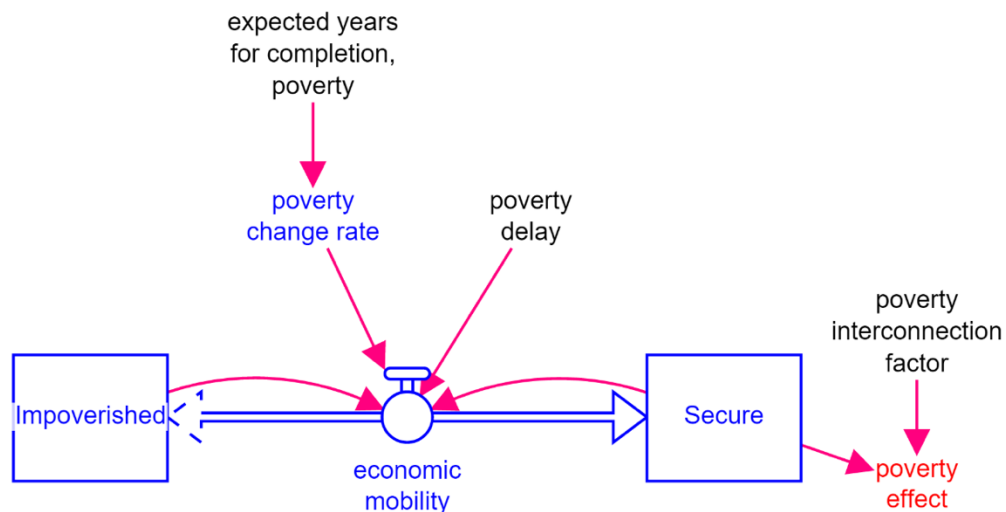


Figure B6. Insecure-secure diffusion model depicting SDG 01 Poverty

The variables that require external data are simply user inputs and extrinsic factors to the model; they are not fundamental structures, just variables. They are where the model is “capped,” they act as entry points into the model,

and they are where further complexity can be added. If the user wants to include more factors (e.g., economic, cultural, technological, etc.), this is the location where the model accepts other inputs as desired by the user or dictated by the situation.

Variables that receive the input of other data are converters that the user does not change as they contain the underlying equations that govern the model. Changing them could cause errors or erratic behavior. These are not to be modified unless the users have a clear understanding over what they are doing with SD modeling.

In Figure 6, the variable *poverty effect* is introduced to calculate the nominal effect of SDG 01 (Poverty) on all the other SDGs. These appear once in each SDG module and should remain unchanged. It is merely colored red to be easily identifiable and outline its importance. It is the variable that is used as the input to calculate the actual interactions later.

#### **4.1.2. Incorporating population growth**

Figure B6 has two stocks, one for a population of *Impoverished* people and another one for those that have escaped or were never in poverty, who are categorized as *Secure*. Because the SDGs are expected to progress over a long enough time-horizon when population change becomes significant, Figure B7 was created by combining the population growth model (Figure B2 with the insecure-secure diffusion model for SDG 01 Poverty (Figure B6). Changes, for better or worse, in one's economic status, that is the flow between the impoverished and secure states for poverty, is described by the term *economic mobility*. When a population improves its economic situation, it is said to be upwardly mobile; when its economic situation worsens, it is said to be downwardly mobile.

The stock-and-flow structure of Figure B7 allows for population changes in the impoverished and secure populations; different socio-economic groups and other population demographics might have different birth and deaths rates from one another. If population change is not important to the user, birth and death rates can be left at 0. The birth and death rates could be influenced by numerous factors, but our model leaves that up to the user to decided, so we “cap” the model here and assume constant values.

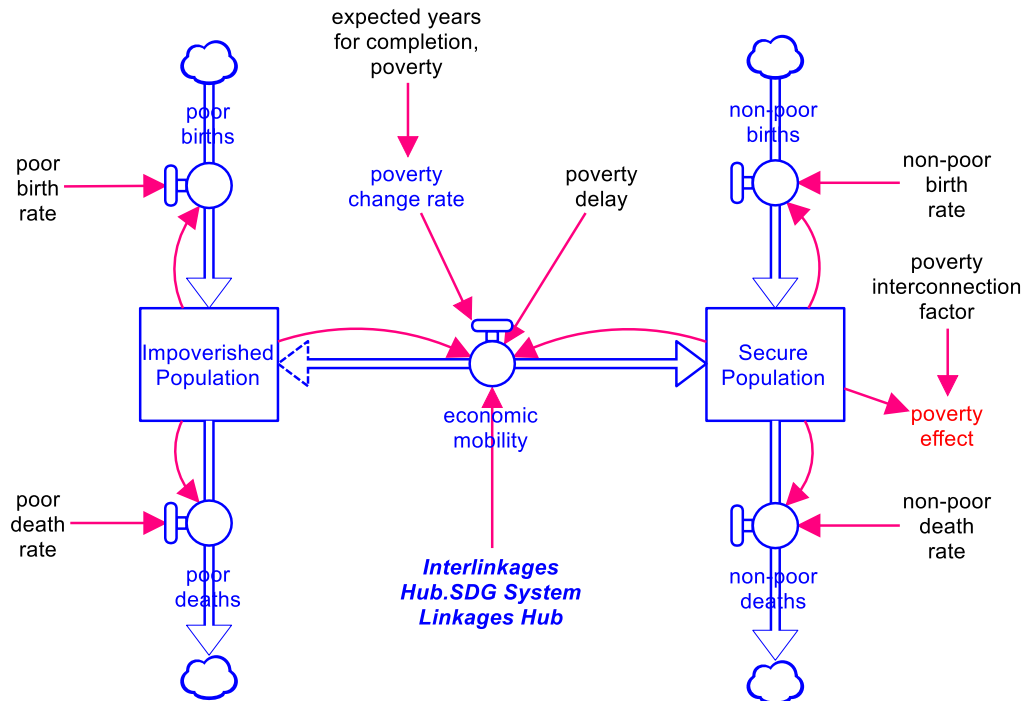


Figure B7. Insecure-secure diffusion model with population change for SDG 01

To illustrate different population growth rates for groups of people, we look again at poverty: low-income people and those living in developing countries tend to have higher birth rates compared to higher income people (Aassve et al., 2005; Schoumaker, 2004) and those living in developed countries (Ahlburg, 1996; Bank, 2017; United Nations Development Programme, 2017). High population growth rates would increase the size of the poor population (*Impoverished*) faster than the non-poor population (*Secure*), causing a feedback loop that exacerbates poverty. To combat this, the number of people escaping poverty needs to be greater than the number of people being born into it.

As a cause, effect, or both, poverty is linked with low food security, poor health, poor gender equality, poor infrastructure, poor oceans' conditions, and to some extent with all the SDGs. Population changes for impoverished people could therefore be important in designing policy that addresses poverty and contribute to the successful implementation of the SDGs.

Realistically, there are not just impoverished and non-poor people, they fall on a spectrum commonly referred to as an income distribution, usually categorized by low, medium, and high-levels of development and at varying income levels (in income per year, \$USD/year for the United States). For simplicity sake, the model of Figure 7 considers two aggregated populations. The same model could be extended to include multiple socio-economic groups. Future work will aim to address this.

#### 4.1.3. Time delay and lag effects

Delays do exist in the real-world and should be included in any modeling. When an order for a quantity of units is placed, the factory cannot immediately begin manufacturing, it takes time to ramp-up production. This lag-time exists in sustainable development as well: when the decision to implement a certain policy is made, it takes time for the proper institutions to be notified, funding to be sourced, and implementation plans and strategies to be devised. Likewise, when an NGO, governmental agency, or some other development entity decides to address poverty, it isn't immediately reduced; there is always preparation time before the policy is fully implemented.

This principle was included in our system dynamics model by using a delay function, which is another factor that has potential to affect economic mobility. Each SDG has a time delay similar to the poverty delay; examples include health delay, food security delay, etc. Delay is defined as the time it takes for change to go from zero to fully "ramped-up." This delay was added using the DELAY1 function available in the STELLA software and can be written as follows:

$$\text{DELAY1} \left( \text{SDG X change rate}, \frac{\text{SDG X delay}}{12}, 0 \right)$$

This function delays the rate at which flow between two states (SDG X change rate) by a certain number of months (SDG X delay), which is converted to years by dividing by 12. The zero in the third position of the DELAY1 function signifies that there is no rate of change at the simulation's start. In other words, it takes time to fully initiate the SDGs implementation strategy, which starts at 0.

#### 4.1.4. Migration between states

Just as each SDG has specific names for the starting and end states (e.g. impoverished and secure for SDG 01), the rate of change between those states has unique names. Change between impoverished and secure states for poverty is economic mobility: for food security, it could be *access rate to food*; for governance, it could be *change in governance effectiveness*; and for partnerships, it could be *change in partnerships*. This is user-defined.

In Figure B7 (SDG 01 Poverty), economic mobility (rate of change between the impoverished and secure state) is controlled by five variables (*poverty change rate*, *poverty delay*, *Impoverished population*, *Secure population*, and *Interlinkages Hub.SDG System Linkages Hub*), depicted by the five arrows heading to the biflow. The *Interlinkages Hub.SDG System Linkages Hub* variable will be discussed in a following section, but in short it is the

coefficient, calculated endogenously, that accounts for the effects of the other SDGs on a specific SDG. It is included in the economic mobility flow rate as follows:

$$\text{economic\_mobility} = \text{DELAY1}(\text{poverty\_change\_rate}, \text{poverty\_delay}/12, 0) * \text{Impoverished\_Population} * \text{Secure\_Population} * (1 + \text{Interlinkages\_Hub.SDG\_System\_Linkages\_Hub}[\text{SDG\_01\_No\_Poverty}])$$

This equation differs from one SDG to the next by the names assigned to the variables: poverty change rate becomes food security change rate, health change rate, etc. Other than that, the mathematical structure remains unchanged for all SDGs.

#### 4.2. Interactions Among the SDGs

Figure 8 shows the overall system dynamics model that links six of the 17 SDGs. Each module in in this figure has the same structure as that shown in Figure B7 for SDG 01 (poverty). The arrows emanating from each SDG module to the center *Interlinkages Hub* are described in the next section (*Effect of one SDG on all SDGs*), while the arrows radiating out from the center hub are described in the following section (*Effect of all SDGs on one SDG*). These two sets of arrows are used to model how the SDGs interact with one another by way of the center *Interlinkages Hub*. Removing the center hub and arrows would be functionally the same as thinking in “silo’s.”

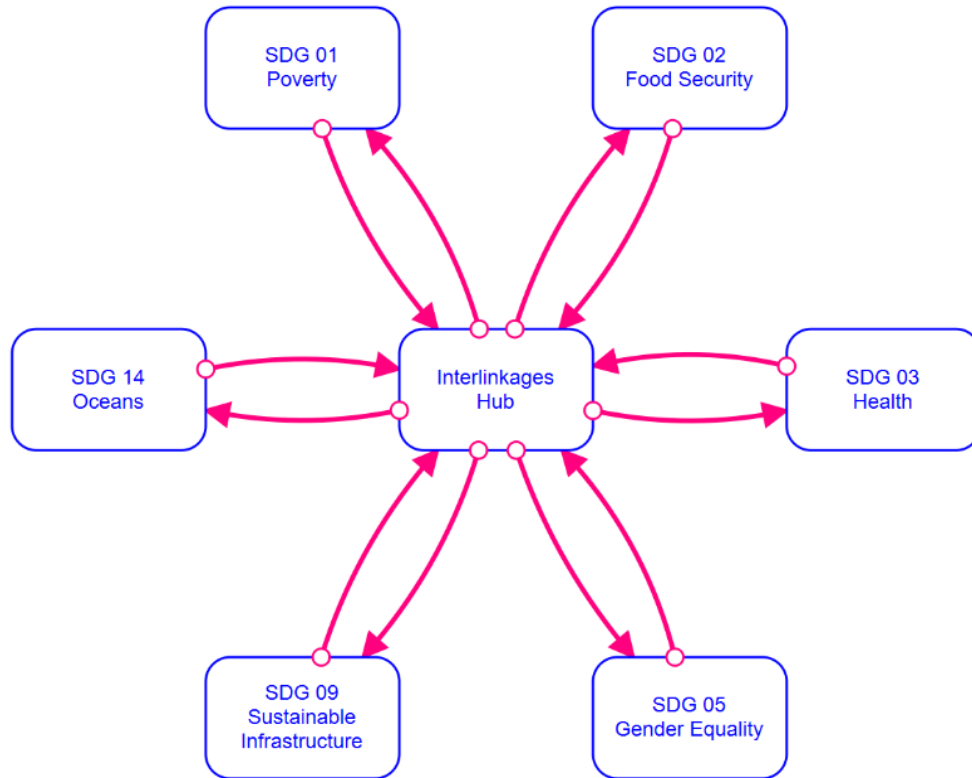


Figure B8. Top-level view of the SDG interconnections

#### 4.2.1. Effect of one SDG on all SDGs

The effect of SDG 01 (poverty) on the other SDGs is modeled using the *poverty interconnection factor* in Figure B7. This is a  $n$ -by-1 array, where  $n$  is the number of SDGs linked to the SDG being considered; the array would be 6-by-1 in the present example. The numbers in this array fall between -1 (complete dependence) and 1 (complete influence). A value of 0 signifies a net-zero or no interaction; -1 equates to a maximally-negative interaction; and 1 implies a maximally-positive interaction. Table B2 lists the input values used in our STELLA model. Poverty's effect on, say, the SDG 14 (Ocean) is -0.1, which means 10% of poverty's full effect (*Secure*) is removed from the effect of the oceans. Poverty slows the progress of SDG 14 because it is a negative interaction, but the overall effect of all the other SDGs might make the effect positive. These values are multiplied by the scalar value of the *Secure* state stock population. This interconnection value, which exists for all SDGs, is pulled out of the poverty module, and sent to the center *Interlinkages Hub*.

Table B2. Poverty interconnection factor

SDG	Interconnection Strength
SDG 01 Poverty	0



SDG	Interconnection Strength
SDG 02 Food Security	-0.4
SDG 03 Health	-0.6
SDG 09 Gender Equality	-0.2
SDG 11 Infrastructure	0.2
SDG 14 Oceans	-0.1

Each SDG module has an equivalent interconnection factor with values unique to each SDG. Combining all six interconnection factor values generates a cross-impact matrix, as discussed in our companion paper. The *column* vector depicted in Table B2 is the same as a *row* vector in the cross-impact matrix, but it is transposed to be depicted as vertical. Aside from that, the key difference between the two is that this cross-impact matrix is quantitative and the one described in our previous paper is semi-quantitative.

#### 4.2.2. Effect of all SDGs on one SDG

Each SDG sends its interaction effect (Figure 8) to the *Interlinkages Hub*, where a transposition function occurs as shown in the following equation:

$$\begin{aligned}
 & \text{SDG\_System\_Linkages\_Hub[SDG\_01\_No\_Poverty]} = \\
 & \text{SDG\_01\_Poverty.poverty\_effect[SDG\_01\_No\_Poverty]} + \\
 & \text{SDG\_02\_Food\_Security.food\_security\_effect[SDG\_01\_No\_Poverty]} + \\
 & \text{SDG\_03\_Health.health\_effect[SDG\_01\_No\_Poverty]} + \\
 & \text{SDG\_05\_Gender\_Equality.gender\_equality\_effect[SDG\_01\_No\_Poverty]} + \\
 & \text{SDG\_09\_Sustainable\_Infrastructure.infrastructure\_effect[SDG\_01\_No\_Poverty]} + \\
 & \text{SDG\_14\_Oceans.oceans\_effect[SDG\_01\_No\_Poverty]}
 \end{aligned}$$

This equation takes the effect of each SDG on poverty (poverty effect in Figure B7), extracts that specific part of the array regarding poverty, and sums those effects into a single value creating the *SDG System Linkages Hub[SDG 01 No Poverty]* variable. The first part of the arrayed variable name refers to the specific variable, while the part in brackets refers to the part of the array, in this case poverty. For food security, the part in the brackets becomes *SDG 02 Food Security*, while everything else remains unaltered.

We can now explain in its entirety all components of the *economic mobility* equation mentioned above. Taking the poverty part from the interconnection equation above, *SDG System Linkages Hub [SDG 01 No Poverty]*, and applying it to the *economic mobility* equation, the effect of interconnections is a coefficient that either increases or decreases the rate of change between two states (i.e., from *Impoverished* to *Secure* in the case for poverty). This is similar to an interest rate, where the rate is added to one and then multiplied by the principle for that time period.

A virtually identical approach can be used for each of the SDGs considered, and at this point, a single iteration of our poverty story is complete. Each iteration represents one year (model's default value), but that could be any user-defined time-scale (day, week, decade, etc.). Our model is set to a duration of 85 years, from 2015 to 2100, implying 85 iterations. That number would climb to 1020 iterations (85 x 12) if the analysis uses a monthly time-interval.

#### **4.3. User-Friendly Interface for Policy Analysis**

The model presented herein can be used as a starting point to analyze the interactions between specific SDGs or all SDGs or the components of any anthropocentric network or complex system. It provides a basic structure for adding and modeling complexity. Finally, it represents a learning tool to demonstrate the importance of systems thinking in sustainable development in a quick-to-understand and easy-to-operate, yet complicated and holistic format. To accomplish this, a user-friendly interface was created. All the equations, model structures, and input happens in the background, so someone without any training in the software or understanding of system dynamics could easily use the model. This would make it especially useful as an education tool or a comparative analysis tool for running multiple scenarios and what-if analyses for development professionals, policy-makers, students, and researchers. Furthermore, the interface saves time by compiling more of the model inputs into an easy-to-use dashboard, while indirectly also aiding in debugging and locating errors.

The interface summarized in Figure B9 is composed of multiple pages. The interface opens on a homepage from where all pages can be accessed. The *Interconnections Among the SDGs* page (shown in Figure B10 with default values) is the main model where the user can change the values of all SDG interactions, as well as see their effects and analyze their impacts. The majority of the model's functionality can be accessed here. The value on the top-left of the graph depicts the aggregate impact between zero and one for all interactions among the SDGs; the larger the number the better. The *Secondary Parameters* page is where the user can alter population birth and death rates, the time delays, and modify the initial conditions for each SDG, essentially all the variables that don't directly influence the SDGs' interconnections. The *Comparative Analysis* page shows the dynamic progress of each SDG compared to previous runs. Finally, the remaining pages enable the user to explore individual SDGs. We also include the "stories" of the bottom- and top-level of the model similar in format to the previous two sections describing the model.

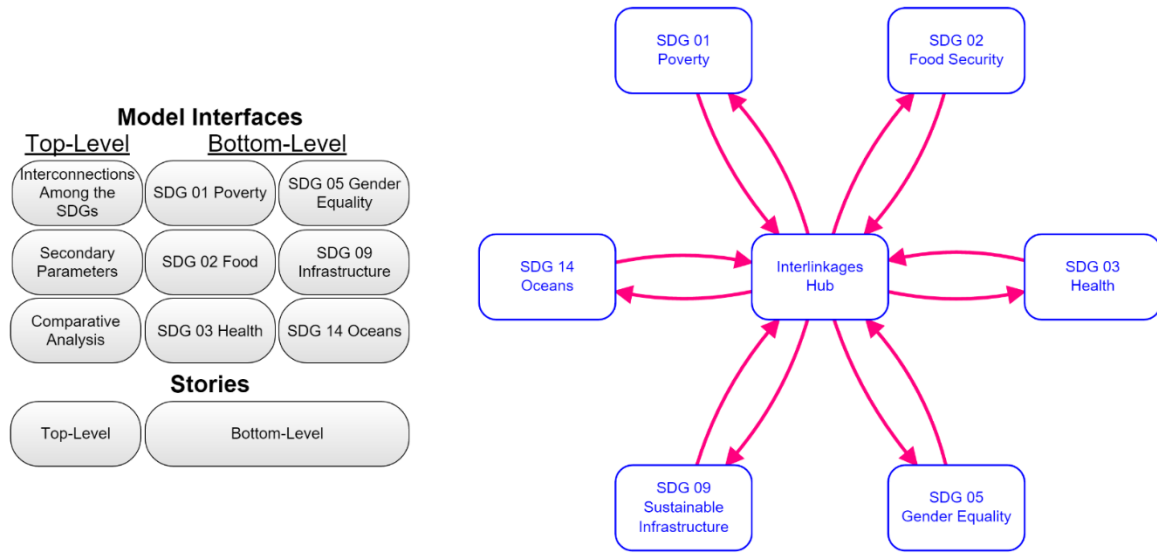


Figure B9. Interface homepage

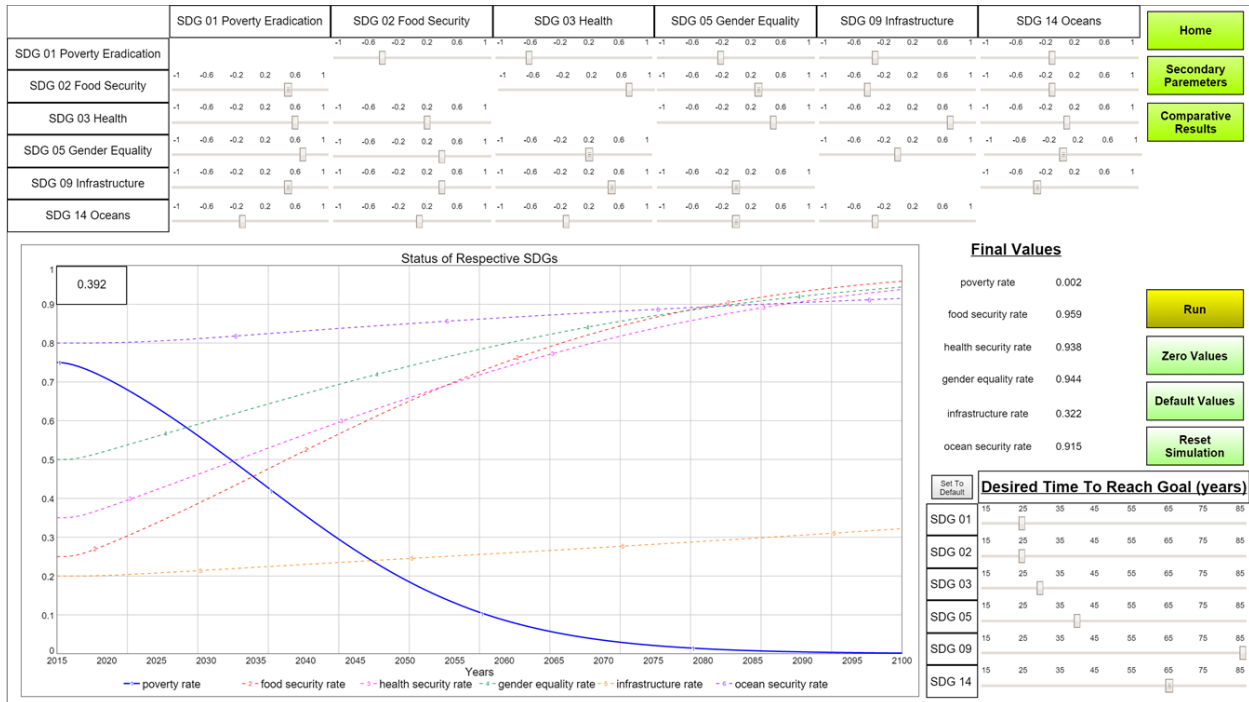


Figure B10. Main interface window

## 5. Conclusion

System dynamics models provide many benefits over the cross-impact analysis (discussed in Part 1) when modeling the behavior associated with the progress of SDGs and their interconnection over time. Its fundamental limitation, however, is that constructing system dynamics models is time-consuming. That being said, system dynamics is versatile as long as the models are carefully built, appropriate variables are selected, and data are available about these variables. SD models are best suited for more complex and ill-defined situations such as those associated with the SDGs. System dynamics requires that detailed analyses be carried out first about the problems being addressed. Cross-impact analysis and network analysis discussed in our companion paper are good examples of such analyses, as they provide a general overview of the SDGs and their interactions. For this reason, our two papers should be read together and considered as two complementary steps (soft and hard approaches) in modeling the complexity of the SDGs in a systemic manner.

System dynamics models can represent more complicated situations than cross-impact analysis. Cross-impact analysis is mostly spreadsheet-based, which makes complex interactions among variables difficult to visualize and build. On the other hand, system dynamics models utilize versatile components on a blank canvas allowing for relatively, easily created models to depict complex interactions. Furthermore, it allows for more “creativity” and can handle more detailed analyses of more complicated systems than cross-impact analysis. Finally, system dynamics modeling by its very nature looks at change over time which is not possible with cross-impact analysis.

The system dynamics model presented herein is limited to six of the 17 SDGs. Its structure is general enough that it can be extended to all SDGs, although, the interface proposed in this paper is simple enough that it can be used by development practitioners and decision makers to explore various scenarios for each SDG and their interactions. Finally, the interface’s general nature can be used to model the real-world complexity of ill-defined systems in which several sub-systems interact in an intra and inter-connected manner.

With the versatility of SD modeling, future work will apply it to applications outside the SDGs. Early work towards that already shows promise for many complex issues including urbanization, migration, and community development. Furthermore, it has been especially useful in modeling the water-energy-land-food (WELF) nexus and for other uses of the nexus approach, where there are multiple relatively discrete sectors that interact with one another. These sectors can be technical, environmental, political, social, economic, or more (as with the SDGs), and are useful

at any scale from the individual community to countries or international. Future work will expand on the S-shaped archetype in section 3 to include other variants and further complexity.

### **Appendix C – Implementing the Food, Energy, and Water Sustainable Development Goals**

**Keywords:** water, energy, land, food, climate, nexus, systems thinking, cross-impact, system dynamics, modeling, policy coherence, trade-off analysis, dialogue

## 1. Definitions

**Interdependence, interactions, and linkages** are terms that refer to how the variables in a system connect, influence, and depend on one another. Scientific fields, especially the social sciences, primarily analyze how a single variable is affected by one or many others. **Causality** refers to the effect of some variable(s) on some other variable(s). It seeks to answer, what *causes* the observed phenomena. They seek to understand small-scale causal linkages, another way to describe interconnections within a system. Most disciplines look at the small-scale structures, where most other effects are considered outside the systems. Systems approaches take many of these small-scale causal structures and combine them to generate a more complete and large-scale picture of the entire system. This big picture of a system enables **feedback loops** to be seen, where variables can affect themselves over time either in the short-term or long-term. They act through chains of interconnected variables that form circular loops. Feedback loops can be balancing or reinforcing. **Reinforcing loops** are used to model self-reinforcing, feedback processes that have potential to cause permanent growth or eventual collapse. Reinforcing loops are prevented from perpetual growth or decline with **balancing loops**, which create self-correcting processes leading to stability and equilibrium (Meadows 2008; Zelinka and Amadei 2019b). As described in the system dynamics literature, various combinations of loops and delays can be created to model the **behavior patterns** – growth, decay, overshoot, oscillations, equilibrium, randomness, and chaos – of complex systems. Unique and complex behavior in these systems come from the interaction of structural components and attributes (e.g. feedback loops, interconnections, initial conditions, etc.) that are at play (Amadei 2015). A **WEF Nexus ‘hotspot’** is a vulnerable sector or region, with a defined scale and facing stresses in one or more of its resource systems due to resource allocations that are at odds with the interconnected nature of the food, energy, and water resource systems within them (Mohtar and Daher, 2016). **Policy coherence** ensures that policies being developed across different sectors within the same scale (e.g., national, for example), and policies being developed across different scales, do not compete with one another (Daher et al., 2018b).

## 1. Introduction to the SDGs and their interconnections

### 1.1. The United Nations’ Sustainable Development Goals

In 2015, the United Nations introduced the Sustainable Development Goals (SDGs), a set of 17 ambitious goals (Figure ) and 169 targets, that are a road map for worldwide sustainable development and for a plan of action “to address urgent global challenges over the next 15 years” (United Nations 2016:2). In launching the SDGs, the General

Assembly of the United Nations “recognize[d] that eradicating poverty in all its forms and dimensions (including extreme poverty) is the greatest global challenge and an indispensable requirement for sustainable development” (United Nations General Assembly 2015:1). The SDGs can be seen in

Figure .



Figure C1. The 17 SDGs; red-boxed SDGs are food (02), energy (07), and water (06), while blue-boxed SDGs are land (15) and climate (13) (Global Goals 2016)

As described in the Resolution 70/1 adopted by the General Assembly on 25 September 2015, the aim of the SDG framework is a) to cultivate and expand humanity’s desire to “do good” while also organizing its ability to do so; ii) “to build on the [previous] Millennium Development Goals (MDGs) and complete what they did not achieve” (United Nations General Assembly 2015:1); and c) “balance the [four] dimensions of sustainable development: the economic, social, [political,] and environmental” (United Nations General Assembly 2015:3) by accounting for their trade-offs and interactions (Zelinka and Amadei 2018; Daher et. al, 2018a; Stephan et al., 2018). In this chapter the authors specifically:

- Identify some fundamental interconnections among the food, energy, and water SDGs using systems thinking
- identify modelling tools and methods useful for understanding the trade-offs and potential competition across implementing different SDGs



- identify governance and policy coherence challenges associated with planning for, and implementing, the SDGs

## 1.2. Systems thinking to understand the interactions among the SDGs

“The interlinkages and integrated nature of the Sustainable Development Goals are of crucial importance in ensuring that the purpose of the new Agenda is realized” (United Nations General Assembly 2015:2). From the inception and ultimately the adoption of the SDGs, there has been an increasing interest in understanding and quantifying their interactions (Costanza et al. 2016). Because of their complex formulation, some goals are bound to affect others negatively or positively, whereas others may not have any *direct* effect, while all SDGs will affect all others through some *indirect* path. For example, increasing agricultural output (SDG 02) will require more energy-intensive (SDG 07) fertilizer and/or more land (SDG 15); but a lack of reliable infrastructure (SDG 09) and good governance (SDG 16), especially in the presence of high inequalities (SDG 10), could make food distribution ineffective negating the higher output.

Furthermore, the interactions are context- and scale-specific; each country, city, or entity attempting to adhere to the SDG framework has unique characteristics and situations. The goals and targets must be “global in nature and universally applicable, [while also] taking into account different national realities, capacities and levels of development, and respecting national policies and priorities” (United Nations General Assembly 2015:13). For example, rural Kenya will not have the same conditions as an island-nation; a city will have different issues than a country; a water-poor country will struggle with problems that a water-rich community will not; political factors might constrain or further enable certain outcomes for the SDGs. Likewise, a country with strong environmental regulations might not have such large negative impacts on the environment resulting from energy-use and economic activity; a country or region in conflict require special attention over peaceful countries. That variability could even exist within the same nation or state. In a recent study focused on identifying interventions to bridge the projected water gap in the state of Texas, three distinct “**water-energy-food nexus hotspots**” (Mohtar and Daher, 2016) were identified. One such hotspot was in an area of growing municipal and agricultural competition in Lubbock; others included the rapidly growing city of San Antonio and the hydraulic fracturing activity in the neighbouring Eagle Ford shale play (Daher et al., 2018c). Even though the goal of bridging the water gap, was guided by a common understanding and quantification of the interconnections between the water system, and other agriculture and energy systems, the solutions explored

needed to be localized to the physical resource, and governance, constraints. The factors leading to the success or failure of implementing the SDGs are innumerable, but merely being cognizant of their complexity and actively trying to address them will be a huge improvement over the traditional “siloes,” linear approaches.

Few works attempt to analyze the SDGs in an integrated way, especially at the national-level (Willis et al. 2016), where many political and economic decisions are made. Adopting a systems mindset will enable development practitioners and decision makers to better understand how prioritizing certain aspects of sustainable development could influence all SDGs, especially the FEW SDGs. Utilizing a systems approach will yield many insights for implementing the SDGs over other approaches (Figure C2).

- better understand how meeting the goals and their targets depend on context, time, scale
- explain existing patterns of human development at different spatial and temporal scales;
- interpret emergent properties of human development such as poverty/wealth, peace/conflict, health, resilience, and sustainability that may involve one or several goals;
- examine various perspectives of human development interventions and consider possible (intended and unintended) consequences of decision making and policies and their implications;
- identify and explore leverage or tipping points, those critical places to intervene at different scales that will most benefit human development;
- predict how countries or regions may respond to various constraints and disturbances and/or strategies of capacity development;
- monitor and evaluate the performance of development interventions and decide on how to adjust as development projects unfold, thus leading to more successful projects in the long term; and
- develop approximate but good enough sustainable development solutions that are more flexible and adaptive to change than the traditional deterministic, rigid, and ultimately inappropriate long-term solutions.

Figure C2. Useful characteristics of systems for the SDGs (Zelinka and Amadei 2019a)

### 1.3. The food-energy-water nexus

The SDGs dealing with food (SDG 02), energy (SDG 07), and water (SDG 06) (FEW) have been deemed higher priority (Weitz et al. 2014) over many of the other goals because food, energy, and water (Food and Agriculture Organization 2018; United Nations General Assembly 1948, 2010) are crucial for human survival and are considered to be basic human rights/services. FEW resources are both directly and indirectly important for most, if not all, human processes. Furthermore, land-use (SDG 15) and climate change (SDG 13), are intimately connected with the FEW nexus, which creates the water-energy-land-food-climate (WELFC) nexus to describe these five interconnected sectors. Population dynamics is the main driver of change in the WELFC nexus: people require water and food to

survive; land for shelter and a place to grow food; energy is crucial for powering all process crucial to the functioning human civilization; and climate is dependent on emissions of greenhouse gas from other sectors, especially energy, but also can affect agriculture due to changing weather patterns. The FEW-related SDGs (signified by the colored boxes in Figure C1) crosscut each other and form a tighter subsystems within the entire SDG framework. Looking at the targets within those SDGs, one can see just how interconnected they are; most targets are important to meeting the targets of all five SDGs (Figure C3, the letters at the end of the targets signify intersectoral connections with other FEW SDGs).

<p style="text-align: center;"><b>SDG 02 FOOD/AGRICULTURE (F)</b></p> <ul style="list-style-type: none"> <li>• By 2030, end hunger and ensure access for all people to safe, nutritious, and sufficient food all year-round (W, E, L, C)</li> <li>• By 2030, end all forms of malnutrition and address the nutritional needs of vulnerable people (W, E, L, C)</li> <li>• By 2030, double the agricultural productivity and the incomes of small-scale food producers (W, E, L, C)</li> <li>• By 2030, ensure sustainable food production systems and implement resilient agricultural practices (W, E, L, C)</li> </ul>
<p style="text-align: center;"><b>SDG 06 WATER AND SANITATION (W)</b></p> <ul style="list-style-type: none"> <li>• By 2030, achieve universal and equitable access to safe and affordable drinking water for all (E, F)</li> <li>• By 2030, improve water quality by reducing pollution, halving the proportion of untreated wastewater, and increasing recycling and safe reuse (E, L, F, C)</li> <li>• By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals (E, L, F)</li> <li>• By 2030, implement integrated water resources management at all levels. (E, L, F)</li> <li>• By 2020, protect and restore water-related ecosystems (E, L, F)</li> </ul>
<p style="text-align: center;"><b>SDG 07 RENEWABLE ENERGY AND ENERGY EFFICIENCY (E)</b></p> <ul style="list-style-type: none"> <li>• By 2030, ensure universal access to affordable, reliable, and modern energy services. (W, L, C)</li> <li>• By 2030, increase substantially the share of renewable energy (L, C)</li> <li>• By 2030, double the global rate of improvement in energy efficiency by 2030. (W, L, C)</li> </ul>
<p style="text-align: center;"><b>SDG 13 CLIMATE CHANGE (C)</b></p> <ul style="list-style-type: none"> <li>• Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries (W, E, L, F)</li> <li>• Integrate climate change measures into national policies, strategies and planning (W, E, L, F)</li> <li>• Improve education, awareness, and human and institutional capacity on climate change mitigation, adaptation, impact reduction, and early warning (W, E, L, F)</li> </ul>
<p style="text-align: center;"><b>SDG 15 LAND AND TERRESTRIAL ECOYSTEMS (L)</b></p> <ul style="list-style-type: none"> <li>• By 2020, ensure the conservation, restoration, and sustainable use of terrestrial and inland freshwater ecosystems and their services in line with obligations under international agreements (W, F, C)</li> </ul>

- By 2020, promote the implementation of sustainable management and restoration of forests (W, E, F, C)
- By 2030, combat desertification and restore degraded land and soil (W, E, F, C)
- By 2030, ensure the conservation and restoration of mountain ecosystems (W, F, C)
- By 2020, take significant action to reduce the degradation of natural habitats and halt the loss of biodiversity (W, F, C)
- Promote fair and equitable sharing of the benefits from the utilization of genetic resources as internationally agreed (F)
- By 2020, take measures to significantly reduce the impact of invasive alien species on land and water ecosystems (W, F)

Figure C3. WELFC-related SDGs and targets (adapted Weitz et al. 2014) with land (L) and climate (C) added by the authors from the United Nations General Assembly (2015); edited down for length

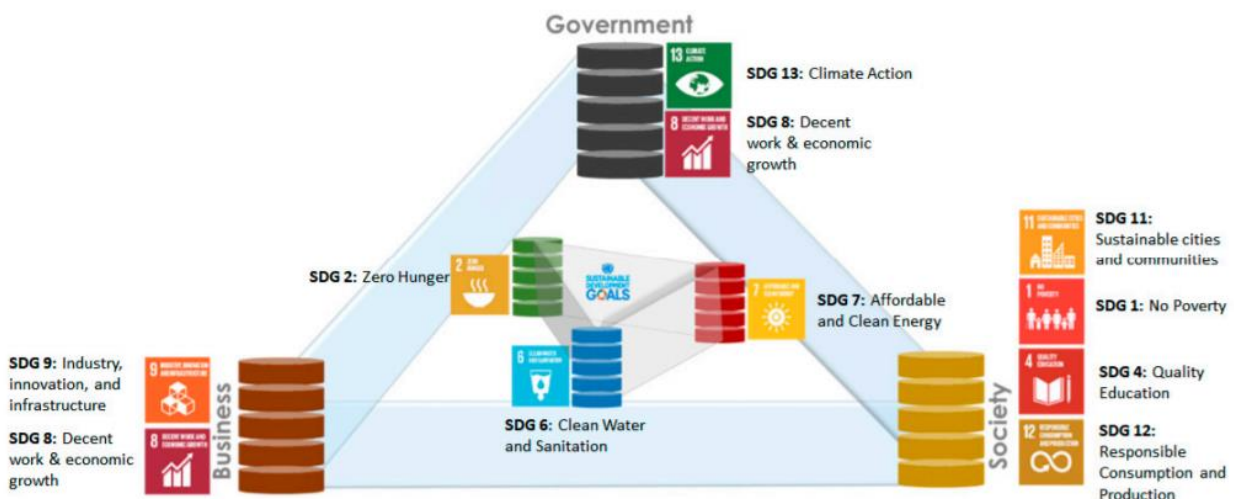


Figure C4. Food-Energy-Water nexus and interactions between business, governmental, and societal players (Daher et. al, 2018b)

The three highly interconnected resource systems are also affected by players who govern, consume, or manage their supply chains. These players also interact among one another. Therefore, in addition to understanding the biophysical resource interactions and trade-offs across the resource systems, we need to similarly understand the interactions which exist among the different types of players (Figure C4).

The United Nations General Assembly in 2015 said the SDGs “are integrated and indivisible, and balance the three dimensions of sustainable development.” Unfortunately, the “inclusive process of intergovernmental negotiations”, which superseded academic and expert discourse, ultimately controlled the design and eventual manifestation of the SDGs. While admirable with intention, relying on political consensus meant that the SDGs are somewhat disorganized, worded strangely, and are difficult monitor. Earlier, we discussed systems approaches to understand, model, and analyze the SDGs (Figure C2); the next section describes two such tools in more detail – cross-

impact analysis (qualitative or semi-quantitative, soft-systems tool) and system dynamics modeling (quantitative, hard-systems tool).

## 2. Modeling trade-offs to strategize pathways forward

The growing need for understanding and quantifying the tight interconnections between water, energy, and food challenges has resulted in the development of different integrative FEW Nexus assessment tools and models, such as “Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism”, MuSIASEM (Giampietro et al., 2013), “Climate, Land, Energy and Water strategies”, CLEWS (Howells et al., 2013), WEF Nexus Tool 2.0 (Daher and Mohtar, 2015; Mohtar and Daher, 2014), among others (FAO, 2014; IRENA, 2015).

In addition to the identification of the proper analytics needed to understand a FEW Nexus hotspot, it is as critical to identify the criteria on which resulting assessments are evaluated and communicated to stakeholders in order to catalyze an informed trade-offs dialogue. With that goal in mind and before one begins to model and analyze those trade-offs, one must first ask some guiding questions, such as those in Figure C5 (Mohtar and Daher, 2016; Daher et al., 2017b).

- At what **scale** and **complexity** do we need to model? What is the appropriate resolution in which assessments could be effectively communicated to different decision makers?
- Which **analytical and trade-off tools** must be used to simulate and evaluate different scenarios of resource allocation, climate change, population growth, drought, different water sources, and technology choices?
- How might approaches for resource allocation **assessments be evaluated**?
- How can **stakeholder input** be incorporated into the criteria for scenario evaluation?
- How do we address **lack of coherence or competition** between different decision-making entities across sectors and scales? How can that lack of coherence be factored into the assessment of the scenarios being evaluated?
- How can **human behavior and perceptions** be merged and integrated into technologically sound solutions for the FEW nexus?

Figure C5. Sample questions to develop assessment criteria for integrative tool scenarios (Daher et al, 2017a; 2017b)

Multiple papers and reports have been produced by various organizations to identify important linkages among the SDGs, how the SDGs affect each other (Coopman, et al., 2016; ICSU & ISSC, 2015; Nilsson et al., 2017; Nilsson et al., 2013; Vladimirova & Le Blanc, 2016), and how to measure qualitatively or semi-quantitatively those interactions (ICSU and ISSC 2015; Nilsson et al. 2017; Sustainable Development Solutions Network et al. 2015). These publications are great starting points, as they focus on the science of linkages, but fall short of modeling and analyzing the impact of these interactions as a system that changes over time. They serve as the scientific foundation

(ICSU & ISSC, 2015) on which methodologies to understand the long-term trajectory of the SDGs with a systems perspective can be applied.

Some mathematical methods exist that could be used to model the trade-offs among the SDGs as strategies for their implementation are made including: (i) equations to calculate the indirect impacts (the effect due to the interconnections) from direct observations of a mathematical system (Bollen 1987); (ii) economic input-output and Leontief models (Moffatt & Hanley, 2001; Sachs et al., 2016; Todorov & Marinova, 2011); (iii) MICMAC structural analysis (Arcade et al., 1999; Glenn, 2004); and (iv) cross-impact analysis (Weimer-Jehle 2006, 2008; Zelinka and Amadei 2019a). These tools are great starting points, as they focus on the science of linkages and the entire SDG framework, but fall short of quantifying the impact of these interactions over time (dynamically). They are generally too simplistic to reliably model complex systems with many interacting variables – that is best left up to computer-aided system dynamics (SD) modeling, described later in this section. Although, the latter of these tools, cross-impact analysis (CIA), provides a good foundation for framing the SDGs at a high-level. There are other methods that can be used to understand complex systems and the SDGs, such as network analysis and agent-based modeling, but they do not apply for all situations like CIA and SD modeling, so they have been omitted. SD modeling complements and builds on CIA and will be presented as such (Zelinka and Amadei 2019a, 2019b).

### **2.1. Cross-Impact Analysis**

A cross-impact analysis (CIA), also called double-causality analysis, is a simple, yet informative tool that can be utilized to yield surprising insight for the interactions among the sectors in the WELFC nexus. A CIM can be qualitative, semi-quantitative, or quantitative but is considered a soft-systems tool. It originated in the mid- to late-1960s (Gordon and Hayward 1968) and was initially developed to analyze weakly (soft) structured systems for when theory-based computational (hard) models do not work due to the systems complexity, uncertainty, and disciplinary heterogeneity (Zelinka and Amadei 2019a). In short these are complex social issues that cross-cut many areas, such as the SDG, but also migration, corruption, and urbanization, for example. CIA is meant to assess the “interrelations [among] the most important influential factors in a system by experts who evaluate [subjectively] pairs of these factors” (Weimer-Jehle 2006:336). Its approach is flexible and lends itself to expert discourse, which is important for effectively identifying the actual causes of a problem as opposed to using a mere intuitive and/or educated guess. Cross-impact analysis is a method to understand complex systems with *relatively* little effort in a concise and

informative way. Due to its flexibility and versatility, it is apt for use in comparing multiple scenarios and finding out the most appropriate ones based on analytical tools rather than, ideally, guesses, bias, and partisan influence.

CIA can be qualitative, which serves the purpose of explaining a complex system with words to a general audience and those unaccustomed to the subject material. Figure C6 is one such representation of the WELFC nexus. The authors compiled a general CIA representing an *average-sized country of average population and at an average level of human development*; no such country exists, but many countries can relate to most of the qualitative CIA in Figure C6. Each cell depicts the *direct* effect of the row onto the column. For example, at the interconnection of water and energy (top-left of Figure C6) is described with two cells. First, is the influence of water (row) on energy (column) that can also be read as energy's dependence on water; water is needed to mine the coal and natural gas used to power the majority of the electricity sector, but is also required to cool down thermoelectric power plants. Inversely, the effect of energy (row) on water (column) is described: energy is required to treat and pump water; energy-use causes water pollution; biofuels and hydropower both use large quantities of water; and energy efficiency reduces demands for water.

	<b>water</b>	<b>energy</b>	<b>land</b>	<b>food</b>	<b>climate</b>
<b>water</b>		mining of fuel stock; thermo-electric cooling/evaporation	erosion; mudslides; fight desertification	irrigation; raising livestock; cleaning food	
<b>energy</b>	treatment/sanitation facilities; water pollution; distribution; hydropower and biofuel energy increase pressure on water resources; energy efficiency reduces those pressures	generation facilities	generation facilities; solar PV, wind, and biofuels require land; energy efficiency; environmental degradation	fertilizer; processing; transportation & distribution;	emits GHG; air pollution
<b>land</b>	treatment facilities; distribution	mining of fuel stock; generation facilities; distribution		agricultural land-use; grazing land	land-use change alters the land's capacity to absorb/emit GHGs
<b>food</b>	agricultural field run-off pollutes water and aquatic ecosystems	biofuels	agricultural land conversion; agricultural field run-off pollute habitats	raising livestock	agriculture is a large source of GHGs
<b>climate</b>	changing precipitation patterns		desertification; floods	extreme and unpredictable weather variability	internal climate feedbacks

Figure C6. Qualitative cross-impact matrix of the WELFC nexus (compiled from Gulati et al. 2013, Mohtar 2016, Måns Nilsson et al. 2017, Willis et al. 2016, and the authors)

In short, CIA can aid decision makers to (i) attain a better qualitative and quantitative understanding of the way the SDGs interact; (ii) detect emerging patterns resulting from those interactions; (iii) use context-specific information about direct impacts to identify indirect effects; and (iv) identify leverage points hidden within the SDGs. In the next section system dynamics modeling is introduced as a more detailed way to look at the complexity of the SDGs and over time.

## 2.2. Systems Dynamics Modeling

System dynamics is an entire discipline in and of itself, so this section will only provide brief overview. The authors recommend the reader review the publications and books mentioned in this section for a deeper understanding. Zelinka and Amadei (2019b) describes in detail a system dynamics model to analyze the SDGs. Landmark books, among many others, that have promoted the applications of system dynamics include those by: Sterman (2000) on business dynamics; Ford (2010) on modeling environmental/ecological processes; and Amadei (2015) which involves application of systems thinking and SD to community development. In general, systems dynamics has unique characteristics that warrant its use in modeling the interaction of the SDGs.

A simple way to see system dynamics is that it studies “how systems change over time” (Ford 2010). The System Dynamics Society (2016) defines system dynamics as a computer-aided approach to policy analysis and design. It applies to dynamic problems arising in complex social, technical, political, economic, or ecological systems — literally any dynamic systems characterized by **interdependence, mutual interaction, feedback, and causality**.

- It is a method that can be used to study **how systems continuously change over time** due to possible changes in and relationships among components and changes in the overall direction of systems.
- SD models are designed to contain the components that “are important to explain [the] dynamic behavior” (Richardson and Andersen 2010; Vennix 1996) of systems including their internal rules.
- Information feedback mechanisms in the system can be included in the form of interconnected loops and circular causality allowing for **reinforcing** and **balancing** trends. This can help in explaining the counter-intuitive forms of behavior of some systems.



- Combining feedback loops, various dynamic patterns can be simulated and used to model different behavioral patterns of system changes such as **growth, decay, overshoot, oscillations, equilibrium, randomness, and chaos.**
- The overall structure of a system is emphasized over individual components because **the structure of a system will always determine its behavior** (i.e. as the structure of a system changes, so must its behavior)

System dynamics can take over where the abilities of cross-impact analysis end – at the point when CIA is counterproductive and no longer practical to analyze the issue at hand. CIA is static, and each iteration would require a new matrix to be filled-out. It is more subject to bias and can only focus on the emergent problem, not the structural cause. The cross-impact matrix, which is at the fundamental core of cross impact analysis, requires judging experts to estimate how variables interact with each other, the degree of their interactions, and the possible results of their impacts (Weimer-Jehle 2006). Essentially, the quality of the analysis depends on the accuracy and expertise of the people undertaking that analysis. The experts filling out the cross-impact matrix are “expected to possess insights which rather should be the results of an analysis” (Weimer-Jehle 2006:337).

### **3. Governance, policy coherence, and management implications**

Food, energy, water, and many other sectors are highly interconnected, but in practice they tend to be governed separately in silos with little communication among relevant agencies (Weitz et al. 2014). This means that each entity involved with the environment and key sectors rarely communicate among each other making identifying more effective governing mechanisms and management strategies nearly impossible. Each agency must attempt to address their issues without key inputs and data from other areas.

The lack of systems thinking in managing the environment and crucial resources and interagency communication are two main reasons why many governance approaches and policy mechanisms often lead to unintended consequences and unforeseen outcomes in the real-world.

The cross-impact matrix in Figure C6 can be used to describe many of the important connection between sectors. Some simple connections include: a) water for irrigation in food production; b) land for plants used for biofuel production; and c) thermoelectric power generation emits greenhouse gases. All of these can be affected by policies.

Stakeholders, who make decisions within water, energy, and food systems, could come from different types of organizations – governmental, business, and civil society. These stakeholders usually have different goals, value systems, and decision making powers, operating at different scales. The decisions made by them, across different resource systems and scales, could have an impact on one another. Such decisions, when done with low levels of communication and coordination, could lead to incoherent policies which potentially compete with one another. A decision to subsidize solar pumping stations for farmers at a national scale, could result in incentivizing farmers to pump more water at lower costs, thus increasing their ability to produce more food. While this would come with advantages to the farmer, it could result in the depletion of water aquifers at the municipal scale, if no proper regulations were put in place (Figure C7). This phenomenon is commonly known as the “Tragedy of the Commons.”

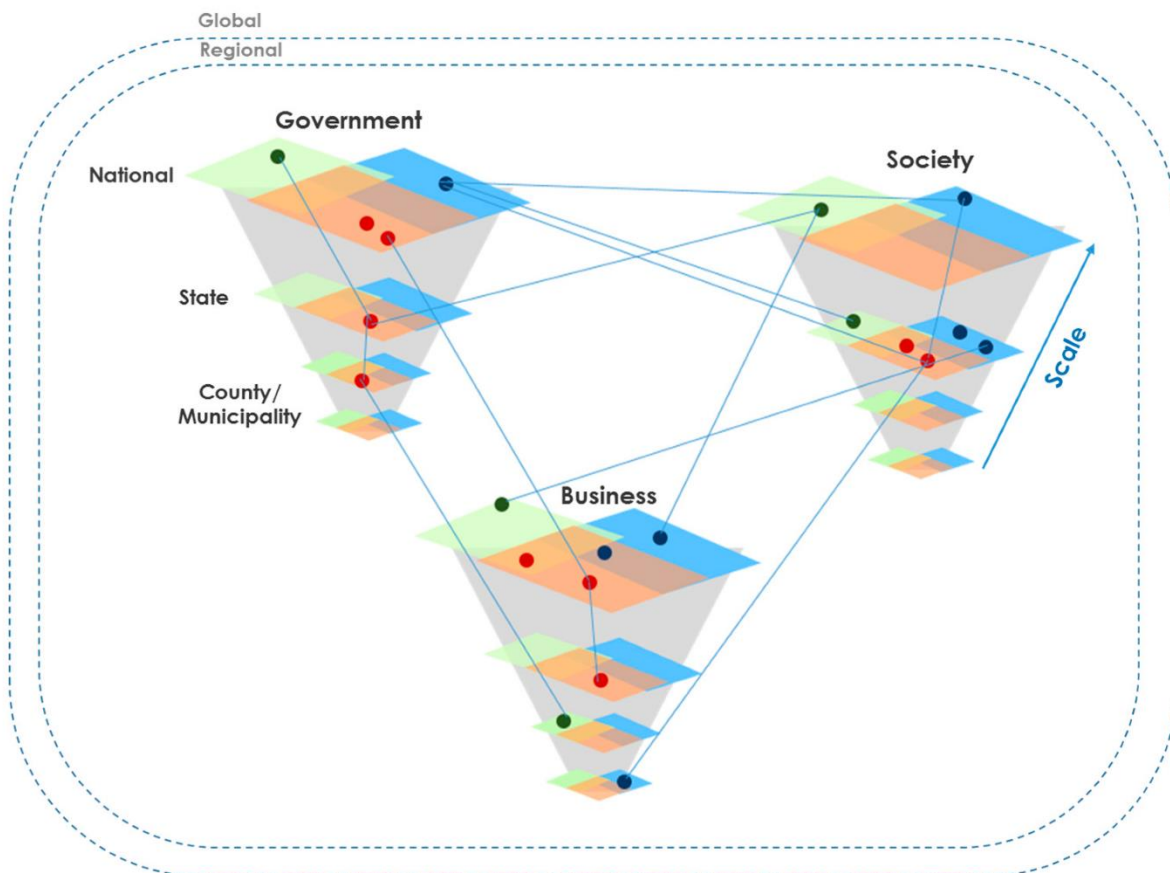


Figure C7. Interactions among different players across scales (Daher et al, 2018b)

In addition to our growing understanding of the extent to which physical resource systems are interconnected, there is a need to improve our understanding on how different players interact and share risks across scales. This highlights the need for better identification of synergies between different decisions and for avoiding the potential

competition resulting from incoherent policies. Specifically, there is a need for developing mechanisms that can simulate policy coherence through quantifying the impact of proposed policies across different sectors, within the same scale, and across scales. There is also a need to identify the compatibility of “current institutional setup” and “cross-sectoral interaction” with the nature of physical resource systems and their interconnections (Daher et al., 2018b).

Sometimes thinking with systems is not so difficult; it might just be recognizing a single important connection, a **leverage point** – critical places to intervene in a system that causes the most effect. If a drought causes crops to die, it should be expected that food prices will go up. Additionally, a drought is ‘slow-moving’ and its onset can be, at least, partially foreseen and planned for. With this in mind, a governing agency can increase water to the farmers so their crops might survive, thereby mitigating the consequences of the drought. With enough foresight, more water efficient infrastructure (e.g. drip irrigation) can be installed reducing the water-requirements of crops, which is an approach to permanently improve the resilience of the food production system. Communication among the relevant entities is the basis of a systems approach at a large-scale.

Systems thinking also must be applied at smaller scales. Oftentimes the very complexity of the issues that systems approaches are meant to analyze influence people to forgo them. Doing so avoids more upfront costs, time, and effort, but can cause long-term and unforeseen consequences. It is the common human trap of prioritizing short-term gains (or avoiding losses) at the expense of the future. At this small-scale is where people make decisions and policies are made. Imbuing these decision and policy makers with the capability to think in systems will better enable them to understand the complex issues over which their decisions and policies influence.

The researchers that study these issues and advise decision makers should also make their work more easily understandable. One such way is to create user-friendly interfaces for the more complex models, such as those in system dynamics modeling. It would remove much of the esoteric and complex technical components of the analysis. Only the relevant information would be presented. These models can resemble a game or a turn-based simulation. These models are based on systems meaning that the information presented in the interface is too (Zelinka and Amadei 2019b).

New game-theoretic models that can inherently integrate multiple timescales in the decision-making processes could be useful. Notions of stochastic games (Basar and Olsder, 1999) can help in capturing the spatio-

temporal FEW dynamics that evolve over time. Moreover, to practically capture decisions at multiple timescales stochastic game constructs, for example, can be coupled with emerging game-theoretic frameworks, such as multi-game solutions (Hamidouche et al., 2016) and multi-resolution games (Zhu and Basar, 2015), that enable analyses of the co-existence of multiple, interdependent games, at different scales.

This concept shares similarities with the Prisoners Dilemma (Poteete et al. 2010), where each prisoner (government agency or entity) must make a decision without the knowledge of what the other is doing. In the classic Prisoner's Dilemma this constraint is forced by the interagents, but lack of communication for implementing the SDGs is self-inflicted. Furthermore, as suboptimum strategies are made the resources might become used up and the environment can degrade at higher rates, which shares some commonalities with the Tragedy of the Commons (Poteete et al. 2010).

Connecting many direct effects can create more complex pictures. For example, an unforeseen population boom in a city will require food imports or nearby food production to increase. Depending on the allocation from where that food is sourced, there will incur higher economic costs and/or environmental costs. A higher food demand increases local prices until food imports catch-up to meet that demand but after a delay (increasing production and transporting that food takes time). In the meantime the city might have to temporarily increase local production which has its own water and energy costs. The sudden spike in food demand has a dynamic, non-linear, and seemingly chaotic effect on other areas and sectors within the system that makes understanding what is happening in those other sectors and communicating with relevant entities crucial. If the available food drops too far, then the population will begin to starve, which has its own set of far-reaching problems.

#### **4. Conclusions**

In order for nations to develop plans and strategies towards achieving the Sustainable Development Goals, it is vital that this process is done with a deep understanding of the interconnections that might improve or inhibit implementation and progress of the SDGs. This has been voiced through recommendations of annual national reports by calling for more intersectoral coherence in the process of planning and policy making. Several tools and methods exist which would play a role in catalyzing a dialogue among different stakeholders that highlight the trade-offs for various pathways forward. Even though addressing complex, interconnected resource challenges could be guided by an overall system of systems understanding of the trade-offs, solutions to address these resource hotspots needs to be

localized and contextualized. It is also important that our understanding of the interconnections between physical resource systems and constraints is complemented with a similar understanding of the dynamics that exist between different stakeholders and decision makers, with differing goals, values, and interests.

## **Appendix D – Integrated Modeling of the Water-Energy-Land-Food Nexus: Importance of Context, Scale, Boundary, and Community Capacity**

### **Abstract**

Water, energy, land, and food resources are critical components in the overall discourse on sustainable human development. There is a consensus in the water-energy-land-food (WELF) nexus literature that the management and allocation of water, energy, land, and food resources at the community level needs to be considered in a more systemic, multidisciplinary, and practical manner. This paper emphasizes that a nexus cannot be separated, modeled, and understood in isolation from the environment and the systems (social, infrastructure, economic, and environmental) with which it interacts. This paper explores the importance of context, scale, and boundary selection when developing hard system-based models of the nexus at the community level. It also emphasizes the importance of accounting for community capacity and the level of community development to provide services across the four sectors of the nexus. Communities with higher levels of development can expect to have higher levels of services to start with when managing and allocating their resources. Finally, a simple system dynamics example is presented to illustrate how to link population, WELF resources, and community capacity.

**Keywords:** WELF nexus, system dynamics, capacity

## 1. Introduction

Food, energy, and water (FEW) resources are critical components in the overall discourse on human and sustainable development. Over the next 40-50 years, rapid population and global economic development will create unprecedented resource demands. By 2050, global food demand is expected to grow by 60%, energy demand by 80%, and water demand by 55% (Ferroukhi et al., 2015). This growth will occur in an existing context of uneven and interconnected FEW resource scarcities.

Food, energy, and water represent basic physiological human needs among many others. The traditional way of meeting these needs has been to design services in these three sectors in isolation (decoupled) regardless if one is interested in supply/demand, infrastructure planning/design, resource management/allocation, technology, and/or governance. More recently, an added emphasis has been placed on understanding the interdependencies that exist among the food, energy, and water sectors. It is now common practice in the development literature to read about “nexus thinking” and the FEW nexus, i.e., the interlinkage that exists among the three sectors. Addressing the nexus requires an integrated perspective that considers not only the characteristics of each sector of the nexus but also the characteristics of their intra- and inter-dependencies.

It should be noted that the FEW nexus is not unique as it is one of the many interlinkages that are at play in human and sustainable development. To the three sectors of the FEW nexus, one could add health, soils, land, climate, transport, communication, state security, human rights, labor, trade, etc. For instance, land is sometimes associated with the FEW nexus, since land is important to produce food, energy, and water supply as well as other ecosystem services (Ringler et al., 2013; Weigelt et al., 2015; Müller et al., 2015; Hurni et al., 2015). The acronym WELF is used instead of FEW in the literature and in this paper when land is considered with water, energy, and food. Figure D1 shows a tetrahedron representation of the WELF nexus where each node corresponds to one sector of the nexus. A fifth node (defined as X) connected to the other nodes could be added at the centroid of the tetrahedron. It may correspond to climate or population.

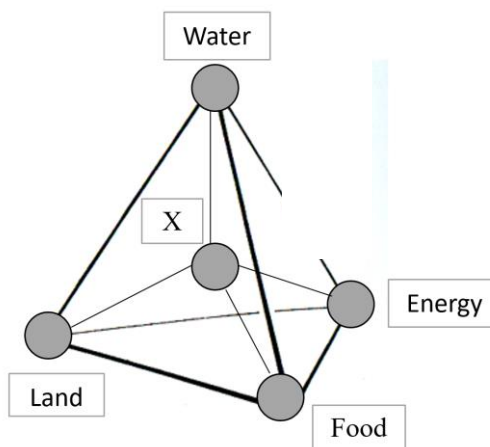


Figure D1. The WELF nexus represented as a tetrahedron. The node X can represent climate or population.

The debate around the importance of the FEW nexus in human and sustainable development started in the 1980s. Driven by a worldwide increase in food and energy prices from 2007-2012 (Allouche et al., 2015) and global challenges associated with climate change, rapid population growth, and urbanization, discussion around the FEW nexus gained momentum at the 2011 World Economic Forum with the publication of *Global Risks 2011* (WEF, 2011) in which the FEW nexus was listed as one of three critical global risks. Another report titled *Water Security: The Water-Food-Energy-Climate Nexus* looked specifically at the role played by water in linking the other nexus sectors together (Waughray, 2011).

Multiple conferences, workshops, and research initiatives (see reviews by Bizikova et al., 2013; Allouche et al., 2015; Leck et al., 2015; Saundry, 2016) have emphasized the value proposition that - rather than considering water, energy, and food in isolation - a “nexus approach” is more appropriate to look at the management and allocation of water, energy, and food resources. The 2011 Bonn conference also recommended that priorities should be placed on developing policy solutions toward “enhan[cing] water, energy and food security by increasing efficiency, reducing trade-offs, building synergies and improving governance across sectors” (Hoff, 2011).

Since 2011, *resource security*, an integrated concept that encompasses the combined security of food, energy, water, and land resources, has become of major concern to decision makers in the private, public, and citizen sectors involved in development worldwide. Simply put, the challenge is how “to feed more people with [less] water, in a context of climate change and growing energy demand, while maintaining healthy ecosystems” (WBCSD, 2009). Key publications (among many others) that have helped shape the discussion around the FEW/WELF nexus include those



of Bazilian et al. (2011), Bazilian (2014), Bizikova et al. (2013), Ringler et al. (2013), FAO (2014), Finley and Seiber, 2014; Hurni et al. (2015), Weigelt et al. (2015), Wakeford et al. (2015), Leck et al. (2015), Daher and Mohtar (2015), Bassel and Mohtar (2015), Keairns et al. (2016), Saundry (2016), and Braat et al. (2016).

Several insights emerge from reviewing the FEW/WELF nexus literature:

- The nexus needs to be modeled in an integrated (e.g. systemic) manner by considering (i) the water, energy, land, and food sectors and their supply chains (i.e., the sequence of activities from acquisition, production, and processing, distribution, consumption, to waste disposal); (ii) the links between the sectors and their supply chains; and (iii) the interaction of the nexus with social, natural, infrastructure, and economic systems. Simply put, the nexus cannot be separated, modeled, and understood in isolation from the environment and the systems with which it interacts.
- The needs for water, energy, land, and food are context and scale specific. Models of FEW/WELF resource management and resource allocation strategies cannot easily be transferred from one context to the next; for instance, from a rural to an urban context or from one climatic region to another. The same could be said about scale (Hoff, 2011). For example, Wakeford et al (2015) looked at how the nexus expresses itself and should be considered in three socio-economic and ecological regimes: agrarian (in Malawi); industrial (in South Africa); and ecological (in Cuba).
- As noted by Sohofi et al. (2016), “the challenge remains as to how the interlinkages [synergy] between systems should be made explicitly” and modeled. This confusion explains, to a certain extent, how the FEW/WELF nexus has often been modeled in a fragmented way by various groups (Bazilian et al., 2011; Weitz et al., 2014; Daher and Mohtar, 2015).
- The limited understanding of the linkages between the sectors of the nexus also explains the limitations of existing decision-making methods used to select, model, and implement integrated interventions across the nexus. Often, they are selected by experts and policy-makers in one or several specific fields and do not always include the stakeholders facing nexus issues. Furthermore, these tools rarely cut across the various technical, socio-political, and economic disciplines that define the context in which the nexus unfolds.

- The range of application of existing models of the FEW/WELF nexus is limited due to current knowledge gaps in understanding the nexus and its components (Hoff, 2011). More specifically, there is a need to develop databases on food, energy, land, and water, their respective value chains, and how these sectors interact (Hoff, 2011; Ferroukhi et al., 2015). There is also a need for understanding the impact of one sector of the nexus on the others; dealing with the complexity and uncertainty inherent in the nexus; and creating multi-scale metrics and indicators for the nexus (Tevar et al., 2016; King and Carbajales-Dale, 2016).
- Finally, even though the concept of an integrated approach to the management and allocation of FEW/WELF resources sounds innovative, it has remained mostly academic and its value proposition has not yet been *operationally* demonstrated in practice and conveyed in a comprehensive and non-academic manner to policy and decision makers (Mohtar and Daher, 2016).

All these insights have led to the consensus in the FEW/WELF nexus literature that the management and allocation of WELF resources needs to be looked at in a more systemic, multidisciplinary, and practical manner. As best summarized by the Stockholm Environment Institute (Hoff, 2011), an integrated approach to the FEW nexus must involve: innovative and efficient technologies to increase the productivity of resources; techniques to reuse waste and by-products; economic incentives for sustainable use of resources; coherence in governance and policy making; and sound ecosystem management and allocation, preservation, and enhancement.

Developing comprehensive and integrated models of the WELF nexus is challenging and requires adopting a systems approach. Despite the multitude of scholarly publications on the need for an integrated approach to the WELF nexus, not much research has been done, for instance, on modeling the nexus using *hard*-systems tools (qualitative and quantitative) such as system dynamics discussed herein. Some soft-systems tools have however been proposed but are limited as to their applications due to their qualitative nature. This paper first explores the importance of context, scale, and boundary selection when developing hard-system-based models of the nexus at the community-level. The second part addresses how to integrate different types of community capacity when addressing WELF-related issues in small-scale and low-income communities. Finally, a simple system dynamics example is presented to illustrate how to link population, WELF resources, and community capacity.

## 2. Landscape Analysis

### 2.1. Definition

The management and allocation of water, energy, land, and food resources requires decision makers to have a good understanding of the existing setting (i.e., the baseline or frame of reference) in which community development takes place and the nexus is embedded. The setting consists of many interacting systems and sub-systems (Figure B2). The setting takes place in a specific *context*, over a certain geographical area (spatial-scale) and time frame (temporal-scale) and is confined by a boundary. It is in that setting that data and information about the WELF nexus are collected and analyzed; constraints and issues are identified and ranked; system-based models of the issues are created; and decisions are made about possible interventions to address these issues. The selected boundary is especially critical since it determines what is included and excluded in resource management.

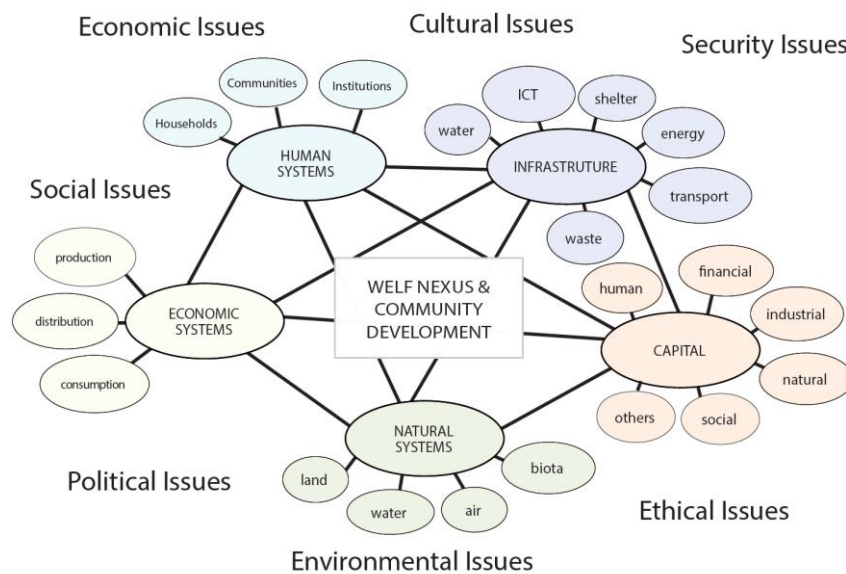


Figure D2. Systems involved in community development and interacting with the WELF nexus. Each system consists of sub-systems. Note: A simpler version of this graph was originally proposed by Jorge Vanegas (personal communication, 2000).

Different terms and metaphors could be used to describe the “setting” in development and WELF studies. In this paper, “landscape” describes the enabling environment in which community development takes place and the nexus unfolds. It builds on the definition proposed by various authors interested in farm, land, and ecosystem management (Scherr et al., 2013):

a socio-ecological system that consists of a mosaic of natural and/or human-modified ecosystems, with a characteristic configuration of topography, vegetation, land use, and settlements that is influenced by the ecological, historical, economic and cultural processes and activities of the area. The mix of land cover and use types (landscape composition) usually includes agricultural lands, native vegetation, and human dwellings, villages and/or urban areas. The spatial arrangement of different land uses and cover types (landscape structure) and the norms and modalities of its governance contribute to the character of a landscape.

We extend landscape beyond the above definition to also include the engineered (infrastructure) systems associated with the FEW supply chains and the economic processes of production, distribution, and consumption across sectors (e.g., agriculture, manufacturing).

It should be noted that the term “landscape” has been included in multiple integrated landscape management approaches/frameworks in the literature, especially about reconciling issues related to natural resource management, conservation, and development (Sayer et al., 2013; Mitchell et al., 2015) and climate (Scherr et al., 2012; Minang et al., 2015). Common characteristics of these approaches include the recognition that: (i) the landscape is a complex and ill-defined system of systems that requires adopting flexibility and adaptability in its management and recognizing that there are no optimal solutions in addressing issues; (ii) multi-stakeholder participation is key to resource management; and (iii) interventions across the landscape need to include social, environmental, and economic components while seeking to increase synergies and reduce tradeoffs. These remarks have critical implications on how to model the landscape of Figure D2 and the embedded nexus using system-based tools as discussed later in this paper.

Before modeling the entire landscape and/or several of its components, it is necessary to identify its basic characteristics (context, scale, and boundary) and collect and analyze data about all sectors of the nexus, their respective supply chains, and the various social, economic, infrastructure, and environmental community systems at play with the nexus.

## **2.2. Context**

In general, the overall state of development, wellbeing, and level of prosperity of a community emerges from the interaction of many socio-economic, geo-political, environmental, and infrastructure systems in a specific cultural and

climatic context. The dynamic at play between these systems varies depending on whether it is in an urban or rural context.

Multiple branches of social science can help to understand the context in which the WELF nexus unfolds. More specifically, the fields of anthropology, economics, geography, history, political science, and sociology (to name a few) provide methodologies and tools to define context. Geography is an important discipline in understanding the nexus. It provides valuable spatial and temporal insights about Earth's physical processes (physical geography) and how populations interact with the Earth and its natural processes (human geography).

As best summarized by De Blij (2009), geography contributes to explain why populations are located at certain locations, do what they do, prioritize certain activities, how they trade with each other, and why some have more advantages than others. Geography also gives insights as to how populations make decisions for a specific ecological and climatic setting based on their belief systems, cultural preferences, value systems, etc. Geography provides a methodology to assess the nature (quality and quantity) and distribution of the natural resources at play in the nexus and gives insights on how to manage and allocate these resources while taking under consideration possible geopolitical and socioeconomic risk drivers, constraints, and limitations. As an example, geography is especially critical in understanding the geo-economic and geo-political dynamic at play in the Hindu-Kush and Himalayan mountain region where close to 1.3 billion people rely on 10 river basins for their domestic, agricultural, and industrial water needs. Similarly, Cook and Bakker (2012) give several examples showing the role that geography plays in defining and addressing water security in Australia, China, the Middle East, and North Africa.

In engineering, geography contributes to making appropriate decisions about what types of infrastructure would work best at certain locations to provide specific services such as water and energy to populations. As remarked by Zahnd (2012) for renewable energy projects in rural parts of Nepal, the topography, the overall geography of mountainous regions, and local cultures limit what technologies are possible including their installation, operation, and maintenance. Simply put, some locations are better suited than others and are more likely to lead to successful interventions. Another example in an urban context presented by Perrone et al. (2011) for the city of Tucson, AZ illustrates how geographic location affects the decision-making and infrastructure building from water supply to consumption at the urban scale.

Human and physical geographic information is critical to land-use and community planning. It may help to decide, for instance, how land is used and whether communities may need to be relocated due to changes in natural conditions following some natural hazards (e.g., induced landslides associated with the 2015 earthquake in Nepal). In general, ignoring geographic information in community development is likely to lead to inappropriate technical and socio-economic solutions to community issues, which may lead to possible conflicts.

The study of climate is critical to understanding the nexus. Climates and their intra-variability (over one year) or inter-variability between years define what's possible for community development and limits the range of possible solutions to nexus issues, since they influence populations and resources within the nexus. One can expect, for instance, the dynamic of the WELF nexus in a dry/arid climate to be quite different from that in a temperate/tropical climate. In their WEF Nexus Assessment Framework 1.0, the FAO (Flammini et al., 2014) describes different approaches to assessing the nexus based on whether countries are dry or wet in addition to whether their economies are agriculture-based.

Climates dictate the characteristics of possible associations of plants and animals in a specific environment. They define the extent and intensity of dry and wet seasons and the land's hydrology, which in turn controls how much freshwater is available for domestic, industrial, and agricultural use. As noted by Grey and Sadoff (2007), countries with "difficult hydrology" (i.e., with not enough or too much water) are more likely to face socio-economic challenges. In arid and semi-arid climates, such as those found in the Middle East, there may be enough water for domestic and industrial use but not enough to grow food; a situation that is likely to deteriorate over time due to rapid population growth and urbanization in that region. A lack of water for food production can be handled by importing food instead of water (Mohtar et al., 2016) or using wastewater for agriculture as in the case of Israel (Siegel, 2015).

The literature on the link between climate and the FEW/WELF nexus is abundant. Climate change has potential to affect: (i) food security by reducing food production; (ii) water security by altering precipitation patterns and natural disasters; and (iii) energy security by increasing energy demand (WBCSD, 2009; Ferroukhi et al., 2015). Climate change affects land-use through, for instance, desertification. All these climate-related risks and their uncertainties have potential to create socio-economic, geo-political, and/or environmental problems which could lead to crises or unrest at different scales and over long periods of time. As an example, some authors have suggested that sustained drought in Syria and the Middle East Fertile Crescent starting in 2011, combined with weak country

governance and a lack of environmental and agricultural policy, led to political unrest and rapid urban migration (Kelley et al., 2015).

Finally, populations play an active role in the FEW/WELF nexus, since they are major consumers of natural resources and impact their environment. The FEW/WELF nexus is likely to be different in an urban context from that in a rural context due to a higher population concentration and stronger demands. Fields of social science such as human geography, anthropology, and ethnography provide methodologies and tools to map (e.g., GIS mapping) the demographics of populations, their customs and cultures, and how they interact with natural systems. These, in turn, affect how resources across the nexus are managed, prioritized, and allocated at different scales.

### **2.3. Scale**

For a given urban/rural, climatic, and socio-cultural context, the WELF nexus and/or each one of its components are likely to unfold differently at various physical and temporal scales: global (country or state), regional, and local or functional such as villages, households, economic sectors, or firms (Fischer-Kowalski and Huttler, 1999). Scale is important since the management and allocation of WELF and soil resources may only be seasonally economical (Wilbanks, 1994). A case in point is what happened in Rwanda before 1994 where plots of family land were divided many times over from one generation to the next resulting in smaller plots that became too small to provide proper household economic support. Correlation has been suggested between this local land dynamic, political unrest, ethnic divisions, and the 1994 country-wide genocide (Boudreaux, 2009).

Likewise, solutions across the nexus may be effective at one scale and not at another. Alcamo (2015) cites how drip irrigation can be very effective in reducing water demand and increasing the water efficiency to grow crops at the local level. At the same time, that increase is often accompanied by a farmers' desire to grow more crops since more water becomes available.

Across the nexus, the *physical* scale plays a critical role in how decisions are made and who makes the decisions. Some decisions are made at the local or community (bottom-up) level and others at the country, state, or regional (top-down) level by various forms of government. Scale also affects how issues at one *spatial scale* are related to issues at another scale and whether solutions scale up. Decisions to intervene in one or multiple sectors of the nexus at the national-level may not be relevant at the regional- and local-scale and vice-versa. The same could be said regarding *time-scale* as a community may be resilient to certain supply-based and demand-based risk drivers over the

short-term but not in the long-term. Scott et al. (2011) provide several US case studies illustrating the disconnect between institutional decision-making and water-energy management strategies at different scales. Reynolds et al. (2003) discuss the importance of scale when distinguishing between local land degradation and regional desertification. As remarked by Wilbanks (1994), the non-linearity of systems in the nexus makes any spatial or temporal scale linear extrapolation (i.e., scaling) impossible.

Another scale issue is about understanding how interventions in the nexus at one scale may impact intervention at other scales. As an example, large water, energy, and agricultural infrastructure projects necessary to the needs of large urban areas may impact smaller community projects with serious socio-economic impact (Flammini et al., 2014; FAO, 2014). A case in point is the upstream and downstream social and environmental impacts associated with the construction of the Three Gorges Dam in China (Xu et al., 2013).

#### **2.4. Boundaries**

Any study of the WELF nexus at the community-level requires that a boundary (spatial and temporal) be selected. Whether natural or artificial, a boundary defines scales at which the nexus is studied, what data need to be collected and analyzed and their level of aggregation, where data should be collected and over what time frame, the issues that need to be addressed and modeled, and the characteristics of proposed solutions. Defining the boundary of a problem is not easy since it clearly sends the message that some study (endogenous) parameters are included within the boundary whereas others (exogenous) are purposely excluded. A challenge in doing such truncation across the nexus is that boundaries for water, energy, land, and food and social/administrative do not always align with each other (Perrone et al., 2011). As recommended by these authors, it then becomes necessary to select, somewhat subjectively, an overall boundary that is good enough and “aligns best” with the boundaries of each resource in the nexus.

Several additional remarks can be made about selecting the nexus boundaries. First, as noted by Ricigliano and Chigas (USAID, 2011), selecting *reasonably* defined boundaries that balance inclusiveness (breadth or extension) and clarity (depth or intensity) are key. In the management of WELF resources at the community-level, breadth deals with the cross-disciplinary interaction between these components and the various components of the landscape shown in Figure D2. Depth is associated with the necessary detail of the nexus and the landscape. Another way to understand that challenge is to select boundaries that provide trade-offs “among [model] realism, precision, and generality” (Costanza et al., 2013).



Second, some phenomena in the nexus may be confined within well-defined geographical/natural boundaries whereas others are not. For instance, the boundary of a watershed (catchment, drainage basin) may be appropriate in identifying the dynamic of a community and how its members use water, energy, food, and land if the community operates in an isolated manner and within the confines of the watershed. On the other hand, the boundary loses meaning if the community members have interactions with other communities and social units outside the boundary. As an example, Day (2009) describes the difficulties in identifying watershed boundaries for community-based water resource management in sub-Saharan Africa. This author concluded that due to village isolation, micro-watersheds were better suited than a large watershed to understand how aquifer systems were used by local villagers.

Third, at times, geographical boundaries are completely meaningless. This is the case for instance when dealing with transboundary and global issues such as population migration, soil degradation, natural hazards, variations in climate change, rogue economic development, and geopolitical issues that do not respect geographical boundaries. In this case, the challenge is to find boundaries that are appropriate to address the issues at stake, which can be difficult.

Finally, on the onset of a FEW/WELF nexus study and a given community context, it may not always be possible to fully comprehend the nexus and its interactions within a selected spatial boundary and/or over a certain time. In that case, in the process of developing solutions for the management and allocation of resources across the nexus, boundaries may need to be flexible and allowed to change until “somewhat” consistent conclusions about the nexus can be reached at different scales. A systems approach to modeling the management of FEW/WELF resources requires an assessment of exogenous constraints and barriers and their level of uncertainty. One way of handling the external environment in the modeling process is to modify the boundaries to integrate critical exogenous parameters in the model as needed. The reverse is also possible as endogenous parameters may be excluded from the model as they lose relevance over time.

## **2.5. Community Assessment**

Once the setting or landscape, in which the WELF nexus is imbedded, is understood, the next stage before any modeling can be carried out, is to identify more specifically the various systems of Figure D2 at play in that setting, collect data and information to qualify and quantify these systems, and identify issues and the various aspects of the

community setting which interact with the nexus. Community assessment (sometimes called appraisal) requires community participation and must be carried out in an integrated manner.

Simply put, the main purpose of the assessment is to learn as much as possible about the situation of something: in our case, the current dynamics and structure of the landscape of Figure D2, how the WELF nexus currently unfolds and expresses itself, and how community development currently takes place. A comprehensive assessment creates a *baseline profile* of the landscape, which can be used to identify existing enabling and constraining factors, what works well, what does not work well, and what could be improved. This in turn, helps in: (i) formulating possible mental models and associated dynamic hypotheses around issues in the landscape, i.e., possible explanations about causes and consequences of each issue and their underlying structure; (ii) modeling these issues; (iii) deciding on places to intervene in the landscape (i.e., possible leverage points); (iv) designing, planning and implementing interventions; and (v) ultimately monitoring and evaluating these interventions.

In community development, assessment or appraisal is often carried out using participatory methods which can be regrouped under the concept of *Participatory Action Research* (PAR). PAR is a recognized form of experimental action research commonly used for community assessment or appraisal in health and social sciences, agriculture, and development (Spradley, 1979; Scheyvens and Storey, 2003; Chambers, 2005). PAR can also be interpreted as a bottom-up approach to community development since: (1) it begins with people's problems and concerns and local knowledge; (2) it is motivated by collective-action; and (3) it ends in action. In this approach, researchers and stakeholders are active participants in data collection and analysis.

Different types of PAR assessment or appraisal have been proposed in the literature over the past 40 years in various fields of health, social science, agriculture, and development. They differ mostly from each other about the field methods and tools (e.g., group and team dynamics, sampling, interviewing, visualizing, mapping, etc.) used to collect and analyze data and whether the appraisal is rapid or in-depth. The what, who, where, when, and how of these various methods is well documented in the ethnography literature (Spradley, 1979; Cornwall and Jewkes, 1995; Chambers, 2005) and is not discussed here.

Two remarks need to be made about the assessment of the landscape. First, assessment is about developing a baseline profile with meaningful and appropriate indicators that best describe the existing structure of the landscape and possibly explain its behavior. It can also be used to explain how community development manifests itself in that

landscape. In general, the most difficult part of any assessment is to collate, organize, and convert raw data into meaningful information and indicators which, when analyzed collectively, translates into knowledge and understanding (Checkland and Poulter, 2006). In our case, data are collected to provide information about the dynamic and structure of the landscape, the community, and each sector of the FEW/WELF nexus. Core information of interest may include physical geographic, human geographic, infrastructure, economic/financial, institutional, and socio-cultural information. Core information needs to be supplemented with sector specific information and of the social, natural, infrastructure, and economic systems with which the nexus interacts. In many ways, this process is dictated by the indicators selected by decision makers to measure WELF security in the context of interest. For example, the Pardee RAND approach to resource security (Willis et al., 2016) uses three indicators (accessibility, availability, adaptive capacity) for water security and two indicators (accessibility, availability) for energy and food security.

A second remark about the assessment of the landscape is that it needs to be carried out in a manner that reflects the interconnected nature of the sectors of the landscape. A *system- or complexity-aware assessment*, requires: (i) seeing and seeking connections in the data and information; (ii) engaging multiple stakeholders; (iii) managing different opinions; (v) using reflection-in-action to monitor and evaluate the assessment; (vi) formulating issues in the landscape in an integrated manner; and (vii) selecting metrics and indicators to measure different aspects of the components of the FEW/WELF nexus and their interactions, the intra- and inter-connectivity of the systems in the landscape, and the interactions of these systems with the nexus.

### **3. Capacity Analysis**

A successful landscape assessment or appraisal provides data and information that are aggregated into several categories such as: stakeholders, gender, health, education, partnership, levels of community capacity to deal with issues or provide services, social network, and strength-weakness-opportunities and threat or challenges (see Amadei, 2015). Another goal of the assessment is to be able to acquire enough knowledge and understanding to identify and rank the significant issues and problems that are at stake in the landscape, the nexus, and the community.

Among the categories mentioned above, we focus in this paper on modeling the capacity (ability) of communities to provide supply chain services (i.e., the sequence of activities from acquisition, production and processing, distribution, to consumption) related to water, energy, land, and food. Capacity and community development level are closely related since an increase in one leads to an increase in the other.

Many categories of capacity contribute to providing supply-chain services associated with water, energy, land, food, and other human needs. In this paper, we consider eight types of capacity using the terminology proposed by researchers at the University of Virginia, Charlottesville (UVC) (Bouabib, 2004) for *Municipal Sanitation Services* at the community level. The methodology is generic enough to be used for other types of services related to energy, food, transportation, education, telecommunication, health, shelter, etc.

In a nutshell, the UVC approach consists of three consecutive steps. First, all possible forms of capacity and associated requirements to provide a certain type of service are mapped. Eight forms of capacity ( $C_i$ ,  $i=1-8$ ), each with  $N_i$  ( $i=1-8$ ) specific requirements were suggested by the UVC researchers and include:

- *Service capacity* compares the current level of service with a desirable one (e.g., quantity, quality, and accessibility of drinking water supply per day per capita). The desired level of service is the only suggested requirement ( $N_1 = 1$ ) for service capacity.
- *Institutional capacity* defines the components of the institutional framework that needs to be in place to provide the services. Five ( $N_2 = 5$ ) suggested requirements include: body of legislation and associated regulation, regulatory standards and codes, administrative authority, administrative process, and stable and good governance.
- *Human resources capacity* relates to the labor that is available to provide the services and its level of training. Four ( $N_3 = 4$ ) suggested requirements include: professional, skilled labor, unskilled labor, and level of illiteracy.
- *Technical resources capacity* relates to the logistics and tactics necessary to address the components of technology that are needed for the implementation of the solutions. Four ( $N_4 = 4$ ) suggested requirements include: operations, maintenance, upgrading or adaptation, and supply chain (spare parts).
- *Economic and financial capacity* represents the financing of the services, the availability of loans and the financial assets in the community. More specifically, six ( $N_5 = 6$ ) suggested requirements include: percentage of the private sector providing services and the existence of bonds, user fees, budget, asset values, and debt.

- *Energy capacity* deals with the available energy, its availability, its costs and reliability necessary to provide the services. Four ( $N_6 = 4$ ) suggested requirements include: primary source, backup sources, percentage of budget associated with energy, and rate of outage.
- *Environmental capacity* looks at the availability of natural resources (water, forest, etc.) needed to implement the solutions and involves two ( $N_7 = 2$ ) suggested requirements: the quality and sensitivity of the environment including the level of stress it can sustain, and making sure that the services will not affect substantially or deplete natural resources.
- *Social and cultural capacity* deals with the community structure and components. It consists of four ( $N_8 = 4$ ) suggested requirements: its social networks and cohesion and capacity of organization, stability, equity, castes and exclusion.

It should be noted that the eight types of capacity and associated requirements listed above are generic and need to be adapted to the context and scale of the community being considered. Other forms of capacity and requirements could be added to that list if necessary (e.g., capacity to handle crises and emergencies related to specific adverse events and hazards).

The eight types of capacity are also dependent on each other. In practice, however, not all them need to be considered for a given type of service; only those that are deemed critical to understand how the service is currently provided, what issues limit the service, and what needs to be done to address these issues. For the WELF nexus, only the types of capacity and their requirements that are believed to affect water, energy, food, and soil security need to be accounted for.

The second step in the UVC approach is to determine *semi-quantitatively*, for a given type of service, a score for each type of capacity also referred to as a *capacity factor* ( $CF_i$ ,  $i = 1-8$ ). As suggested by Bouabib (2004), it is calculated as the weighted sum of each capacity's requirements as follows:

$$CF_i = \sum_{j=1}^{N_i} C_{ij} \cdot w_j \quad (1)$$

where  $w_j$  is a weighing factor associated with each capacity requirement rating  $C_{ij}$ . In the method proposed by Bouabib (2004), each requirement is arbitrarily rated *semi-quantitatively* on an arbitrary scale ranging between 0

and 100 and broken down into levels (Levels 1-5), with 20 units each. Each level must have specific descriptors selected by the user. An example is shown in Table 1 for the technical capacity. An example of application of the method at the community level can be found in Bouabib (2004).

Table 1. Breakdown of Technical Capacity Factor into Four Components for Drinking Water Supply Source (Bouabib, 2004).

	Score as %	1-20	21-40	41-60	61-80	81-100
4	Technical Capacity					
C <sub>41</sub>	Operations	Manual collection and untreated water use	Pumping water	Pumping water Control water quality	Monitor water systems Control water quality Control pipes	Monitor water systems Control water quality Monitor pipes network Monitor treatment
C <sub>42</sub>	Maintenance	None	Disinfection Minor repair	Check water systems Major repair	Check/maintain water systems Major repair Maintain pipes	Check/maintain water systems Check/maintain network Check/maintain water meter Maintain IT systems
C <sub>43</sub>	Adaptation	None	Rarely	Occasionally	Usually	Frequently
C <sub>44</sub>	Supply Chain	None	National supplier	Regional supplier	National manufacturer Regional supplier	National manufacturer Local supplier

Finally, the third step in the UVC approach is to identify for each type of service a *Community Capacity Assessment*  $C_A$  defined as the lowest value among seven capacity factors with

$$C_A = \text{Min} (CF_i, i = 2 - 8) \quad (2)$$

According to Bouabib (2004), this lowest capacity factor can be understood as a measure of the stage of community development (or readiness) in providing that *specific* service. It is referred to as the *Technology Management Level* (TML) by Bouabib and its value varies over a five-points rating as shown in Table 2. The lowest capacity factor for each service can also be understood as the place in the community that is most vulnerable and where intervention to improving the service is first needed. It should be noted that the UVC approach is quite conservative as it uses a weakest link criterion (or a pessimistic rule criterion). As noted by Bouabib (2004), other criteria could be used instead.

Once the TML has been identified for a given type of service, various types of supply chain service options and associated technologies can be selected to provide the service (Ahmad, 2004). The rationale is that a community at a certain stage of development (TML) can only handle a certain level of technology when providing a specific service. As a community transitions from one stage of development to the next, more advanced technical solutions and associated infrastructure can be implemented, maintained, and operated.

Table 2. Community Development Levels (Bouabib, 2004).

Community Capacity Assessment $C_A$	TML	Explanation
1 – 20	1	No local capacity to manage the service.
21 – 40	2	Capacity to manage systems for small collections of residential units.
41 – 60	3	Capacity to manage community-based systems.
61 – 80	4	Capacity to serve multiple communities from a centralized system.
81 – 100	5	Community has the capacity to manage a centralized system, along with individual service to more remote units.

The UVC methodology described above applies to one type of service at a time. The situation becomes challenging when, in the community-based management of FEW/WELF resources, several forms of services need to be provided simultaneously to ensure water, energy, land, and/or food security. In that case, the lowest capacity factor,  $C_A$ , and stage of community development, TML, need to be determined first for each type of service. There is no guarantee, however, that all types of service would have the same type of limiting capacity though. In other words, the security of the entire nexus and stage of community development may be limited by one form of capacity for water, another for energy, and so on. In this case, intervention at the nexus and community level may require addressing the limiting factors for each type of capacity and those that cut across the five types of capacity used in this analysis.

#### 4. The Messy Nature of the WELF Nexus

The challenge faced in community-level WELF resource management and allocation is devising *good enough* decisions of interventions that account for the dynamics of Figure D2 and the embedded nature of the nexus and its interaction with the various systems of the landscape. This dynamic is a characteristic to a class of problems that cannot be easily formulated, modeled, and solved and are referred to as “wicked” (messy or ill-defined) problems as defined by Rittel and Weber (1973). Paraphrasing these authors, unlike “tamed” problems, wicked ones have unique characteristics:

They are difficult to formulate and can be defined differently depending on context and scale (physical and temporal);

- There is no finish line, i.e., “wicked problems have no stopping rules;”

- There are “no true or false answers;”
- They are hard to evaluate since they create unintended consequences that are unique;
- They are irreversible and attempting to correct some unintended consequences may create more disruptions;
- There are multiple solutions to the problems that require using caution, flexibility, and adaptability in selecting the most appropriate solutions if such solutions can even be found.

Wicked problems represent a challenge to those faced with making management decisions and selecting solutions to address these problems. Simply put, these problems cannot be approached with traditional linear and reductionist thinking tools and a command-and-control mindset. Systems (or integrated) thinking represents a tangible alternative to reductionist thinking to handle their complexity and uncertainty. As defined by Richmond (1994), “systems thinking is the art and science of making reliable inferences about behavior by developing an increasingly deep understanding of underlying structure.” In the context of the FEW/WELF nexus, *nexus thinking* is synonymous to systems thinking.

The value proposition for using system thinking to address a multitude of complex world’s problems has been emphasized by many authors including Laszlo (2001) and Mitleton-Kelly (2003), among others. A wide range of systems science tools have also been proposed, a review of which can be found in Myers (2009). Among all these tools, we use system dynamics which allows for qualitative and quantitative models of wicked, messy, or ill-defined complex systems. It is not the purpose of this paper to describe in depth what system dynamics is or its history. Only a short overview of the basic components of system dynamics is carried out. The emphasis is placed instead on how to use the method to capture the dynamic of the landscape of Figure D2 and the embedded FEW/WELF nexus.

## **5. System Dynamics Modeling**

### **5.1. Overview**

Systems dynamics (SD) is a branch of systems science that originated with the work of Dr. Jay Forrester at MIT in the 1950s and 1960s, and it studies “how systems change over time” (Ford, 2010). System dynamics has been applied to multiple areas including environmental/ecological processes (Ford, 2010), business and management sciences



(Sterman, 2000); community development (Amadei, 2015). In general, SD has unique attributes that warrant its use in modeling the dynamic interaction of the FEW/WELF nexus:

- It can be used to study how systems continuously change over time due to possible changes in and relationships among components and in the overall direction of systems allowing for both qualitative and quantitative modeling.
- It facilitates a big picture perspective allowing for the entire system to be visible, as opposed to individual components.
- SD models are designed to be self-contained in terms of cause-and-effect inside their boundaries including their internal rules.
- Non-linearities in the system are included in the form of first order differential equations that are solved numerically.
- Information feedback mechanisms in the system can be included in the form of interconnected closed loops and circular causality allowing for reinforcing and balancing trends. This can help in explaining the counter-intuitive forms of behavior of some systems.
- The method emphasizes that the structure of systems (i.e., their components, mutual interactions, and environmental interactions) affects their continuous behavior.

As described in the SD literature, various combinations of reinforcing and balancing loops and delays can be created to model the behavior patterns of complex systems and unique repetitive patterns called archetypes. The models can be represented in an object-oriented form of causal-loop diagrams or stock-and-flow diagrams. *Causal loop-diagrams* show how elements of a feedback mechanism interact in a causal manner and are mostly used at the *strategy-level*. They are qualitative in nature and are *not* used to conduct numerical simulations of systems. On the other hand, *stock-and-flow diagrams* consist of combinations of several building blocks. They help visualize flow, accumulation, delay, and dissipation processes (*qualitatively*). They also allow for numerical (*quantitative*) simulations and parametric or sensitivity studies and can therefore be used at the *operation-level*.

In general, both causal-loop and stock-and-flow diagrams are useful tools for: (i) depicting how parts of a system interact and create patterns of behavior; (ii) communicating the dynamic of systems with others; and (iii)

designing and planning interventions to address issues faced by the system. Only stock-and-flow diagrams are used in this paper.

## 5.2. System Dynamics Example

Figure D3 shows, as an example, the stock-and-flow diagram of a system dynamics model illustrating the dynamic at play between a population and WELF resources it depends on. It was created using the *STELLA Architect* system dynamics software (version 1.6) available through *isee Systems* ([www.iseesystems.com](http://www.iseesystems.com)). It consists of several key building blocks (stocks, flows, convertors, and connectors) as described by Richmond (2004).

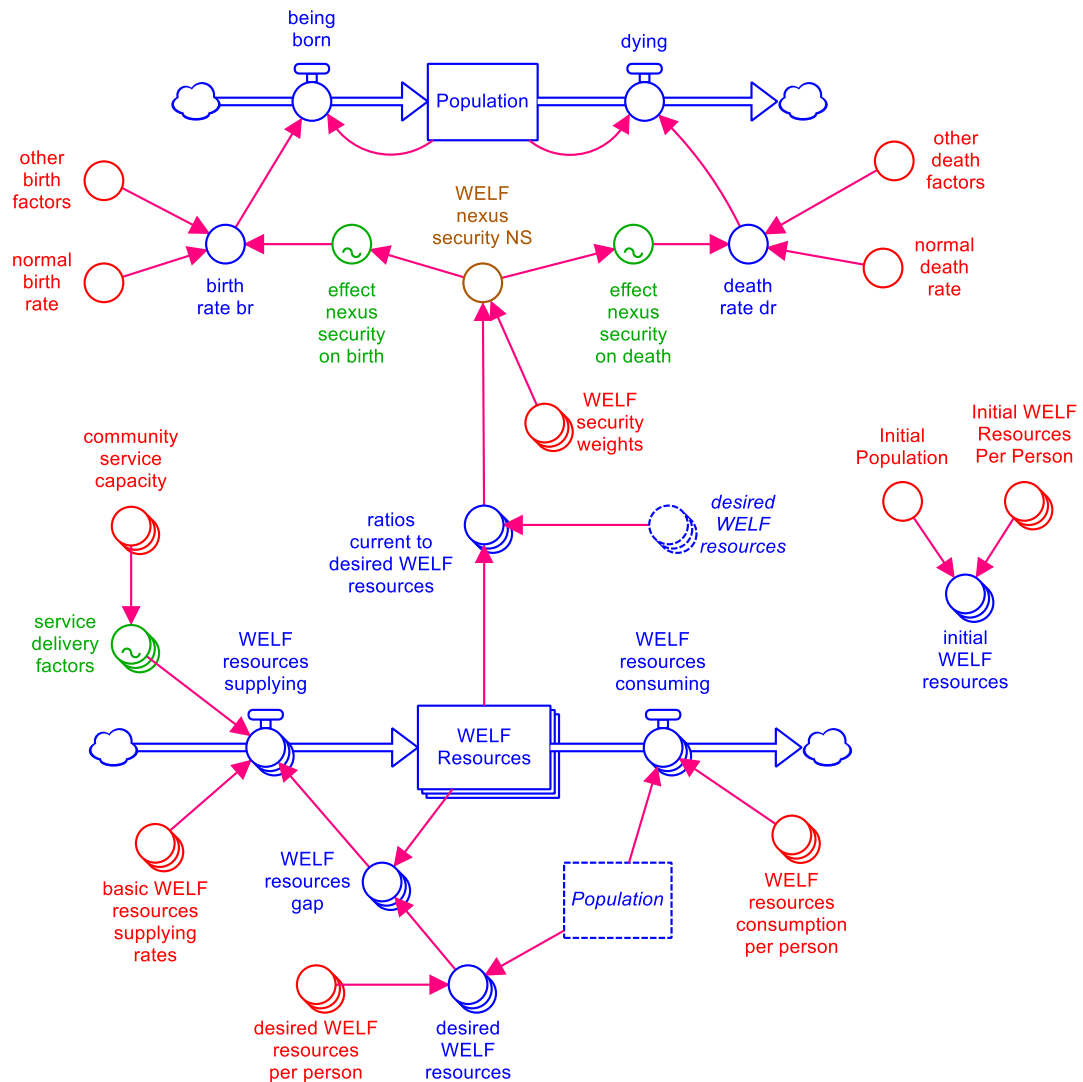


Figure D3. Stock-and-flow diagram of system dynamics model illustrating the dynamic at play between a population and WELF resources.

**Stocks** are represented by the two boxes *Population* and *WELF Resources* in Figure D3. They model the accumulations of people and WELF resources (e.g., water, energy, land, food), respectively. Stocks are state variables:

they define the current state of a system. Note that Figure D3 makes use of the “ghost” icon function for “population” (box with dotted lined) and “desired WELF resources”. It is a useful feature in *STELLA Architect* in creating shortcuts in stocks and flows models. The WELF resources stock is layered, which indicates that it is a (4x1) array that describes the accumulations of four types of resources: water, energy, land, and food.

**Flows** are represented in the form of pipes (with a faucet controlling the flow) that point to or from stocks. In Figure D3, they include: being born, dying, WELF resources supplying, and WELF resources consuming. Flows are control variable and result in changes over time (dynamic behavior) in the stock accumulations and in the entire system. A *cloud* at the end of a flow represents an infinite source or sink outside the boundaries of the model. The flows labelled “WELF resources supplying” and “WELF resources consuming” are (4 x1) arrays to represent the inflow and outflow of the four distinct WELF resources.

**Convertors**, represented by circles, convert or transform information from a stock-and-flow path to another path. Figure D3 contains many such converters with some layered ones representing (4 x1) arrays. Converters can also be described in a functional form that depends on time or a connected variable. In this case a “~” appears inside the converter and denotes a build-in or build-up graphical function. In the example of Figure 3, the converters “effect nexus security on *birth* and *death*” depend on the WELF nexus security converter.

Finally, **connectors**, represented by arrows, connect the various components and variables and transmit information throughout the model. The tail of each arrow represents the cause, while the head represents the effect.

### 5.3. Telling the Story Mathematically

Behind the stock-and-flow diagram of Figure D3, there is a story which involves a population,  $P$ , that consumes four different types of WELF resources ( $R_i$ ,  $i=1-4$ ). These resources are provided through four supply chains, the extent of which depends on the community capacity. The WELF resources stock represents an accumulation of resources that meet specific criteria of availability, accessibility, affordability, and others selected by the user. The goal of the community is to acquire over time a desired level of such resources defined as  $K_i$  ( $i=1-4$ ) represented by the converter “desired WELF resources” which is the product of “population” and “desired WELF resources per person.”

In Figure D3, the overall increase or decrease of the population depends on the birth rate ( $br$ ) and death rate ( $dr$ ), their relative values, and the current size of the population. In mathematical form, the change of the population  $P(t)$  (with an initial value  $P_0$ ) is equal to:

$$\frac{dP}{dt} = (br - dr)P \quad (3)$$

In the WELF resources part of Figure D3,  $a_i$  ( $i=1-4$ ) represent the WELF resources supplying rates and depend on  $(4 \times 1)$  array converters described below. Likewise,  $b_i$  ( $i=1-4$ ) represent the WELF resources consuming rates (product of population and the WELF consumption rate per person). For the dynamic shown in Figure 3, the rate of change of each resource  $R_i$  is equal to:

$$\frac{dR_i}{dt} = a_i(K_i - R_i) - b_i \quad (4)$$

with  $i = 1-4$  and  $R_i = R_{oi}$  at  $t = 0$ . In this equation, both  $K_i$  and  $b_i$  depend on the size of the population. Solving the dynamic shown in Figure D3 requires solving a total of five non-linear first order differential equations (one for the population  $P$  and four for the resources  $R_i$ ) that are interrelated. A numerical example of application of the model and a web-based interactive user interface are available at <https://exchange.iseesystems.com/public/bernardamadei/welf-02/index.html#page1>.

The  $(4 \times 1)$  array converters that define the “WELF resources supplying rate”  $a_i$  ( $i=1-4$ ) are unique. The converter “basic WELF resources supplying rates” describes the basic rates of adjustment to close the gap between desired and current WELF resources. The converter “service delivery factors” accounts for the capacity (or ability) of the community to deliver (provide) services associated with supplying water, energy, land/veg, and food/ag resources. The service delivery factors vary between 0 and 1. For each sector of the nexus, the capacity for service delivery is assumed to vary between 0 (no capacity) and 100 (full capacity) and can be determined, for instance, using the UVC capacity analysis ( $C_A$  defined in eq. 2). All measures of capacity are included in the  $(4 \times 1)$  array represented by the converter “community service capacity.” In the model of Figure D3, built-up graphical functions are introduced by the user to relate the service delivery factors to community capacity. In general, the factors decrease from 1 to 0 as the community has less capacity to deliver supply chain services. This, in turn, results in less WELF resources being supplied to the population. A zero value means that the community has no capacity to supply resources at all.

In Figure D3, each level of resource security is defined as  $R_i/K_i$ . The overall security of the WELF nexus,  $NS$ , is determined as the weighted average of the resource securities as follows

$$NS = \sum_{i=1}^4 w_i \frac{R_i}{K_i} \quad (5)$$

where  $w_i$  ( $i=1-4$ ) are weights that depend on the priority accorded to each resource security. The value of NS is assumed to affect the birth and death rates,  $br$  and  $dr$ , using build-up graphical functions selected by the user. The birth and death rates also depend on “other birth factors” and “other death factors” that are selected by the user.

#### 5.4. The Community Development Story

Figure D3 illustrates that systems dynamics models are developed once a story is in place and not the other way around. In general, behind the dynamic at play between the WELF nexus and the community in which the nexus is embedded, there is always a *community development story* that can be narrated as follows:

- i. A community in a specific setting (context, scale, boundary) is currently at a certain level or state of development. In that state, various social, natural, infrastructure, and economic systems are at play and some services are provided under a certain level of policies and regulations. The state of community development is limited by the community’s capacity to provide services.
- ii. The community is interested in transitioning to a preferable state of development over time. This desired state of development requires that specific goals and objectives are met, levels of services are put in place, governance is formed, policies are crafted and instituted, and that the systems have the proper structure to provide these services.
- iii. Stakeholders are called to work in a participatory manner with the community and the government to develop an integrated plan of action as the community moves from one state of development to the next.

Understanding the story is critical to developing a system-based representation of the nexus. From the story, issues in one or several sectors of the nexus can be identified and ranked and their mental (conceptual) models and associated dynamics developed. Mental models represent the starting points from which system dynamics models are developed. Once a story is in place, modeling that story using system dynamics necessitates following a road map which according to Ford (2010) consists of eight steps: (i) problem familiarization; (ii) problem definition; (iii) model formulation by constructing stock-and-flow diagrams and (iv) causal loop diagrams; (v) parameter estimation; (vi) simulation to explain the problem being addressed; and (vii) simulation analysis consisting of sensitivity analysis and (viii) policy analysis. The first four steps are qualitative and the last four steps are quantitative.

## 6. Conclusions

There is consensus in the FEW/WELF nexus literature that the management and allocation of water, energy, land, and food resources at the community-level needs to be viewed in a more systemic, multidisciplinary, and practical manner. This recommendation is a much-needed improvement from the current approach which only considers the four sectors of the nexus in isolation.

A systems approach to the FEW/WELF nexus combined with community development has a strong value proposition. It can be used to: (i) understand better how the nexus interacts with the community's enabling and constraining environment; (ii) explain existing patterns of community behavior around the nexus over time; (iii) interpret emergent properties of community systems such as resilience, and sustainability that may involve one or several sectors of the nexus; (iv) examine various perspectives of community development interventions across the nexus and consider intended and unintended consequences of these interventions; (v) identify leverage points that benefit the nexus; (vi) predict how the community may respond to various constraints and disturbances and/or strategies of capacity development; and (vii) develop approximate, but good enough, FEW/WELF-related solutions to community needs that are flexible and adaptive to change.

System dynamics represents a powerful and alternative hard-systems approach to modeling the nexus and how it interacts with various systems for a given landscape context, scale, and boundary. System dynamics modeling requires following a series of steps from assessing the landscape in which the nexus is embedded, developing mental models, assembling stock-and-flow models, collecting data, reproducing existing conditions, conducting sensitivity analysis, and ultimately proposing interventions for the management and allocation of water, energy, land, and food resources. This entire process requires that a community development story is developed in a participatory manner with all stakeholders involved in the decision making.

## **Appendix E – A Modified S-Shaped Growth Behavior to Model Complex Anthropocentric Systems**

### **Abstract**

This paper presents a new insecure-secure diffusion (change-of-state) archetype that is based on the S-shaped growth behavior. The archetype is particularly useful in modeling the dynamic of anthropocentric systems related to development and aid for which flow is allowed to occur back and forth between stocks. In these systems, the main actors are directly and strongly influenced by complex human socio-economic-political interactions that are themselves not humans but are indirectly influenced by human interactions. It is shown how the proposed archetype can depict the evolution of the Sustainable Development Goals (SDGs) over time, global trade, and the dynamics behind migration, urbanization, and land-use change. Three versions of the archetype are presented: a two-chambered and extended linear form, a three-chambered triangular form, and a four-chambered hierarchical form. The different versions can be used in different situations.

## 1. Introduction

Several archetypes, sometimes called generic structures, have been proposed in the system dynamics literature (Braun 2002; Forrester 1969; Goodman 1994; Kim 2000; Meadows et al. 1982; P. Senge et al. 1994; P. M. Senge 1994). They represent common patterns of behavior in complex systems. According to Meadows (2008), archetypes are traps or grooves forcing a system to produce the same answer under the same conditions; they create *habits* that, in turn, define the character of the system and ultimately its destiny. As noted by Meadows, recognizing the archetypes at play is also an opportunity to force change “ahead of the game” and creates a way out of the trap or the groove. Archetypes clearly demonstrate that the structure of systems controls their behavior, a guiding principle in systems science.

According to Sterman (2000), the vast majority of archetypes include, in their respective causal-loop diagrams, basic modes such as: (i) linear growth or decay; (ii) exponential growth or decay that can both be modeled by a single reinforcing or balancing loop; (iii) goal-seeking that can be modeled using a single balancing loop; (iv) delay; and (v) oscillation which can occur when a delay is combined with a balancing loop. Other higher forms of behavior can be obtained by combining the aforementioned basic modes such as: S-shaped growth (sequence of reinforcing and balancing loops), S-shaped growth with overshoot and oscillation, or overshoot and collapse (sequence of multiple reinforcing and balancing with or without delay). Other modes of system behavior include equilibrium, random behavior, and chaos.

This paper considers a new archetype using the S-shaped growth behavior to model the dynamics of various systems associated with global sustainable development. This type of growth, also called *logistic growth*, appears throughout multiple fields of science and has been used to model: (i) epidemics (susceptible-infected-recovered epidemiological model, also called SIR); (ii) innovation diffusion (logistic innovation diffusion model); and (iii) the market penetration of products (Bass diffusion model) (Sterman 2000). In short, S-shaped growth is described when a group is acquiring something that they did not have before. As a generic “state A” turns into “state B,” “state B” shows an S-shaped pattern of growth. For instance, in epidemiology, a potentially susceptible population becomes infected with an illness; for innovation in markets, a population adopts a product or service; for population dynamics, population growth occurs under the constraints of an ecological carrying capacity.

Logistic growth can also be applied to various aspects of international development and aid, which this paper illustrates through using the Sustainable Development Goals (SDGs). In 2015, the United Nations introduced the



SDGs as a new 15-year long road map for worldwide sustainable development (United Nations 2016). The SDGs are summarized in Table E1 and are further subdivided into 169 targets. The logistic growth behavior can be applied to all SDGs and their targets, since they can be interpreted as going from not being adopted to being adopted (or implemented). In general, growth is initially slow after an SDG is first implemented because it takes time (delay) to inform relevant agencies, propose projects, etc. Eventually, work towards addressing (project implementation phase) the SDG will reach its fastest rate (inflection point), at which point it will start to slow resulting from constraints, such as “the last-mile problem,” an issue especially pervasive in sustainable development. It refers to the difficulty in reaching those last few people at the end of the line due to, for instance, their geographical remoteness and lack of access to capital (Balcik et al. 2008; Chambers 1983; Minten et al. 2013). This is similar to the effect of saturation of products in a market and can be modeled the same way.

Table E1. The 17 Sustainable Development Goals (adapted from Global Goals, 2016).

Goal	Title	Description
SDG 01	Poverty	End poverty in all its forms everywhere
SDG 02	Food Security	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
SDG 03	Health	Ensure healthy lives and promote well-being for all at all ages
SDG 04	Education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
SDG 05	Gender equality	Achieve gender equality and empower all women and girls
SDG 06	Water and Sanitation	Ensure availability and sustainable management of water and sanitation for all
SDG 07	Energy	Ensure access to affordable, reliable, sustainable, and modern energy for all
SDG 08	Economy	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all
SDG 09	Infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation
SDG 10	Inequality	Reduce inequality within and among countries
SDG 11	Cities	Make cities and human settlements inclusive, safe, resilient, and sustainable
SDG 12	Consumption	Ensure sustainable consumption and production patterns
SDG 13	Climate	Take urgent action to combat climate change and its impacts
SDG 14	Ocean	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development
SDG 15	Land	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
SDG 16	Governance	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable, and inclusive institutions at all levels
SDG 17	Partnerships	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

Logistic growth also appears in human security (equality, safety, income, health, education, etc.), rural-urban migration (urbanization), and resource availability, as in the water-energy-land-food (WELF) nexus (water security,

energy security, land security, and food security), all of which are also represented by their own goal(s) and target(s) in the SDGs.

Multiple systems are at play when considering the evolution of the SDGs, human security, urbanization, and resource security. We define them as anthropocentric systems, i.e., systems “whose main actors are directly and strongly influenced by complex human socio-economic-political interactions that are themselves not humans” (Zelinka and Amadei 2019a) but are indirectly influenced by human interactions.

The next section describes the proposed insecure-secure diffusion archetype and associated SD models. Three simple SD models are included in this paper. They provide an overall understanding of the archetype and an overview of its possible applications in development and aid-related fields.

## 2. Insecure-Secure Diffusion Archetype

In the fields of marketing and management science, the innovation-diffusion model (IDM) is used to represent the adoption rate of new products and technologies into a market by people who, in turn, are affected by internal and external forces. Essentially, the IDM was designed to model market penetration and has been used for mobile phones (Swinerd and McNaught 2014) and many products including refrigerators, record players, TVs, air conditioners, and many more (Kumar et al. 2015).

Internal forces can represent word-of-mouth (positive feedback) from people that have already adopted the product, the difficulty in a new product being adopted in the absence of people that have already done so (negative feedback), and market saturation (negative feedback) which is similar to the last mile problem in sustainable development, mentioned above. In the IDM stock-and-flow diagram of Figure E1, this dynamic is represented by two stocks (*Current Adopters* and *Potential Adopters*) and a uni-directional flow (*adopting rate*). External forces represent external (exogenous) influences on the *Potential Adopters*, such as advertisements from the media. The *adopting rate* depends on a *transfer rate*, a nominal growth rate that can be affected by other factors in the model (endogenous). The adopting rate may represent, for instance, market saturation and word-of-mouth.

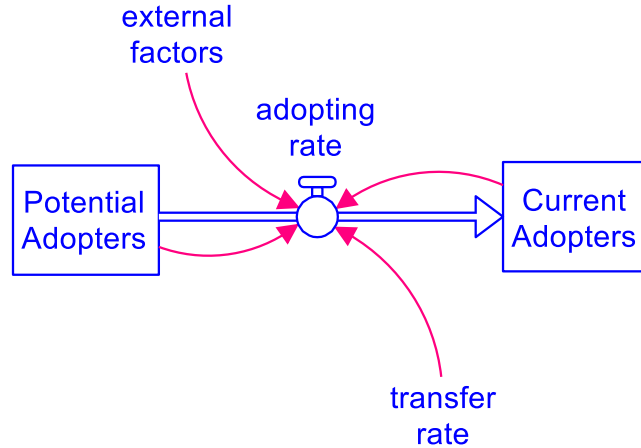


Figure E1. Logistic innovation-diffusion system dynamics model.

In general, the dynamic shown in Figure E1 yields a positively-skewed normal distribution (bell-shaped) for the *adopting rate* and a logistic S-shaped growth curve for the *Current Adopters* (Figure E2). Once a technology or product is adopted, a person cannot un-adopt it, unless a new, superior, and similar-functioning product is released (like when the horse-drawn buggy made way for the car). For this reason, the IDM is uni-directional. The transfer rate is a user-entered value (like population growth rate), that describes how a product or service is adopted by the population.

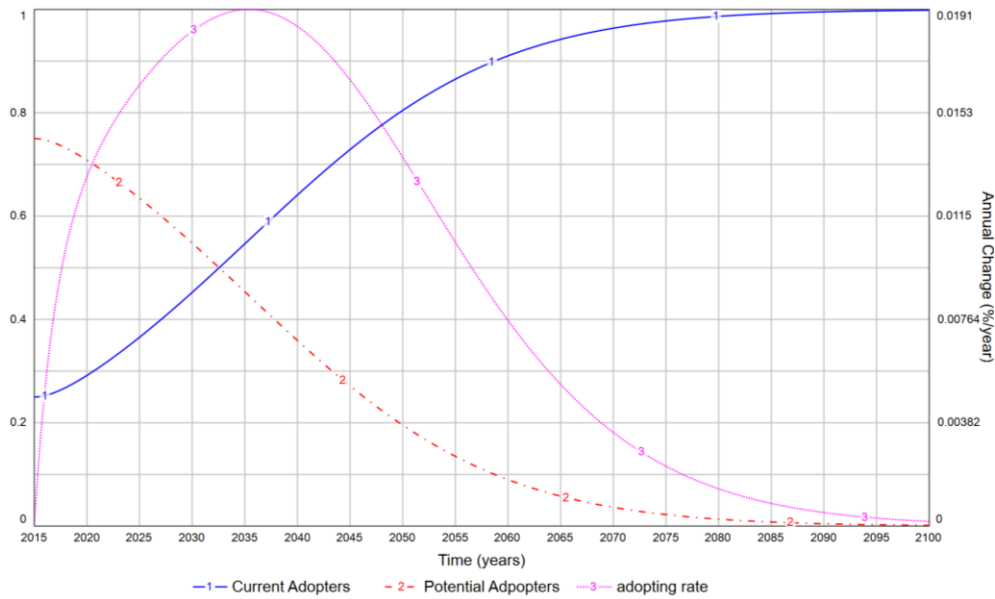


Figure E2. Graph of logistic innovation-diffusion system dynamics model in Figure 1.

The generic IDM model depicted in Figure E1 was modified to generate the stock-and-flow diagram in Figure E3, which now allows for flow in both directions (from *Potential Adopters* to *Current Adopters* and from *Current Adopters* to *Potential Adopters*). Since, in this case, the terms *Potential Adopters* and *Current Adopters* used in the

original IDM no longer apply, they are replaced by *State A (Insecure)* and *State B (Secure)*, respectively to be able to depict non-linearity and feedbacks more accurately. The bi-flow model of Figure more accurately depicts what is happening when information can flow back and forth between two states over time.

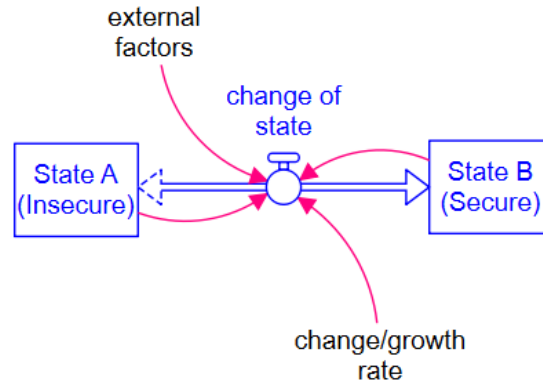


Figure E3. Insecure-secure diffusion, or change-of-state, system dynamics model.

As an example, when addressing poverty (SDG 01), people can escape poverty or fall back into poverty; they can oscillate between these two states any number of times. It is also similar to the confidence model used by Featherston and Doolan (2013) where a person could gain confidence or trust in something (board of director's in their case) or lose confidence in something. Instead of confidence, we use a desired *Secure State*, which for SDG 01 is income *secure*. Similarly, losing confidence is akin to being impoverished, which is the income *Insecure state*. The change of state is a function of the size of the *Insecure State* and the *Secure State* (poor versus non-poor population), the effect of the interactions of the other SDGs (explained later), and the effect of outside influences.

It might be helpful to think of what is happening in Figure as analogous to a see-saw. Instead of two populations, consider two closed chambers filled with a constant volume of liquid. The *change-of-state* is like a pump that moves the liquid in a pipe between the two chambers; the speed at which this liquid flow is controlled by the relative amount of liquid in each chamber and the pipe size and friction, referred to as internal factors represented by arrows from the stocks to the *change-of-state* biflow. If there is more liquid in one chamber, that side is “heavier” and causes more liquid to flow from the other chamber to that chamber (i.e. a positive feedback loop). But if one side is emptier, there is less liquid available that can flow out (i.e. a negative feedback loop). The external factors might enable or balance this feedback loop. If the external factors are greater than the push and pull of the internal factors, then the flow will happen in the opposite direction.

Instead of a liquid, Figure E3 is a population moving between an insecure state and a secure state due to various internal and external factors. Because we are presenting a generic methodology, the names for each stock – a current *Insecure State* and a desired *Secure State* – are placeholders representing whatever the user’s situation requires (equality, income, health, education, urban migration, water security, land security, etc.). We chose those names to signify a transition or change from one state to another.

For modeling purposes, it is crucial to define the indicators describing what each state means so that the system dynamics model can accurately reflect the change-of-state structure. As an example, we consider in Table E2 six of the 17 SDGs of Table E1. An SDG has either been accomplished or it hasn’t according to some indicators. When certain conditions are met, the state of the SDG begins to change from insecure to secure, thus signifying progress towards the implementation of that specific SDG. The insecure and secure state indicators used in Table E2 were left purposely broad and qualitative; in reality more specific and quantitative indicators would need to be selected by the users for a specific context.

Table E2. SDG-specific secure and insecure state qualitative indicators.

<b>SDG</b>	<b>Insecure State</b>	<b>Secure State</b>
SDG 01 Poverty	Below international poverty line (~USD \$2.00/day)	Above international poverty line (~USD \$2.00/day)
SDG 02 Food Security	Lacks access to the proper quantity of calories/nutrients	Has access to the proper quantity of calories/nutrients
SDG 03 Health	General poor health	General good health
SDG 09 Gender Equality	General gender inequality	General gender equal
SDG 11 Infrastructure	Lacks access to basic infrastructure services	Access to basic infrastructure services
SDG 14 Oceans	More than a certain percentage of fisheries being overexploited, and pollution is problematic.	Most fisheries are not overexploited, and pollution is negligible

### 2.1. Modeling the SDGs and their Interactions

This section starts with an operational-level explanation of poverty, as an example for all individual SDGs, by building on the insecure-secure diffusion model introduced in the previous section (Figure E3). The following sections provide a brief description of how the structure can be adjusted and applied to other issues and topics in development.

In system dynamics modeling, it is assumed that the structure of a system determines its behavior. Since all SDGs are assumed to behave the same way (individuals within a population can be either insecure or secure), all SDG system dynamics modules can have the same structure. For clarity’s sake, we will only depict the modular structure for SDG 01 (poverty); the only difference between the SDG 01 module and the others is the specific input data and

names of the module variables. To generalize the methodology to all of the 17 SDGs of Table: (i) the SDG 01 structure is repeated an additional 16 times and the variables for each SDG structure are renamed according to their specific SDG, for example *Impoverished Population* can be changed to *Food Insecure Population*, *economic mobility* to *securing food*, etc.

## 2.2. Generic SDG Stock-and-Flow Diagram

The generic insecure-secure diffusion model of Figure E3 was repurposed to model SDG 01 (Figure E4). There are two types of variables to keep in mind: variables that depend on external (exogenous) data (e.g., *poverty change rate*, *poverty delay*, and *poverty interconnection factor*) and variables that internally (exogenous) convert data (e.g., *economic mobility*, *Impoverished Population*, and *Secure Population*, and *Interlinkages Hub.SDG System Linkages Hub*).

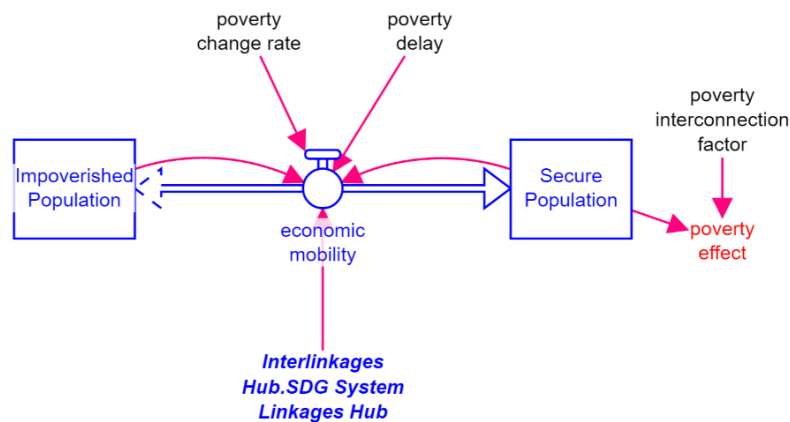


Figure E4. Insecure-secure diffusion model depicting SDG 01 Poverty.

The exogenous variables are simply user inputs and extrinsic factors to the model; they are not fundamental structures, just variables. They are where the model is “capped” and act as entry points into the model. If the user wants to include more factors (e.g., economic, cultural, technological, etc.), this is the location where the model accepts other inputs as desired by the user or dictated by the situation.

The endogenous variables that receive the input of other data are converters that the user does not change as they contain the underlying equations that govern the model. Changing them could cause errors or erratic behavior. These are not to be modified unless the user(s) have a clear understanding of SD modeling.

In Figure E4, the variable *poverty effect* is introduced to calculate the nominal effect of SDG 01 (Poverty) on all the other SDGs. This appears once in each SDG module and should remain unchanged. It is merely colored red to

be easily identifiable and to outline its importance. It is the variable that is used as the input to calculate the actual SDG interactions later by the *poverty interconnection factor*.

### 2.3. Incorporating population growth

Figure E4 has two stocks, one for a population of *Impoverished* people and another one for those who have escaped or were never in poverty and are categorized as *Secure*. Because the SDGs are expected to progress over a long enough time-horizon when population change becomes significant, Figure E5 was created by combining two simple population growth models with the insecure-secure diffusion model of Figure E4. Change, for better or worse, in one's economic status (i.e., the flow between the impoverished and secure states for poverty) is described by the term *economic mobility*. When individuals in a population improve their economic situation, they are said to be upwardly mobile; when their economic situation worsens, they are said to be downwardly mobile.

The stock-and-flow structure of Figure E5 allows for population changes in the impoverished and secure populations; different socio-economic groups and other population demographics might have different birth and deaths rates from one another and usually do. If population change is not important to the user, birth and death rates can be left at 0. The birth and death rates could be influenced by numerous factors (e.g., water, food, energy, health), but our model leaves that up to the user to decide. Thus, we, again, “cap” the model here and assume constant values.

In general, low-income people and those living in developing countries tend to have higher birth rates compared to higher income people (Aassve et al. 2005; Schoumaker 2004) than those living in developed countries (Ahlburg 1996; Bank 2017; United Nations Development Programme 2017). High population growth rates would increase the size of the poor population (*Impoverished*) faster than the non-poor population (*Secure*), causing a feedback loop that exacerbates poverty. To combat this, the number of people escaping poverty needs to be greater than the number of people being born into it.

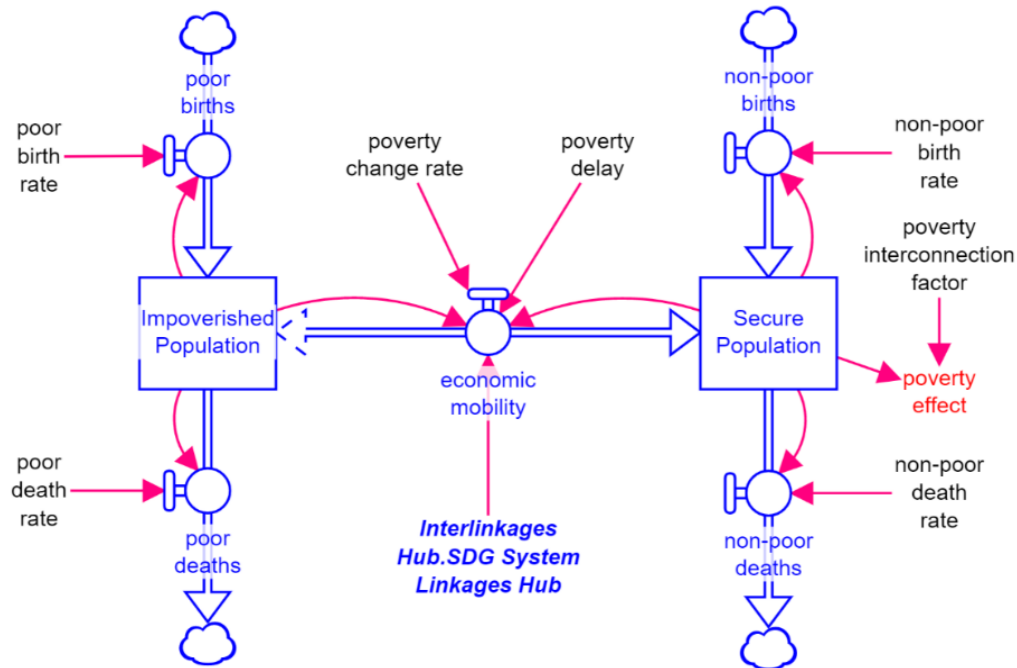


Figure E5. Insecure-secure diffusion system dynamics model with population change for SDG 01.

Realistically, there are not just two groups of impoverished and secure people. People fall on a spectrum commonly referred to as an income distribution, usually categorized by low, medium, and high-levels of development and at varying income levels (in income per year, \$USD/year for the United States). For simplicity sake, the model of Figure E5 considers two aggregated populations. The same model could be extended to include multiple socio-economic groups using chain-like stock-and-flow diagrams. Future work will aim to address this and will be briefly discussed later in our three-chambered version.

#### 2.4. Time delay and lag effects

Delays exist in the real-world and should be included in any modeling. When an order for a quantity of units is placed, the factory cannot immediately begin manufacturing, it takes time to ramp-up production. This lag-time exists in sustainable development as well: when the decision to implement a certain policy is made, it takes time for the proper institutions to be notified, funding to be sourced, and implementation plans and strategies to be devised. Likewise, when an NGO, governmental agency, or some other development entity decides to address poverty, it isn't immediately reduced; there is always preparation time before the policy is fully implemented.

This principle was included in our system dynamics model by using a delay function, which is another factor that has potential to affect economic mobility. Each SDG has a time delay similar to the poverty delay; examples



include health delay, food security delay, etc. Delay is defined as the time it takes for change to go from zero to fully “ramped-up.” Delay for each SDG X was added using the DELAY1 function available in the STELLA software and can be written as follows:

$$\text{DELAY1} \left( \text{SDG X change rate}, \frac{\text{SDG X delay}}{12}, 0 \right)$$

This function delays the rate of flow between two states (SDG X change rate) by a certain number of months (SDG X delay), which is converted to years by dividing it by 12. The zero in the third position of the DELAY1 function signifies that there is no rate of change at the start of the simulation. In other words, it takes time to fully initiate the implementation strategy for each SDG, which starts at 0, unless there are existing ongoing projects

### 2.5. Migration between states

Just as each SDG has specific names for each state (e.g., impoverished and secure for SDG 01), the rate of change between those states also has a unique name. The change between impoverished and secure states for poverty is defined as economic mobility. Likewise, for food security, it could be *access rate to food*; for governance, it could be *change in governance effectiveness*; and for partnerships, it could be *change in partnerships*. These are user-defined and context specific.

In Figure E5, economic mobility (the rate of change between the impoverished and secure states) is controlled by five variables (*poverty change rate*, *poverty delay*, *Impoverished Population*, *Secure Population*, and *Interlinkages Hub.SDG System Linkages Hub*), depicted by the five arrows heading to the biflow. The Interlinkages Hub.SDG System Linkages Hub variable will be discussed in a following section, but in short it is the coefficient, calculated endogenously, that accounts for the effects of the other SDGs on a specific SDG. These five variables are included in the economic mobility flow rate as follows:

$$\begin{aligned} \text{economic\_mobility} = & \\ & \text{DELAY1}(\text{poverty\_change\_rate}, \text{poverty\_delay}/12, 0) * \\ & \text{Impoverished\_Population} * \\ & \text{Secure\_Population} * \\ & (1 + \text{Interlinkages\_Hub.SDG\_System\_Linkages\_Hub}[\text{SDG\_01\_No\_Poverty}]) \end{aligned}$$

This equation differs from one SDG to the next by the names assigned to the variables: poverty change rate becomes food security change rate, health change rate, etc. Other than that, the equations and structures remain unchanged for all SDGs.

### 3. Sub-archetypes

The methodology presented thus far, applied to the SDGs, considered a change only between two states so a generic *two-chambered* form was appropriate, but it can be expanded to other issues and to multiple states. While maintaining the two-chambered form, migration presents a good example: one state (location) is rural and the other is urban. The basic structure of the model does not change, just the surrounding system and the user-inputs. The stocks represent two populations, but instead of a population of insecure people and a population of secure people, there is a rural population and an urban population. Economic mobility is replaced by rural-urban migration.

The archetype can be extended to model more complex phenomena such is the case with an *extended linear* form, which can be used to measure the income distributions of countries for example. The World Bank classifies countries into four groups: low-income, low middle-income, upper middle-income, and high-income. The two-chambers model is expanded to depict these four groups, one stock for each country group. A low-income country must first become low middle-income before it can graduate to higher income levels; it cannot jump levels. For this reason, it must be linear. The structure would contain four groups of countries in each of those four income levels and three biflows connecting them.

Similarly, the linear form can be used to measure income distributions and inequality within a country, as opposed to among countries. Each chamber represents an income level, but instead of groups of countries, they are groups of people at various socioeconomic income. The first chamber could be impoverished people (similar to the two-chambered model), and each other group can be at different income levels in the same way that countries are categorized. For example, these groups can be the impoverished for those making less than \$2 per day, the moderate-poor for those between \$2 and \$5 per day, the upper-poor between \$5 and \$10 per day, and so on. This set-up can simulate dynamic changes in income levels within a country for modeling the effects of potential policy interventions.

A special case of an elongated linear form is represented in Figure E6 and consists of a *three-chambered form*. This *triangular* form is useful for analyzing more complex urbanization processes by including a peri-urban group. Any of these subpopulations can move to the other two: rural to urban and peri-urban; urban to rural and peri-urban, and peri-urban to rural and urban. Each migration type is governed by a unique set of processes and causal mechanisms. The three-chambered triangular form accounts for population changes for each stock, but to avoid clutter, population inflow (births and immigration) and outflow (deaths and emigration) were reduced to a single biflow with

a net population change (*demographic rate*). Although not described in this work, the triangular form can theoretically be expanded to a *four-chambered square* form, a *five-chambered pentagonal* form, etc. This might be useful for modeling highway networks where vehicles can only travel to the next exit in either direction. Essentially, this becomes a unique version of the *linear* form so that the ends of the line are connected to create a circle (of sorts). This phenomenon will be left for others and future work to explore.

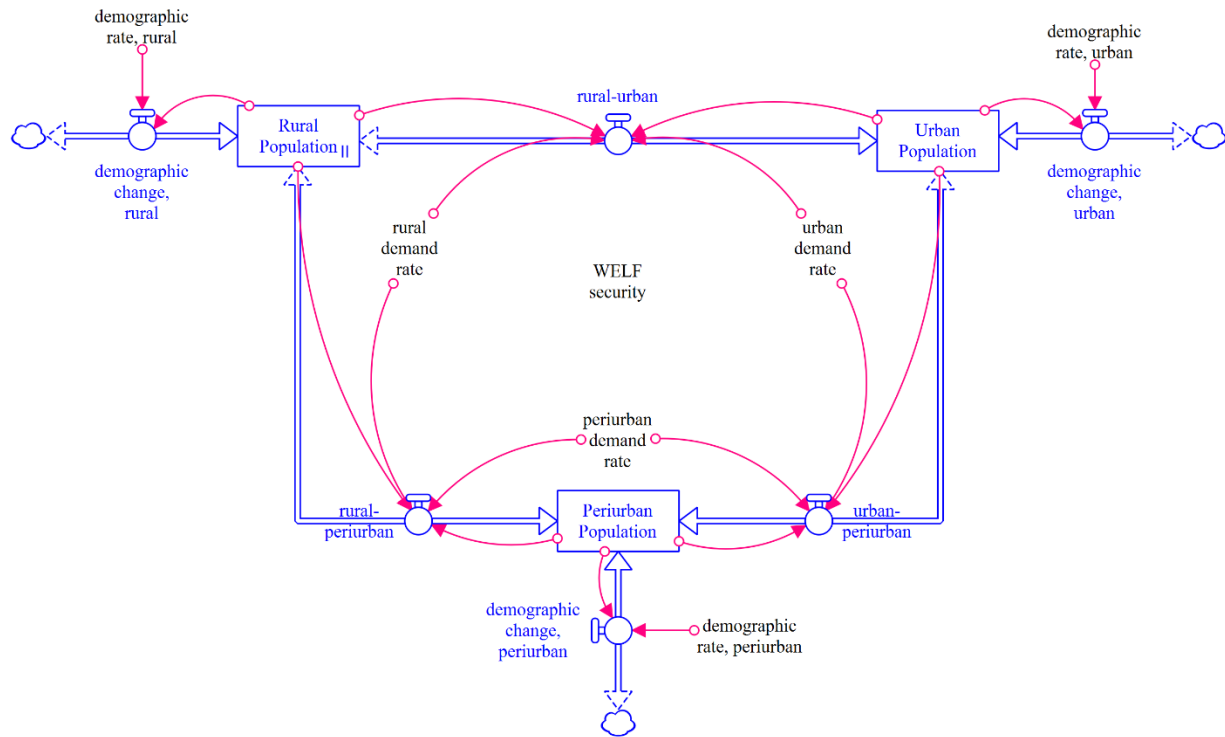


Figure E6. Triangular multi-chambered urbanization form

The last type of stock-and-flow structure considered herein (although there are undoubtedly more), is shown in Figure E7. This *multi-chambered hierarchical* form is useful for modeling land-use changes or large nested systems within systems (income distributions between *and* within countries, for instance). This type can have any number of chambers, but it utilizes a central chamber from where individual “branches” emanate out. For the case of land-use change, as a population grows, land is developed for housing, which reduces the available land devoted to the environment. Since people require not only land on which to live but also food and agricultural land, the various chambers are related and influence each other. For example, in order to feed a growing population, wild environmental land must be converted to agricultural land at a rate dependent on population growth. In that way, population is a driver for two chambers. Any number of chambers can be added. A fourth chamber can represent environmental

degradation, which is indirectly a function of population growth through the environmental impact of the other two chambers. If a policy is enacted that forms protected land like a national park, a fifth chamber can be included as well.

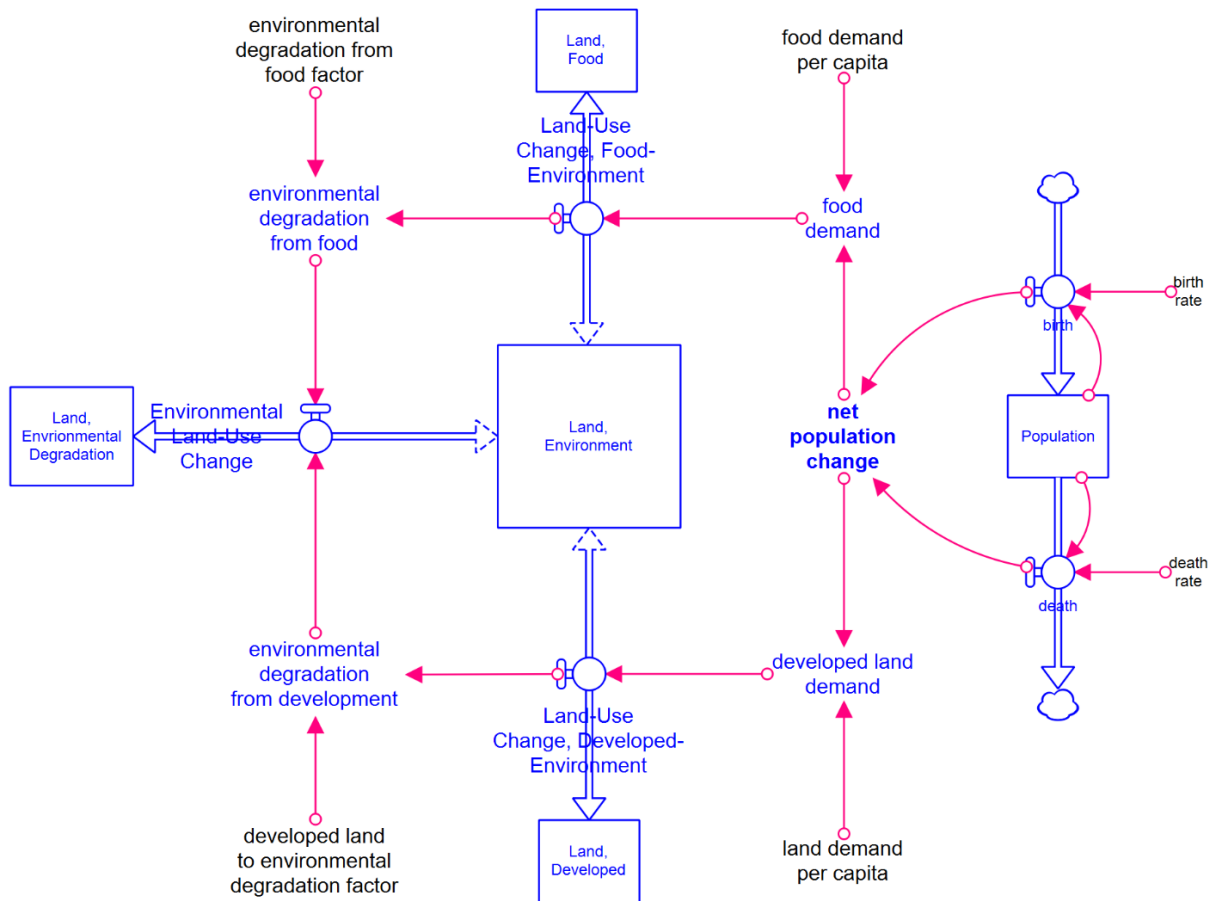


Figure E7. Hierarchical land-use change form.

Each chamber can be further subdivided into lower-level chambers that resemble the larger structure of Figure E7, resembling a crude fractal. For example, developed land is realistically composed of various kinds of land-use (e.g., residential, commercial, industrial); food land can be devoted to livestock and plants; the environment can be pristine untouched land and national parks; and degraded land can be polluted land, desertification, etc. These subcategories are what make the structure hierarchical, although less complicated models probably do not require extra level levels. Residential land, for instance, can be further categorized into rural, peri-urban, and urban land-use, or anything the user desires.

Also, as described earlier, a population of healthy people becomes infected and then recovers according to the Susceptible-Infected-Recovered (SIR) epidemiological model of which each of the three can be considered a different state. The SIR is structured with three stocks and two unflow structures, but realistically, people can become

re-infected once they recover or they might have a depressed immune system, either naturally or from the illness, causing them to be more susceptible. In situations like these, a three-chambered linear model or even the three-chambered triangular form is possible. Depending on the specific context and situation being modeled, combinations of various forms with different placements of unflows and biflows can be used. Health is complex, so any number of reasons can be included and ultimately modeled.

#### **4. Discussions and Conclusion**

This work presents a new insecure-secure diffusion (change-of-state) archetype which can be interpreted as a “two-way” S-shaped model. The same ways as the dynamic behind the Tragedy of the Commons archetype can be used to explain many phenomena spanning many issues, the proposed model can capture the dynamics of various situations associated with development and aid and for which flow is allowed to occur back and forth between stocks. It was shown, for instance, how the model can depict the evolution of the SDGs over time or the dynamics behind migration and urbanization. The system dynamics model can be seen as a hard model that can be used to conduct qualitative and quantitative analyses.

The insecure-secure diffusion archetype focuses on flows; hence the emphasis is on changing states and not on the actual states themselves. By doing this, the model requires only relative changes and not absolute data, simplifying the equations required for the simulation to work. The population at any time is divided by the initial population. If no population change occurs throughout the simulation, the total population will always be one; if the population doubles by the end of the simulation, the population will yield a final value of two. These relative population calculations enable model simplification without sacrificing accuracy and reliability.

The urban migration model (Figure E6) can be used to influence how land-use change (Figure E7) affects the SDGs (Figure E5) and the security of specific resources such as water, energy, land, food, income, education, health, etc. This allows for modularity by connecting the various forms together so that a standardized method to simplify the modeling of anthropocentric systems such as these. This allows more time to actually focus on the issues, rather than constructing models, so that effective, comprehensive systems-based solutions can be devised. With just the structures described herein, complete system dynamics models can be constructed to represent complex interconnected and anthropocentric systems.

## **Appendix F – A Systems Approach to Modeling Corruption: Bridging the Disciplinary Divide Between the Social and Technical Sciences**

### **Abstract**

Corruption is considered one of, if not the, largest issue hindering progress towards sustainable development and ultimately the global eradication of poverty. Corruption decreases the amount of aid that reaches its intending destination for those in need. It also reduces the efficiency of international aid thereby undermining its validity. Corruption depresses the incomes and overall GDP of many countries in Africa, especially those reliant on aid with rich deposits of natural resources. This paper focuses on the effects of corruption on natural resource governance. Specifically, the paper addresses the so called “natural resource curse” as a guiding framework, which is an especially problematic paradox in African countries. The premise is that an abundance of natural resources leads to more corruption, thereby to less economic growth, less democratic government, and lower levels of development, as measured by the Human Development Index, than countries with less natural resources endowments. A novel systems modeling methodology combining civil systems engineering, system dynamics, and political science is presented to analyze the interactions of corruption with the environment in the context of the natural resource curse in African countries. Until now, few systems approaches have been proposed to analyze different acts of corruption (rentier effect, repression effect, and modernization effect) in any fashion, and the ones that do rely entirely on perception-based data, namely the Transparency International’s Corruption Perception Index. The systems-based methodology presented herein is compatible with the social sciences and directly utilizes peer-reviewed literature as a tool to build models. In doing so, we advocate more collaboration and transdisciplinary research among technical scientists and engineers, system dynamicists, and social scientists (especially political scientists to address corruption issues and complex issues more broadly). New system-level understanding of corruption can be extracted from methods such as the one proposed and presented herein. To demonstrate this capability, a qualitative system dynamic stock-and-flow diagram is created where each variable and interaction is sourced to at least one peer-reviewed, social science article that can greatly increase model validation and confidence in accuracy; it depicts the world as it is, not as the modelers thinks it is. The proposed methodology can effectively aggregate the relevant data and literature into a high-level model, yielding significant insight and value to decision makers and those working with complex social and political issues.

**Keywords:** corruption, natural resources, governance, qualitative data analysis, system dynamics

## 1. Introduction

The paper aims to bring social and political scientists together with engineers and system dynamicists. Throughout this paper, we argue that these two groups have much to offer to each other. A major barrier to their collaboration, however, is that “[s]ocial scientists and system dynamicists approach research from very different perspectives...[as] there appears also to be a fundamentally different understanding of the way in which [causality] can be validly inferred” (Morris 2001). These differences can be remediated through hybridization of methodologies used by both groups – the more qualitative and societal focus of the social sciences with the more quantitative and technical nature of engineering and system dynamics. The transdisciplinary approach presented herein “can contribute an attractive alternative in the social sciences, broadening the scope of research” (Morris 2001). This unique approach is useful for all social issues but is especially designed for complex systemic issues such as corruption.

The proposed methodology uses a systems-based approach, specifically the qualitative portion of system dynamics modeling. It assumes that corruption is a behavior caused by structural deficiencies in the governance system. In the next section, we begin with a discussion of corruption, its impacts, definitions, and its various interdisciplinary perspectives. In the third section, the topic of corruption is bounded to natural resources governance (henceforth the Natural Resource Curse), since corruption in and of itself is quite complicated and expansive. Five fundamental causal mechanisms will be discussed as they form the main structures of the Natural Resource Curse (NRC) and the backbone of an eventual systems model, to be the topic of future work. The results section shows a systems representation of the dynamics of corruption in the form of a stock-and-flow diagram and provides a discussion of how to understand and read it. Lastly, we conclude with a discussion of the method and policy recommendations.

## 2. Corruption

Corruption is a problem, plain and simple. It exists in various degrees and forms in all societies; it can happen at any time, in any time-period, and has been present throughout history. It is endemic in all human systems, is a societal problem, and is a global phenomenon that “transcends national boundaries and frontiers (Iyanda 2012)”:

- 3.3% of the \$30 trillion global economy is lost to bribes each year (Goel and Nelson 2010)
- 5-25% (\$26-130 billion) of World Bank funds were lost or misused due to corrupt practices (Berkman et al. 2008) with more recent estimates as high as a \$1 trillion (Liotta and Miskel 2012)

- Corruption also exacerbates income inequalities and poverty; the Gini coefficient, a measure of income inequality ranging from 0 (perfect equality) to 1 (perfect inequality), worsens by 11 percentage points and income for the bottom quartile of people falls by 4.7 points with a one standard deviation increase in corruption (Gupta et al., 2002)
- Developed countries are not saved from the economic impacts of corruption, where 1% (\$170 billion) of the European Union's GDP is lost due to corrupt actions (Oberoi 2014)
- India lost \$7.7 billion a year (in 2000 \$USD) between 1948-2000 in illegal capital flows (Oberoi 2014)
- Corruption depresses the quality of Indian businesses by roughly 40% (Oberoi 2014)
- 25 - 40% of any given African country's GDP is lost from corrupt practices (Oberoi 2014)
- A one standard deviation reduction in corruption improved annual investment in a country by 4% of GDP and increase GDP's annual growth by 0.5% (Oberoi 2014)
- Corruption depresses the Kenyan economy by 12% of GDP (Liotta and Miskel 2012), nearly as large as their entire industry and manufacturing sector at 14% ("Economy of Kenya" 2017)
- The average Kenyan income was 424 times smaller than what parliamentary members awarded themselves for their salaries, a direct indicator of corruption (Liotta and Miskel 2012)

### 2.1. What Is Corruption?

Corruption is a broad term with many *definitions* spanning multiple disciplines, but a general definition that encompasses most others is when someone does something without authorization for personal gain and usually at the expense of another. Transparency International's (2016) definition is similar and the most widely used: "the abuse of entrusted power for private gain." Jancsics (2014) labels an agent as corrupt when they intentionally sacrifice their organization's interest or betrays its trust. Multiple definitions are compiled by Iyanda (2012) but when they are aggregated they sound familiar: (i) unlawful use of official power to enrich oneself usually at the expense of others; (ii) when someone knows better but chooses the worse option; and (iii) when someone acquires something to which they are not entitled. Taken together these definitions have common *components* that determine when something is a corrupt act: (i) it is illegal, secret, or informal exchange of formally allocated resources; (ii) at least one corrupt party is formally involved in the entity from which resources (broadly defined) are extracted; and (iii) the corrupt act is



against formal rules, laws, or policies (Jancsics 2014). Beyond those mechanisms, corruption requires three *conditions*, or an *enabling environment*, to arise and then persist: (i) discretionary power or authority among relevant people; (ii) the incentives to be corrupt (i.e. incentives, utility, or gain to be made from being corrupt); and (iii) weak institutions which make it easier for corruption to happen and continue (Aidt 2003).

An act is considered corrupt so long as it adheres to the conditions and contains the components described above; Table F1 lists and explains some common corrupt acts. Corruption is the prevalence of and damage caused by corrupt acts. In this work, corruption is synonymous to rent-seeking, which is the desire and tendency for an entity to engage in corrupt acts for extracting illegal rents. Rents are the benefits (financial, favors, or otherwise) acquired through the corrupt acts.

Table F1. Corrupt actions common in natural resource governance; adapted from Rose-Acker and Palifka (2016) and Iyanda (2012)

Bribery	Money, gifts, or favors given to a government or corporate official in exchange for breaking rules to give preferential treatment, an advantage, or otherwise some kind of benefit to be received (see extortion)
Extortion	Demanding a bribe or favor from an official, where the official usually is at a position of lesser power (see bribery)
Exchange-of-favors	The exchange of one broken rule for another.
Clientelism/patronage	General favoritism to a specific group (see nepotism and cronyism)
Nepotism	Putting someone into a position of power based on the strength of social connections rather than on merit or the legal process (see clientelism/patronage and cronyism)
Cronyism	Giving preferential treatment to one's group (racial, ethnic, religious, political, or social) over other groups (see clientelism/patronage and nepotism)
Embezzlement	Theft from the employer (firm, government, or NGO) by the employee.
Kleptocracy	An autocratic state that is managed to maximize the personal wealth of the top leaders and is closely related to economic inequality; there are virtually no differences between the economic elites from the political elites, with Russian oligarchs as a prime example.
Influence peddling	Using one's power of decision in government to extract bribes or favors from interest parties.
Tax evasion	Avoiding tax can be legal or illegal. It can be a subset of bribery and is a mechanism reduces the efficiency of revenue generating tools. Utilizing legal loopholes is a form of corruption in that the citizen is not paying all the taxes that they are supposed to due to structural inefficiencies or problems in the revenue accumulation systems of a government.
Conflicts-of-interest	Having a personal stake in the effect of the polices one decides; although not directly a corrupt act, a conflict-of-interest can heavily influence corrupt practices.

## 2.2. Disciplinary Perspectives of Corruption

The definitions of corruption differ by discipline of which most come from the social sciences. For *economists*, people are rational actors that seeks to maximize their profits (utility) and corruption is a mechanism to do so. Corrupt practices are also manifestations of wage differentials between public servants and their more profitable private sector counterparts; governments cannot, or will not, compete with private companies in the market when it comes to salaries of their employees (Ades and Di Tella 1999). When the costs of corruption are smaller than its benefits, corruption is more widespread and systemic (Andvig et al. 2000; Heath et al. 2016) as is especially the case in the developing world. In general, economists are interested in the impact of corruption on economic development (Torsello and Venard 2016), thus they tend to view corruption mostly as a problem to be solved as opposed to a phenomenon to be understood.

There are multiple theories about corruption in *political science*, which represents the most common discipline involved in corruption research. One states that corruption is a way to overcome burdensome bureaucratic red tape to increase efficiency (Andvig et al. 2000), or colloquially, corruption ‘greases the wheels.’ Similarly, poor institutional structure and quality can be a catalyst for corruption, which causes inefficient bureaucracy. Weak institutions make corrupt acts easier and less risky. Another states that corruption is a natural by-product of non-democratic (anocratic and autocratic) governance systems (Heath et al. 2016). The institutional perspective, described by Gerring and Thacker (2004), further states that Unitarianism and Parliamentaryism governments exhibit lower corruption, since a single person does not hold disproportionately large amounts of power as is the case in dictatorship and other autocratic governments.

A popular view among economic and political science scholars is that of the principle-agent, where the individual is incentivized to act corrupt and intentionally does so; many theories stem from that (Jancsics 2014). Economic and political theories of corruption are highly-interrelated with one another, and are rarely, if at all, purely economic or political in nature. Economic and political definitions also tend to focus on large government or corporate entities, which center on structural (institutional and bureaucratic) explanations for corruption. This structural approach (collective-action problem) differs from the principle-agent approach in that it stresses a more institutional, systemic approach and views corruption as a “social trap” (Mungiu-Pippidi 2013; Persson et al. 2013; Rothstein 2011). Corruption is a manifestation of institutional quality, or lack thereof, and differs from the principle-agent to a more

collective-action problem (Rothstein 2011). At this institutional-level “the only thing worse than a society with a rigid, over-centralized dishonest bureaucracy, is one with a rigid, over-centralized, honest bureaucracy” (Huntington 2006). In international relations and in the context of the global political economy, closed societies and economies suffer from high corruption because they are less reliant on the global economy removing leverage that the international community might have (Gerring and Thacker 2005). In sum, the economic and political science literature takes two theoretical approaches: that of the principle-agent that operates at the micro-scale and the collective-action that operates at the macro-scale (Jancsics 2014; Mungiu-Pippidi 2013; Rothstein 2013).

Other fields, such as *sociology*, use more social and cultural perspectives to explain corruption, which explain some endemic and societal-level corruption and operates primarily at the macro-scale. A sociological approach to understanding corruption “derive[s] from exchange theory, which emphasizes the nature of the social relationships between [various] actors (Heath et al. 2016).” More demographic theories involve gender, where higher levels of female empowerment and involvement in the government and the general economy lead to lower corruption (Branisa and Ziegler 2010). Coupling that idea with others from political science, Branisa and Ziegler (2010) describe how social institutions that reduce gender inequality improve good governance (reducing corruption).

*Anthropology*, which is underrepresented in the corruption literature, takes a different approach from other fields of social sciences. Anthropologists try to avoid discrete definitions in their analyses, and instead rely on contextual morality as their guiding principle in that “[d]ifferent societal contexts can have diverse and multiple moralities (Torsello and Venard 2016).” Anthropologists avoid definitions because in doing so, they argue, biases from categorizing and nuance of local culture is lost. With multiple moralities, corruption is not viewed as something good or bad, it simply is; the specific local context determines if it is a positive or negative factor. For example, the researcher might view petty corruption as a corrupt act in all cases, but the local culture might view some petty corruption as a “practice that smoothens social exchange,” according to Torsello and Venard (2016) or something that greases the wheels. Furthermore, what might “look like corruption to outside observers might serve crucial social and symbolic functions from the inside or in a local context” (Jancsics 2014; Torsello and Venard 2016).

According to Torsello and Venard (2016), the anthropologist researcher focuses on the thought-processes, worldview, and perceptions as non-static phenomenon in relation to social transformation, globalization, and development. Anthropologists focus on the impact of culture generally more than the other social sciences but shares

concepts with social norms that are often discussed in the political science literature. To anthropologists, social norms exhibit a “dynamic nature of the morality of corruption (Torsello and Venard 2016),” which contrasts with the more static representation in political science.

*Psychology*, like anthropology, takes an individual-level perspective and might view political corruption as a person succumbing to their intrinsic motivations or personal desires over the loyalty to their government job (Ryan and Deci 2000).

These five disciplines – economics, political science, sociology, anthropology, and psychology – are part of the social sciences, but they all attempt to understand corruption in different ways. In reality, it takes an amalgam of all disciplines (including ones not discussed here) to begin to form a more complete understanding of corruption, its influences, and its causes. Focusing on just one area, ignores aspects of others including different scales – micro- and macro-scale. Anthropology as a singular field, comes close to an approach (based on individual circumstances) to define and understand corruption. Taking parts from all areas, the next section attempts to use a systems perspective on corruption.

### **2.3. Systems Definition**

In many contexts, the definitions of corruption depend on societal norms, which are highly influenced by and structurally ingrained within local, national, and ethnic culture. For example, some societies have lived with corruption for so long that it has become normal for them, so what might seem corrupt for some societies will be business-as-usual for theirs. This is especially pervasive in many African and Eastern countries that were former colonies of imperial powers (Bhattacharyya and Hodler 2010; Goel and Nelson 2010). These various perspectives are of interest to anthropologists and sociologists but also involve political and economic theories as well.

Many disciplines have commonalities in their approaches to understand corruption and model its effects. General issues of political, governance, and societal structure and norms span most social sciences. In much the same way as poor government structure can worsen corruption (political science), cultures with hierarchical and highly centralized religions (sociological and anthropological) and economies (economic), and a general acceptance of power differentials are more likely to be corrupt (Husted 1999; Jancsics 2014; Seleim and Bontis 2009). Furthermore, strong personal relationships augment expectations that favors will be reciprocated (Heath et al. 2016), a process that can be understood using social network analysis (Borgatti et al. 2013).

Other societies might be so distrustful of their government that corrupt practices could be the only viable response to a corrupt government. Other nations have societies that inherently function based on societal power differentials, like the caste system, which causes endemic lack of trust among different socio-economic groups ingraining corruption into that society (Bjørnskov 2003; Rothstein 2013; Uslaner 2013). In these groups, particularistic norms regulate behavior and could dominate universalistic norms under which the society as a whole operates (Jancsics 2014). Furthermore, social networks in general strengthen interpersonal bonds and trust, thus reducing transaction costs associated with corrupt acts (leading to nepotism in government corruption).

A common theme arises: corruption is a behavior that emanates from a system's structure – the way a society is organized (religion, culture, or otherwise) and the institutions of the government – as well as the duration those structures and institutions have been around and have persisted. In general, a poorly structured (social, political, governance, economic, etc.) system will generate poor behavior. Institutions can act as “opportunity structures to conduct corrupt practices” (Jancsics 2014). Corruption is not a universal concept and varies by culture or community. Socially, an act that is viewed as elite capture to foreigners may not be perceived as such within the community who view it as a leader earning their share. Nepotism is an example of a corrupt act (Table 5), but the community might simply view it as doing favors (Seleim and Bontis 2009), helping a friend, or even a form of economic bartering. There are obviously a lot of overlaps among these themes because corruption is not discrete, but rests on a multidimensional set of spectrums.

The focus of this work is on the structural causes to corruption. It is based on the concept of system sciences that the structure of a system determines its behavior (Amadei 2015; Benson and Marlin 2017; Ford 2010; Sterman 2000; Ullah et al. 2012). Furthermore, Rose-Acker and Palifka (2016) state that a “high level of corruption indicates that something is wrong with the state's underlying institutions...[signaling] a need for structural reform – not just more vigorous law enforcement.” A systems approach to understanding corruption requires a systems-oriented definition of corruption: *corruption is anything an actor (human) does to enrich themselves usually at the expense of other actors by undermining the system effectiveness.* A systemic solution to corruption would be to restructure the governance system through structural reform to alter the negative behavior (reduce corruption). In this way corruption is never directly addressed, rather indirect actions propagate throughout the system eliciting lasting behavioral change and outcomes of that system (i.e. political officials can be dis-incentivized to act in a corrupt manner by reducing the enabling environment to be corrupt).

This definition of corruption is broad enough to contain virtually all acts considered corrupt, as well as most definitions of corruption regardless if they are economic, political, social, or environmental in nature. It is dynamic in that, if what a society views as corrupt changes so does the definition, so long as it adheres to the general definition; an interesting approach used by anthropologist (Torsello and Venard 2016) discussed earlier.

The definition of corruption changes with the perspective of the observer or, in our case, the researcher or modeler who is trying to understand a specific situation. But it is important to keep in mind that, as summed up by Oberoi (2014), corruption is “what every society decides it is; it simply has to be internally consistent with formal institutions of a given society.”

#### **2.4. Scales and dimensions of corruption**

Corruption can operate at any level, from petty corruption between common citizens to grand corruption that occurs among the political and economic elite. *Grand corruption* involves a small number of powerful actors dealing with massive quantities of money and can be political or corporate in nature (Rose-Ackerman and Palifka 2016). It is often between the two, especially in the case of natural resources and large infrastructure projects. This form of corruption is out of reach to most citizens, who can only really be guilty of petty corruption (Rose-Ackerman and Palifka 2016). This street-level corruption is involved with everyday activities of citizens (Iyanda 2012). As a result, grand corruption is more pervasive in national governments and other locations in the economy that deal with commanding and authoritative figures operating in high-power centers involving large sums of money (Iyanda 2012; Rose-Ackerman and Palifka 2016) such as in the military and national defense (Gupta et al. 2001), natural resources (Bulte and Damania 2008; Busse and Gröning 2012; Corrigan 2014; Dimant and Tosato 2017; Kolstad and Søreide 2009), and the infrastructure sectors (Tanzi 1998).

*Business corruption* (petty corruption’s private sector counterpart) occurs with small- to medium-sized businesses who interact with average citizens, while *corporate corruption* (grand corruption’s corporate counterpart) involves large multinational companies interacting with governments. In contrast, businesses and corporations might also act corrupt to avoid regulations. For example, Mitchell (1994) describes a situation when oil-tankers would dump their waste oil out in the ocean before entering port so authorities would not detect and fine them. This compliance problem is a form of corruption when business act in ways that prioritize company gain over societal good; this views corruption as a collective-action problem as opposed to the principle-agent problem (Bauhr 2017; Mungiu-Pippidi

2013; Persson et al. 2013; Rothstein 2011). Eventually, the *structure* of the environmental regulations governing how tankers disposed of their waste oil was successfully reformed to disincentivize this negative *behavior* (Mitchell 1994).

### 3. The Natural Resource Curse

This section is a truncated version of a more extensive literature review, which was used to directly construct the stock-and-flow diagrams shown later in Figures F1-F5. The methodology to convert this literature review into a systems model is explained in the following section.

The natural resource curse is a phenomenon in which countries with large quantities of natural resources and mineral wealth counterintuitively suffer from lower economic and social development (Bhattacharyya and Hodler 2010; Busse and Gröning 2012; Corrigan 2014; Frankel 2010; Kolstad and Søreide 2009; Teksoz and Kalcheva 2016). It occurs throughout the Global South but is especially pervasive in many African and some Middle Eastern countries: all of the 12 oil exporting countries in Africa are in the bottom half of the United Nations Human Development Index (Diamond and Mosbacher 2013).

The guiding principle in the natural resource governance literature is to understand “why some countries succumb to the resource curse while others seem to benefit economically from their natural resources (Corrigan 2014).” The most common reason proposed in the literature involves poor institutional quality and governance. That is only part of the picture, but there are a few specific, well-documented causal pathways that connect natural resources with governance, namely the rentier, repression, and modernization effects (Bhattacharyya and Hodler 2010; Busse and Gröning 2012; Corrigan 2014; Kolstad and Wiig 2009).

Each pathway incorporates different corrupt acts (see Table 5), in different combinations, and at different points along the chain, while at the same time intersecting and influencing one another. The *rentier effect* (Figures F1, F2, and F3) is directly influenced by the amount of revenues (rents) the government is able to extract from natural resources (with oil being the prime example) and occurs when those revenues are substantial in relationship to other sources of income. Substantial in this context refers to when resources revenues are so large that the government needs not rely on other sources of income. The effect comes from what the national government does with those revenues (Teksoz and Kalcheva 2016). The rentier effect can be further delineated into the taxation, group formation, and spending effects. The resource revenues could be used to reduce the need to tax the population (*taxation effect* in Figure F3), making them happier with the government, which in turns reduces their desire to hold the government

accountable; unrest and general unhappiness with the government accumulates at a slower rate (Busse and Gröning 2012; Corrigan 2014) increasing the tolerance of corruption. This money can also be used for development projects to appease or distract the population. Along the same lines, Busse and Gröning (2012) describe a *group formation effect* (Figure F2) which occurs when the government uses the rents to prevent the formation and operation of social and special interest groups who would otherwise influence the government to reduce corruption. The same effect can happen when those revenues are spent on cronyism (broadly favoritism), which Busse and Gröning (2012) refer to as the *spending effect* (Figure F1). These tend to resemble kleptocracy in extreme cases, such as what is occurring with Russia's current political trajectory. Either way, through the reduction in taxes and the increase in general favoritism, accountability is reduced because the population sees more money and will turn the other way when the government or political officials participate in corrupt acts. This favoritism leads to more natural resource economic policies accelerating their extraction. In the short- to medium-term, revenues increase feeding back into the cycle. Over time, the amount of resources diminishes with little benefit to show for the steep payment (Corrigan 2014).

The *repression effect* (Figure F4) is when the government uses the revenues to suppress opposition, as opposed to gaining favor among the populace. It is a more extreme version of the group formation effect and can be violent or militaristic. The rents again come from the significant natural resource wealth endowed within a country's borders, but also can come from individual government officials, who receive illegal income from corrupt acts like bribery (Busse and Gröning 2012; Kolstad and Wiig 2009). The government might spend more on the military further entwining the political and military spheres in a country. When that happens, it is easier for the military to oppress or terrorize the people. In extreme cases, the repression effect can take the form of violent suppression of protests or attempted revolution. A salient example is the Arab Spring. In short, the repression effect "could impede aspirations among the population for more democracy or better institutions and government services (Busse and Gröning 2012)."

Busse and Gröning (2012), Corrigan (2014), and Kolstad and Søreide (2009) all describe a *modernization effect* (Figure F5) when the government actively delays modernizing and industrializing their country because such a society will have alternative sources of economic and political power with which to oppose the government. In some cases, it can be viewed as a passive and indirect version of the repression effect. Delaying modernization reduces the enabling environment for protests to form and revolts to succeed. An economy based on natural resources and agricultural has little need for a large skilled labor force, and education positively correlates with demand for political reforms. The government actively comes in the way of social and cultural change in fear of losing power. Many



countries in the Middle East (Frankel 2010), namely Iran and Saudi Arabia, have been especially susceptible to this form of corruption.

#### **4. Methods and Results**

“One might say that the ultimate goal of any science is to establish *causal relations* (Denis 2016),” where at its core causality is the relationship shared by two or more variables. Science attempts to simplify complex systems (Sterman 2000) to identify direct causality (that is causal relationships where one variable directly influences another without intermediaries) of specific structures within those systems. Science (social, natural, physical, etc.) utilizes many tools to analyze causality, and it is the knowledge produced through these tools that will be the focus of this analysis. Explicitly, this work explores how to put together all those simple disjointed pieces produced from the (social) scientific research in a way that is valid and coherent. The proposed methodology is a hybrid of qualitative data analysis (QDA) and systems dynamics. The technique, called qualitative structural data analysis (QDSA), is applied to the relevant social science corruption literature to form a deep understanding of the Natural Resource Curse in the form of a stock-and-flow diagram, which has the potential to yield deeper insights than current methodologies in the social sciences. This method can be used for many social issues whose behavior is determined or governed by a complex system, especially those “whose main actors are directly and strongly influenced by complex human socio-economic-political interactions but are themselves not humans,” which we refer to as *anthropocentric systems* (Zelinka and Amadei 2019a).

Through a detailed literature review, it has become apparent to the authors and many corruption scholars over recent years that corruption negatively affects multiple sectors through many channels and causal mechanisms; simply put, corruption is a complex issue. Most articles go through individual mechanisms or attempt to relate corruption by only a few dependent variables. Few articles look at the interactions among the multiple mechanisms at work, and fewer still analyze the various upstream and downstream causes and effects of systemic corruption. In short, the vast majority of the existing work looks at corruption through disciplinary silos, a narrow focus, and generally without much consideration to account for complexity. A systems-based approach is necessary to understand and effectively model these kinds of complex social issues.

##### **4.1. Interdisciplinary Collaboration**

Corruption is mostly the focus of social sciences with most of the literature emanating specifically from political science, economics, and to a lesser extent all other social sciences (Jancsics 2014). Although many of the issues regarding corruption overlap many fields within the social sciences, there is relatively little collaborative work among them (Jancsics 2014; Torsello and Venard 2016) and much less so with the technical sciences and engineering. For example, only a few articles use system dynamics to analyze corruption (see Méndez-Giraldo et al., 2017; Soto Torres et al., 2007; Ullah et al., 2012; Ullah and Arthanari, 2011). Jancsics (2014), a sociologist, notices this deficiency in the corruption literature and the social sciences in general; he describes the “lack of interdisciplinary communication about corruption, such that models developed by different academic disciplines are often isolated from each other.” He discusses three types of corruption studies and approaches: a micro-level perspective, a micro-level perspective, and a relational approach focusing on social interactions and networks that bridges the other two. Each social science discipline generally operates at different scales (psychology versus sociology, international relationships versus development studies, micro- versus macro-economics, etc.), possibly explaining some of the lack of collaboration – it is more difficult to work together when people inherently do not perform research at the same scale. The last approach can be used to bridge the disciplinary divides (Jancsics 2014) by providing a method compatible with system dynamics.

Collaboration between the disciplines is not a new idea but has received little attention (Morris 2001). System sciences, we argue, can bring together various fragmented fields through a transdisciplinary and collaborative approach. They can blend crucial elements of the social sciences with that of the technical science and engineering through an hybrid qualitative and quantitative methodology (see Zelinka and Amadei, 2018b). Social science methodologies, generally, tend to emphasize individual relationships and avoid the big picture, although they are proficient at detailing individual factors and nuance to identify fundamental and underlying mechanisms through which corruption affects the natural resource sector, or vice versa; but it can be subject to tunnel vision. Engineering methods can fill in data gaps and present a set of quantitative tools and modeling techniques with which social scientists might not often use in their work. Engineering, generally, is good at understanding the big picture, but misses the nuance when understanding social issues.

The weaknesses in the social sciences, engineering, and system dynamics can be overcome, at least partially, through acceptance and collaboration. Indeed, a collaborative system is greater than the sum of its parts; it shows synergistic properties. When groups work together, individual parts can be thoroughly analyzed and understood,

ideally, but can also be combined to provide a relatively accurate and valid representation of the issue at hand. Transdisciplinary collaboration can provide high-resolution details at a large-scale to see how the many mechanisms interact with one another, explore reverse causality, and detect indirect influences and effects. Perhaps most importantly, a system approach can make complex and ill-defined social issues understandable to a non-social-scientist, namely policy and decision makers. System dynamics is a computer-aided modeling approach used in the technical sciences and engineering that can function as a tool to model and understand ill-defined social issues better.

#### **4.2. System dynamics modeling**

This paper will forgo a detailed description of system dynamics modeling as it is covered in the authors' other paper in this conference (see Zelinka and Amadei, 2018b). Systems dynamics is a relatively recent branch of systems science that originated with the work of Dr. Jay Forrester at the Massachusetts Institute of Technology in the 1950s and 1960s. It represents a milestone in the overall evolution in the application of systems thinking and the development of tools to address complex issues in a wide range of disciplines such as engineering, business, economics, health, planning, management, etc. A simple way to see system dynamics is that it studies “how systems change over time” (Ford 2010). The System Dynamics Society (2016) defines system dynamics as a computer-aided approach to policy analysis and design. It applies to dynamic problems arising in complex social, managerial, economic, or ecological systems — literally any dynamic systems characterized by interdependence, mutual interaction, feedback, and causality.

Since its inception, system dynamics has accrued popularity in various STEM and some social science fields, including topics such as corruption (Méndez-Giraldo et al. 2017; Soto Torres et al. 2007; Ullah 2012), urban migration and demographic process (Tarbert et al. 2018), the Sustainable Development Goals (Moffatt and Hanley 2001; Måns Nilsson et al. 2017; United Nations Economic and Social Council 2015; Zelinka and Amadei 2017, 2019b, 2019a; Zhang et al. 2016), health and infectious diseases (Ghaffarzadegan et al. 2010; C. S. Peadamallu et al. 2012), education (C. Peadamallu et al. 2010); sustainable community development (Amadei 2015), environmental and ecological process (Ford 2010), and business and management science (Sterman 2000). In general, systems dynamics has unique characteristics that warrant its use in modeling complexity in social and governance systems (Zelinka and Amadei 2018b).

#### **4.3. Qualitative Structural Data Analysis**

This section is a brief overview of *qualitative structural data analysis* (QSDA), which codes and then translates text from peer-reviewed articles and reports from reliable sources into causal-loop diagrams (CLDs), stock-and-flow diagrams, and eventually full system dynamics models. Corruption is an endemic social issue that has been around since the dawn of human civilization, but there exist few reliable methods to understand its systemic causes, effects, and impacts. Corruption will provide a proof-of-concept case study of QSDA to understand and then model complex social issues commonly studied within the social sciences. The methodology proposed herein is in its early stages, and as such it will undergo many future iterations. Even in its current state, it can be used to provide an informative and reliable representation of the Natural Resource Curse mentioned earlier in this paper (Section 3). A stock-and-flow diagram depicting the causes and consequences of corruption in the natural resource sector focuses on the five significant mechanisms detailed in the literature and discussed earlier. Each variable, type of variable (direct versus indirect and moderating versus mediating), relationships among variables, and directions of those relationships (positive or negative) can be captured in QSDA. Eventually, a system dynamics (SD) model can be constructed that encompasses the entire literature synthesis and all the articles analyzed within. The main difference between a stock-and-flow diagram and a full system dynamics model is the inclusion in the latter of initial conditions and equations, which will be left to future work.

QSDA is heavily influenced by the qualitative data analysis (QDA) which “is the range of processes and procedures whereby we move from the qualitative data that have been collected into some form of explanation, understanding or interpretation of the people and situations we are investigating” (Gibbs and Taylor 2010). *NVivo 11* by *QSR International* was the QDA software utilized for our QSDA, and although, not originally designed for addressing such needs, NVivo proved to be sufficient for the task at hand. Nominally, the coding mechanisms between the two analytical methods are the same, but instead of being used to interpret and understand qualitative information like in QDA (Bernard and Ryan 2010), QSDA is used to structurally identify and (reliably) source variables, relationships, and more complicated causal mechanisms. The variables become the convertors, stocks, and flows that constitute CLDs, stock-and-flow diagrams, and system dynamics models; the relationships become the interconnections; and the causal mechanisms – the rentier, repression, and modernization effect – become large structures around which the rest of the model is built.

In any system dynamics model, there are three types of variables: flows, stocks, and convertors. These basic components appear in Figures F1-F5. Stocks, represented by rectangular boxes, are net accumulations of something

at one point of time and represent state variables that define the current state of the systems. Flows appear as pipelines with a faucet controlling the flow and refer to processes that cause change over time (dynamic) of information or materials; they are control variables that create change in the systems and affect stocks. Convertors, shown as a name or a circle-and-name, transform (convert) information from one stock-and-flow path to another. For example, greenhouse gases (GHG) are emitted per year (flow) and accumulate in the atmosphere (stock). Each person uses electricity that in turn emit GHGs; electricity and GHGs are two stocks-and-flow paths connected by at least one convertor. The *variables* are called *nodes* in NVivo. While manually coding the literature, each variable type was noted and when the stock-and-flow diagram was constructed, the variables were assigned their appropriate variable type.

NVivo uses the term *relationships* to signify the interconnections between two variables. Interconnections can either negatively or positively affect another variable. Once the five larger causal mechanisms, discussed in the NRC section above, were classified, the necessary variables were identified and connected as needed with relationships. *Cases* in NVivo represent units of observation, which in QSDA are causal mechanisms and other important structures. They are composed of individual nodes, relationships, or groups of them. Cases can group multiple sources that relate to the same structure or mechanism and help to organize them for when it comes time to construct the stock-and-flow diagram and then the system dynamics model.

Once all these variables, interconnections, and causal mechanisms were identified and properly coded from the literature in NVivo, the information was, as objectively as possible, incorporated into STELLA (Systems Thinking Experiential Learning Laboratory with Animation) Professional (version 1.6), a system dynamics modeling software by *isee systems, Inc.* The components of the QSDA were added into a single stock-and-flow diagram that encompassed all five major causal mechanisms identified in the literature review. For ease of viewing, each mechanism was given its own figure and highlighted in blue as shown in Figures F1-F5.

## **5. Discussion and Conclusion**

Because the literature review above is directly based on the same QSDA as the figures below, a detailed explanation and walkthrough of the stock-and-flow diagram is not required. Each variable, interconnection, and structure depicted in the stock-and-flow diagram can be sourced to specific articles and locations within those articles. All articles used in our analysis were themselves based on many peer-review articles. Hence, the QSDA effectively aggregates very

many articles, thus acting as a form of a systems-based meta-analysis. Since all the articles used in this analysis are peer-reviewed, the assumption is that any models based on them exhibit a high level of validity. The methodology presented herein is designed to reliably connect the model with the articles on which it is based.

It is the goal of this work to show that social scientists, engineers, and system dynamicists have much to offer each other and that collaboration among them is crucial to understand and analyze complex issues. QSDA provides proof-of-concept of a transdisciplinary method through which these seeming conflicting groups might regularly form collaborative research groups. The authors see a day soon when most articles are published under the auspices of multiple fields, and systems thinking prevails over linear thinking. This work is meant to advocate for that paradigm shift and provide a means to do so.

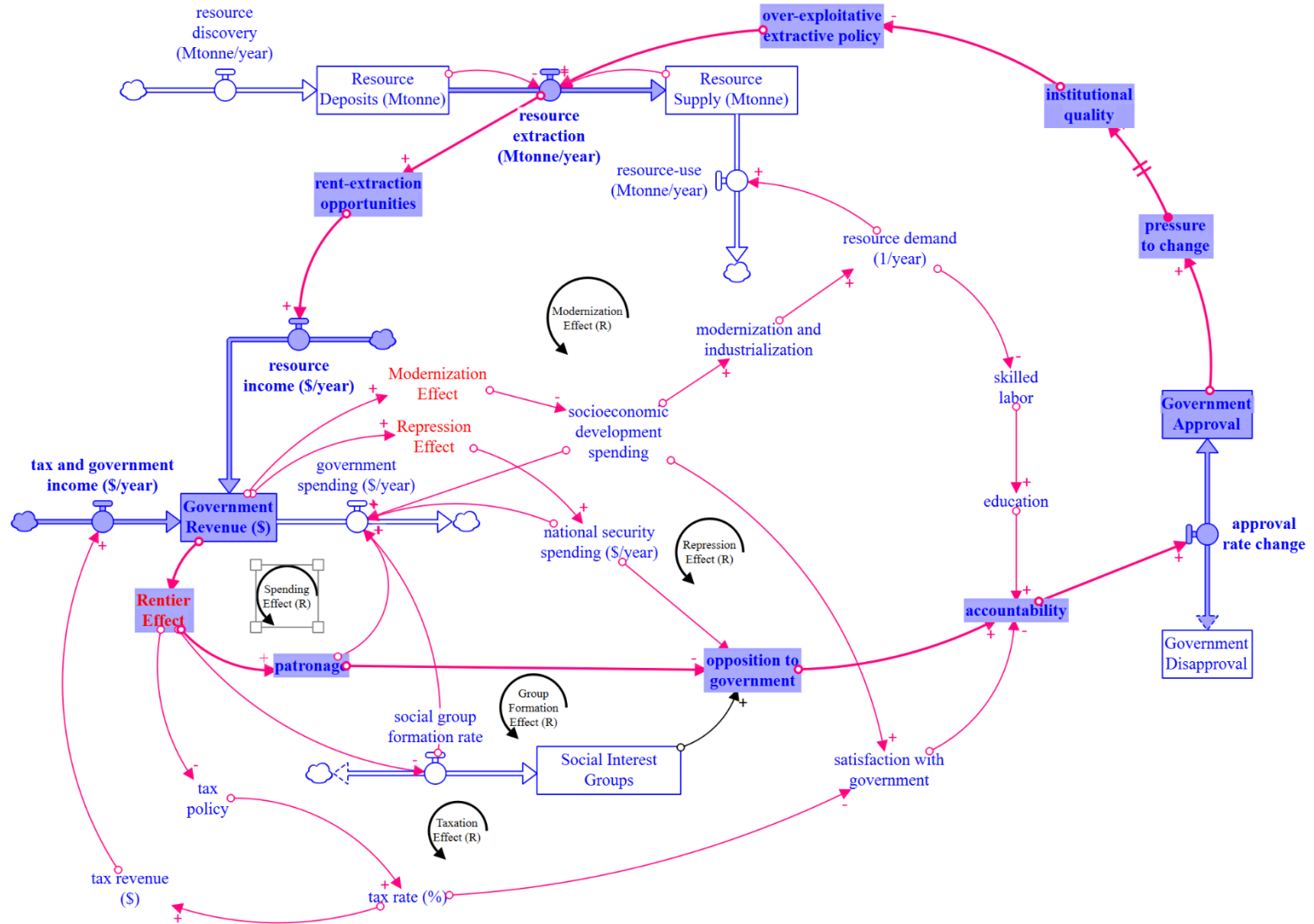


Figure F1. Rentier effect (spending effect)

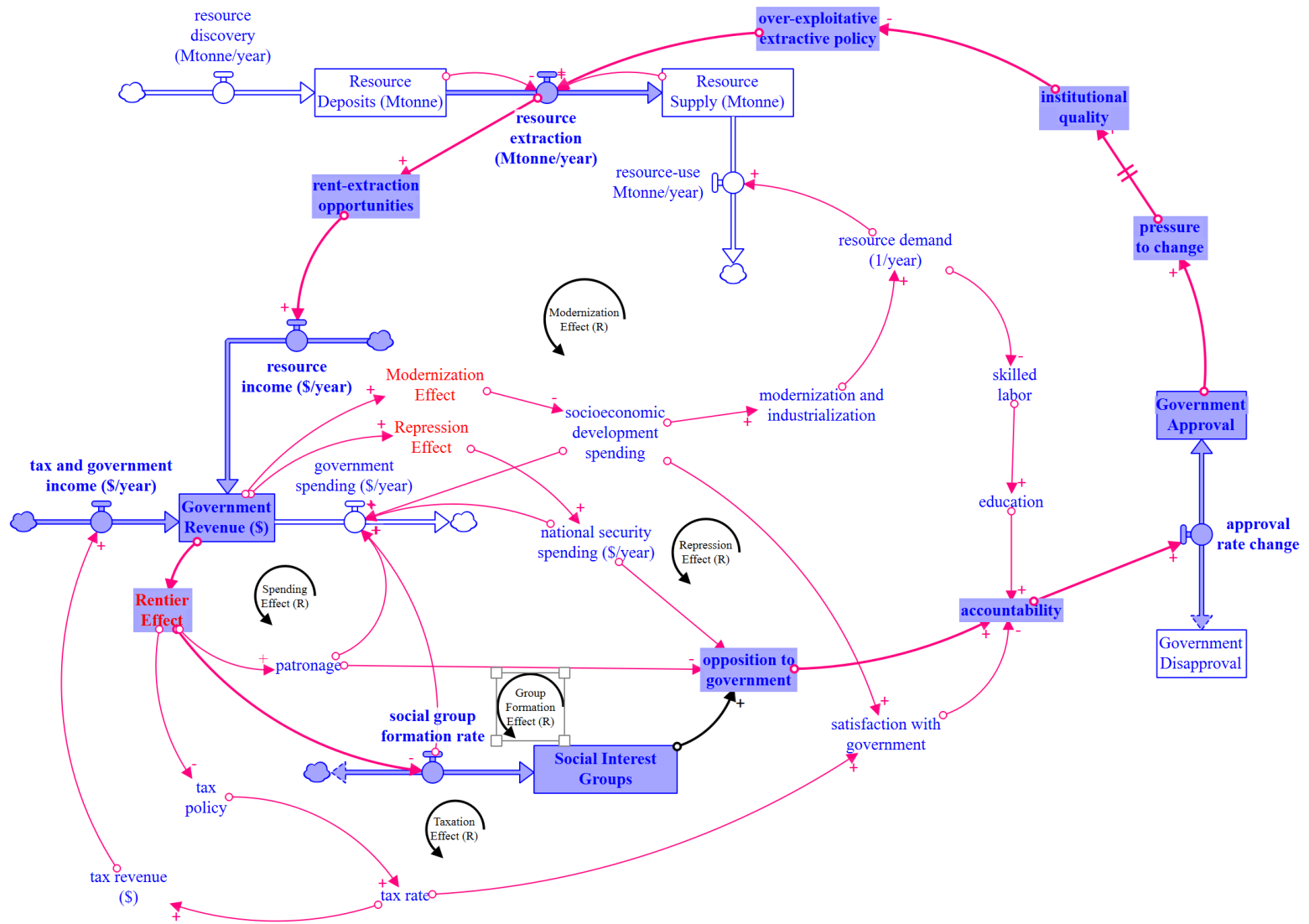


Figure F2. Rentier effect (group formation effect)



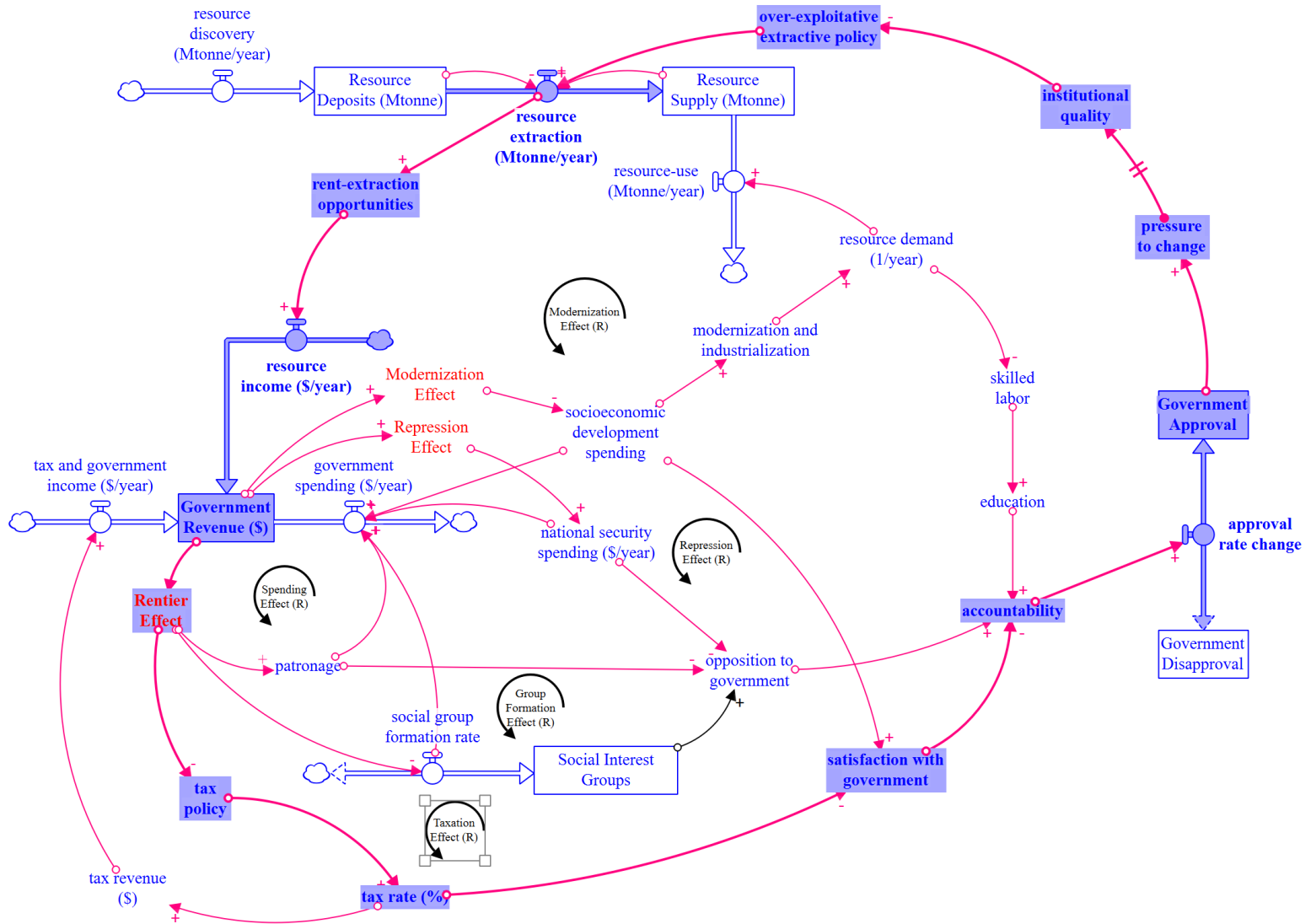


Figure F3. Rentier effect (taxation effect)

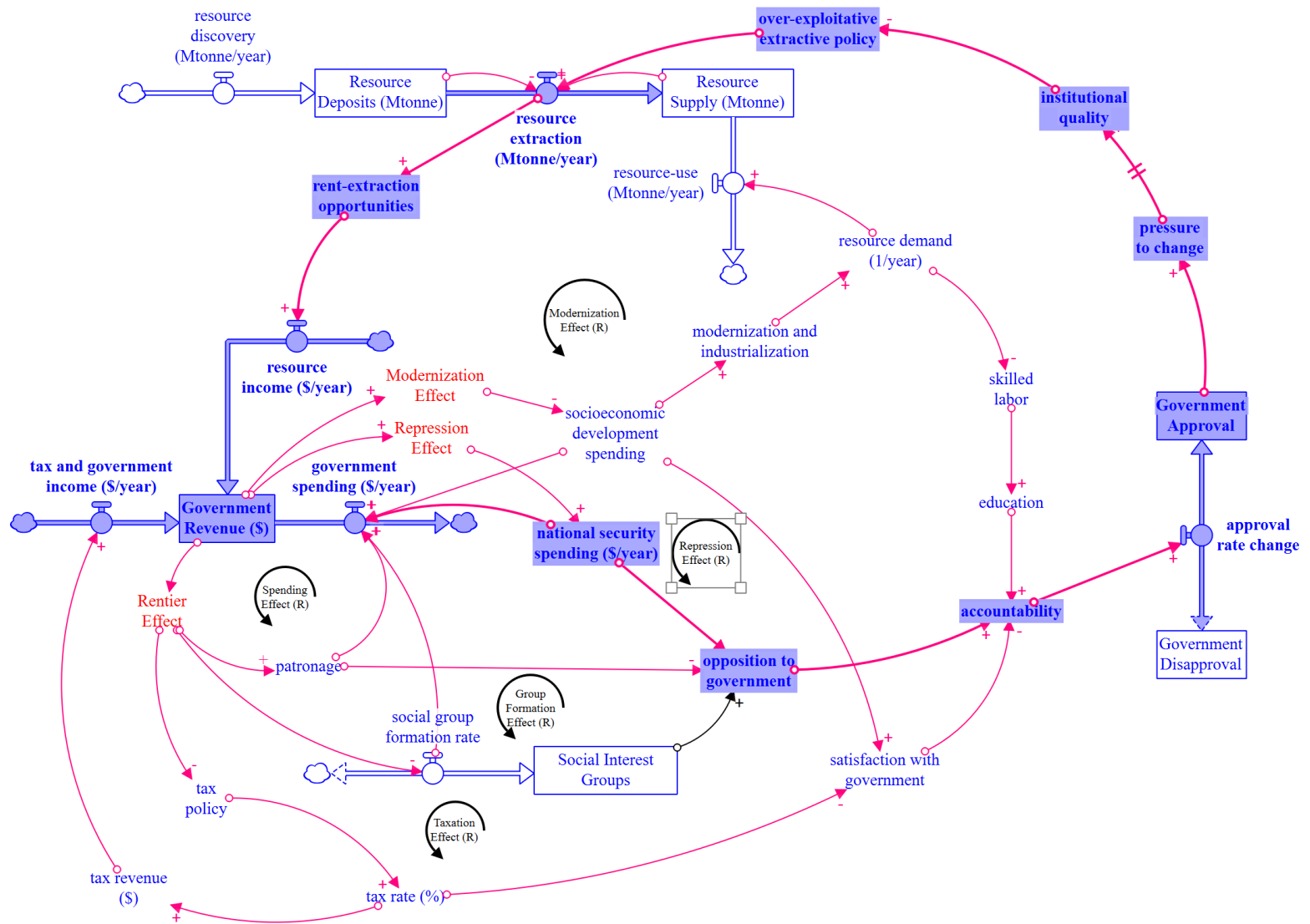


Figure F4. Repression effect

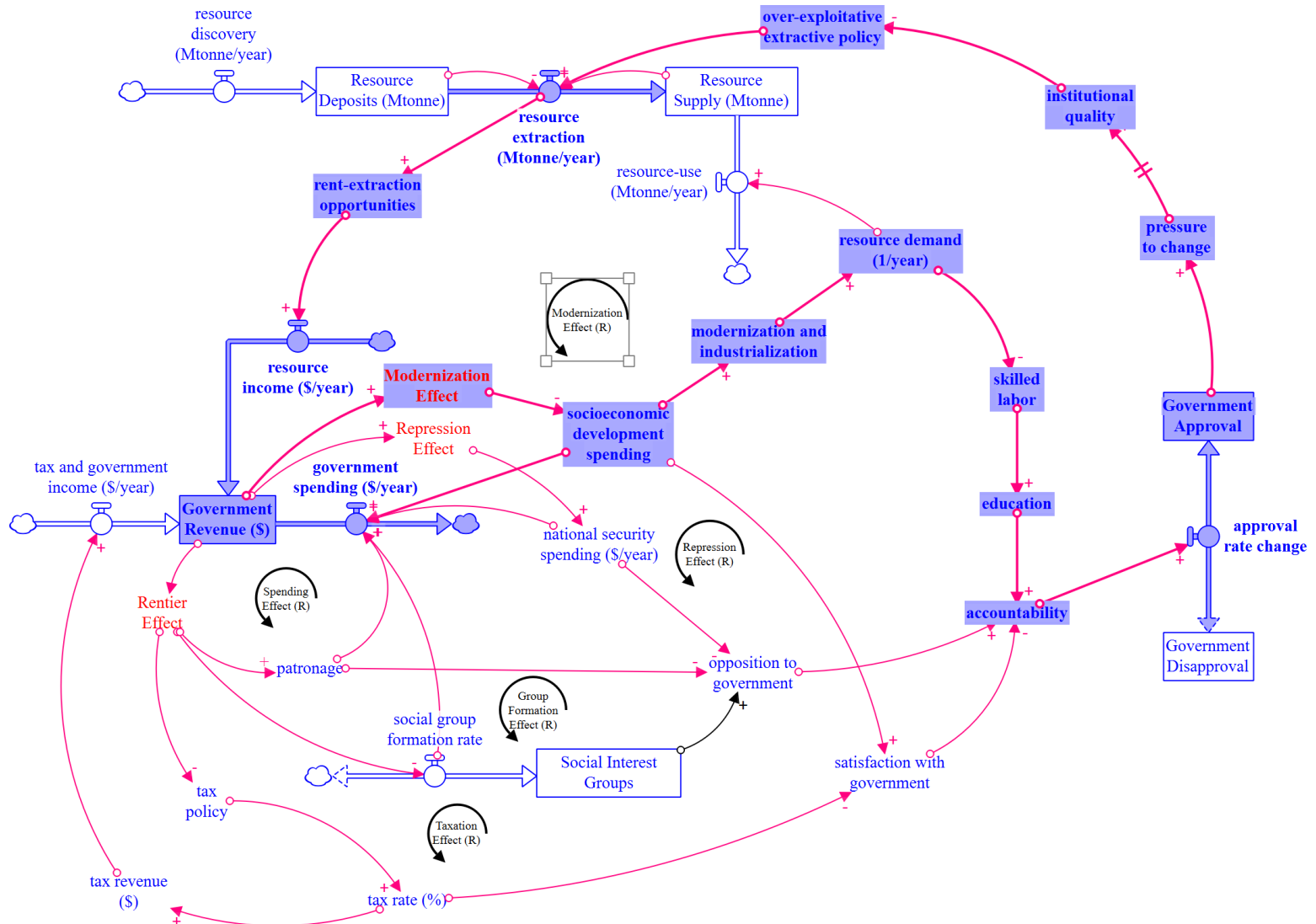


Figure F5. Modernization effect