Understanding Urban Sustainability and Quality of Life: A System Dynamics Approach

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UNDERSTANDING URBAN SUSTAINABILITY AND QUALITY OF LIFE:
A SYSTEM DYNAMICS APPROACH

by

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Bachelor of Science
University of Illinois, Urbana-Champaign
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For an urban area to be sustainable, its resources cannot be depleted faster than they can replenish. If an urban area is to provide a high quality of life (QOL), it must offer and maintain an amenity package that satisfies its resident’s preferences. Past studies on these topics all have a common thread: sustainability and QOL both pertain to people’s relationship to capital. Capital is something that can accumulate and add value to a person or society. If sustainability and QOL are a function of people’s relationship with capital, how they use it, deplete it, replenish it and transform it into something else is important to know.

Using the system dynamics method for understanding complex problems, I model the relationship between people and capital and illustrate how capital levels determine migration in and out of an urban area. The most common forms of capital affecting urban systems are economic, natural, human and social capital. Previous models that incorporate two or three of these stocks helped inform the structure of this model. However, no model includes the dynamics of all four forms of capital. I build upon these models to provide a more comprehensive model of society’s behavior. By validating the model based on
historic examples of urban decline and re-growth, I explain the implications and opportunities for analysis of urban behavior with this systemic approach.
ACKNOWLEDGEMENTS

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CHAPTER 1
INTRODUCTION

The purpose of this study is to examine the relationship between urban sustainability and quality of life (QOL). Over 50% of the world’s population now lives in urban areas, and both that fraction of the world’s population and the total number of people living in cities is expected to continue increasing (McGranahan, et al., 2005). Closer analysis shows many American cities are losing population to other cities or outlying suburbs. Place based rankings determined by both subjective and objective measures have identified, for example, that areas such as Cleveland, Ohio and Detroit, Michigan are low on desirability (Taylor, et al., 2009; Bradbury, Downs & Small, 1982).

This study examines which factors and feedbacks might govern people’s migration in or out of a particular city. I assume people are free to move from place to place, and do so as a result of preferred conditions in another city. In this thesis, I investigate what conditions spark people’s desire to move and what would they look for in a new home. Then, if these conditions are met, are they sustainable? This study approaches these questions by summarizing the amenities of an urban area as different forms of capital: economic, natural, social and human. Sustainability and QOL, therefore, are a function of people’s relationship with capital: how they use, create and transform it into something else. By evaluating capital levels, the services they provide, and estimating an average citizen’s preferences, I have an objective and subjective way to evaluate a city.
In this paper, I model people’s relationship with different forms of capital and the influence different forms of capital have on each other using system dynamics modeling. I monitor the accumulation of different forms of capital to evaluate sustainability and use the distribution of capital among the current population as proxy for quality of life. In the first chapter, I define sustainability and quality of life and discuss how it has been measured in previous studies. Then, in chapter two, I discuss the system dynamics approach to problem solving. Chapter three is a description of the system dynamics methodology and my approach to applying it to population trends. Chapter four describes the histories of three test cases used to validate the model. Chapter 5 contains a full description of the system, synthesizing expertise from urban planners, sociologists, economics and ecologists. Finally, I will report on the use of my model in urban dynamics analysis and conclude with a discussion of weaknesses and opportunities in the line of research.
CHAPTER 2

PROBLEM STATEMENT

According to urban sociologist Harvey Moloch (1976), a city’s primary economic and political goal is growth or expansion. We often measure such growth by a city’s population levels. As Figure 1 shows, this is precisely what cities worldwide have achieved. This trend indicates that a more desirable set of amenities exist in cities compared to rural areas. A high concentration of people in a small area poses threats to social, environmental and economic welfare. A growing population puts additional stress on these systems, and if these risks are not managed properly, the long term sustainability and desirability of a city is likely to slip (McGranahan, et al., 2005).

Understanding the structure that governs the change in urban populations is the first step toward understanding how urban sustainability and quality of life might be managed. And therefore, in this study, I will focus on the relative attractiveness based on quality of life and sustainability indicators that dictate people’s movement between cities.
Looking at a population trend without looking at other indicators of quality of life will not provide an understanding of how livable or sustainable that city is. Instead, an analysis must include the specifics of both the people and their environment, for example, how productive, wasteful, and cooperative they are. In this work, I use a system dynamics modeling to explain and illustrate these components and how they are interconnected to explain why some cities, like Minneapolis - St Paul for example, have had more success retaining an economically productive population than other pre-industrial Midwestern neighbors like Milwaukee or Cleveland.
Consider the historic population trends of these American cities. As we see in Figure 2, each of these Midwestern cities experienced rapid growth followed by decline. There are subtle differences in the timing of each city’s growth and decline as well as the level of recovery in population levels. If growth is indeed the primary goal, it would seem each of these cities is failing. I argue that this is not the whole story, and that by understanding and analyzing the reasons Minneapolis has had a stronger rebound in population growth, we can
better prepare future cities on the verge of decline from suffering the same
downward fate Cleveland has experienced.

Therefore, the goal of this study is first to describe the structure underlying
urban population change as a function of the sustainability and quality of life the
area offers and second to identify policy levers for promoting long term social and
environmental viability. Sustainability is often viewed as a luxury of the wealthy
(Campbell, 1996). Some go as far as to find “sustainable development” and
“economic growth” as synonymous (Woodwell, 1998). However, economic
decisions need to be made within the context of the social
desires of residents and limitations of the environment
(Levett, 1998). A purely economic focus limits people’s
ability to bring social and environmental concerns into an
examination of sustainability and livability. I argue that
viewing an urban area as a place that accumulates and
distributes multiple forms of capital provides a richer basis
for understanding sustainability and QOL issues.

Discussions about sustainability and quality of life have a common thread
(a full review of the literature in the following chapter). Implicitly or explicitly,
sustainability and QOL both pertain to people’s relationship to capital (Figure 3).
Therefore, examining how people use, deplete, replenish and transform capital
can help identify points of leverage for promoting sustainability. I use the term
“capital” to mean something that can accumulate and add value to a person or

![Figure 3: Interaction between people and capital](image)
society. Later sections expand this definition and highlight four different forms of capital in greater detail.

2.1 Sustainability

Sustainability, or sustainable development, is commonly defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development [WCED], 1987). Resources should be used as needed for present needs, but not faster than they can naturally regenerate to be available for the future (Wackernagel et al, 2006). For example, ground water should not be taken from the ground faster than rain can replenish it, forests should not be cut faster than they can regenerate and farming should not be performed at a rate that degrades the nutrients in the soil.

The United Nations Conference on Sustainable Development promotes a framework for sustainable development that emphasizes a three pillar approach to institutional reform: economic development, social development and environmental protection. “Poverty eradication, changing unsustainable patterns of production and consumption and protecting and managing the natural resource base of economic and social development are overarching objectives of, and essential requirements for, sustainable development” (Johannesburg Plan of Implementation [JPOI], 2002, Chapter 2).
There are a number of ways to illustrate the relationship between the three pillars (Cato, 2010). For example, Campbell (1996) discussed the intersection of environmental, economic, and social pillars as it applies to the field of urban planning in a "planner’s triangle." In this modification of a "three ring" framework (Cato, 2010), illustrated in Figure 4, sustainable development is the equitable balance of the physical, social, and economic environment. This figure places sustainable development in the center of equally important economic, social, and environmental sectors of a city to signify their equal importance (Cato, 2010). Stakeholders from the fields of public health, business, planning, and environmental protection fall somewhere along this spectrum of priorities and their position shapes the lens through which they see a city (Campbell, 1996).

Campbell’s inclusion of the resulting societal conflicts illustrates the tensions keeping us from fully realizing sustainability. Another popular framework is a Russian Doll structure, depicted in Figure 5, which adds a different
dimension by illustrating the embedded nature of the sectors (Levett, 1998; Cato, 2010).

Levett (1998) proposes two advantages to thinking about sustainability as embedded systems rather than independent realms. First, society and the economy would not exist without the life-supporting services provided by the environment. Second, he argues the economy - its institutions and behaviors - are all a social construct and thus fit within the society sphere. Because the outer sphere, the environment, has physical limitations, it therefore binds the inner economic and social spheres (Cato, 2010; Daly, 1990). Levett warns against using the term "balance" in discussions of sustainable development but argues sustainability is a reconciliation of quality of life and environmental limits. Economic priorities cannot be weighed equally against environmental priorities if the economy is pushing beyond the boundaries of environmental capacity.

A common method for operationalizing sustainability is using an Ecological Footprint measurement. This measure addresses the question, "how much of the regenerative capacity of the biosphere is being occupied by human
activities?” (Wackernagel, et al., 2007, p.1) It is measured as global hectares (gha) of biological capacity, or biocapacity. Biocapacity captures the total production capacity of a hectare for a given year (Wackernagel, et al., 2007). Measuring in area is appropriate because “life happens on surfaces,” write Wackernagel, Wermer and Goldfinger (2007, p. 1), and “hence, surface areas matter, and most resource and waste flows can be measured in terms of biologically productive area necessary to maintain these flows.”

Different land types have different biocapacity. Adding them provides an aggregate total global productivity. Each country’s biocapacity is computed looking at the resources available within their borders as well as the waste demands (Wackernagel et al, 2006). By comparing the population’s material standard of living or the demand (ecological footprint) per person to the area’s biocapacity, the result is either a reserve or deficit of natural capital (Wackernagel et al, 2006). For example, the United States imports biocapacity to meet the demands of the population. In 2010, the US had a population of 291 million with an average ecological footprint of 8 gha/person. Our biocapacity, however, was only 3.9 gha/person, creating an ecological deficit of 4.1 gha/person (National Footprint Accounts, 2010). This is indicative of unsustainable practices where the economy and society are pushing beyond the environmental sphere’s limitations.

A city has many important roles to fill. “The city needs to meet social, environmental, political and cultural objectives as well as economic and physical ones” (Egger, 2006, p. 1239). Highly developed American cities have placed
economic growth as their central focus and have in turn created a ecological deficit. This indicates an unsustainable, though high quality of life. Is there a way to sustain or improve QOL without sacrificing long term longevity of a place? In the following section, I review quality of life studies and indicators to prepare for a discussion on how I measure it in this study.

2.2 Quality of Life

Quality of Life (QOL) is “meant to represent either how well human needs are met or the extent to which individuals or groups perceive satisfaction or dissatisfaction in various life domains” (Costanza, et al. 2006, p. 268). QOL can be studied from a number of different angles and at different scales. Rogerson (1999) reviewed 20 years of QOL research to find the most commonly cited research dimensions. He went on to categorize the studies based on their conceptualization of QOL. Figure 6 illustrates the three main conceptualizations and how they are related.

To the left, studies that fall into Type A are characterized by their focus on objective environmental conditions. To the right, studies under Type B focus on the characteristic of people, and studies found under Type C evaluate environmental conditions compared to people's preferences. Below is a review of each type.
QOL studies that fall into Type A are objective measures of the quantity and quality of environmental attributes. A company may evaluate the environment based on access to resources, proximity to markets, growth potential and other means of production (Rogerson, 1999). An individual may look at the parks and community space per capita, weather, or certain well represented services, like health facilitates (Sawicki, 2005).

Type B looks at the characteristics of the residents. An early congressional report from the US Department of Health, Education and Welfare (1970) focused on health and illness, social mobility, income and poverty, public order and safety, learning, science and art, participation and alienation (Sawicki, 2002). Other common objective or social indicators include high school graduation rates and volunteerism. These measures have the benefit of being easily quantified. Diener and Diener (1995) found measuring the wealth of a nation is so strongly correlated with other social indicators (such as infant mortality and literacy) they raised the question whether anything other than economic measures was necessary. Despite the strength in these correlations,
Diener and Diener (1995) proceeded to compare countries of similar economic status that vary widely in QOL, concluding that other indicators are indeed necessary for estimating QOL. Therefore, social indicators are widely used today in conjunction with economic indicators to provide a more robust look at social wellbeing (Bognar, 2005).

Type C is the comparison between Types A and B (Rogerson, 1999). For place based indicators to be relevant, they must be perceived by residents to be important, thus fulfilling some aspect of their quality of life (Sawicki, 2005). “It is of course possible to live in a healthy environment and not be happy or satisfied with one’s life” (Egger, 2006 p.1234). Because what one resident values may differ from another, an urban area should be evaluated both in terms of its objective qualities as well as its residents’ perception and appreciation for those qualities. Also, when polled, individuals often indicate their “most important problem” is a quality of place (QOP) or sustainability issue. These two approaches, subjective and objective measures of QOL, are addressed in more detail below.

Subjective well being (SWB) studies are “concerned with individual’s subjective experience of their own life” (Diener and Suh, 1997) and seeks to understand “people’s happiness or life satisfaction” (Bognar, 2005 p. 563). While this is harder to capture, it is an important to consider and is highly indicative of reality when used in conjunction with objective social indicators. Levett (1998 p. 200) argues, “objective’ proxies are only valid in so far as they reflect people’s preferences and values.” From this perspective, researchers have an objective
sense of the state of a community, but also on the satisfaction of preferences among citizens. “The basic premise of SWB research is that in order to understand the well being of an individual, it is important to directly measure the individual’s cognitive and affective reactions to her or his whole life as well as to specific domains of life” (Levett, 1998 p. 200).

While the strength and stability of the economy is often cited as a major indicator of quality of life (QOL), it certainly does not tell the whole story. Elements of social cohesiveness, health, and education also weigh heavily on people’s standard of living and how high they rate their personal well being. (Diener and Suh, 1997; Bognar, 2005). As Jeremy Bentham wrote in 1789, “the best society is one where citizens are happiest” (Schalz, Ackbaro and Kapmeier 2007).

The concept of QOL has been applied to urban areas, and many cities have used some measure of QOL in marketing attempts to grow the population and attract businesses. The United States is largely a service based economy which means firms are highly mobile. Therefore, maintaining an amenity package that satisfies residents is more important than ever to community stability (Rogerson, 1999). Rogerson’s (1999) review revealed quality of life to be major element of city competitiveness, influencing the migration of people and capital. Because the quantity of humans requiring resources from the urban environment is a major determinant of sustainability (Wackernagel et al, 2006), it is crucial to understand these drivers of migration to and from a place.
Therefore, to understand urban sustainability, the drivers of population change must also be understood. If population change is the main pressure on urban resources, understanding the drivers of in and out migration is also critical. This review provides the foundation for operationalizing the complex relationship between quality of life and sustainability.
CHAPTER 3
APPROACH AND METHODS

The multifaceted nature of urban systems is managed by having a number of departments and committees focusing on specific domains. As discussed in Radzicki and Seville (1993), despite frequent interaction, these segmented groups may have little knowledge of their exact influence over each other. Therefore, an appropriate approach to urban problems must be able to bring together expertise of many subsystems and organize them in a usable and clear way.

System dynamics modeling recognizes the world as a highly complex, interconnected system. Within the discipline are tools for addressing complex problems that exist over long time frames (Sterman, 2000). By taking a holistic approach to better understand complexity, policy decisions can be better informed to better serve the long term needs of stakeholders (Sterman, 2001).

System dynamics is based on the philosophy that the structure of a system causes the system’s behavior. Thus, to understand the behavior, one must have a thorough understanding of the relationships between the system’s components (Richardson and Pugh, 1989; Sterman, 2000; Stave, 2003). The system dynamics approach, “represents a way of understanding reality that emphasizes the relationships among a system’s parts, rather than the properties of the parts themselves” (Hjorth and Bagheri 2006, p. 79).

The steps of the modeling process are as follows (Sterman, 2000):

1. Define the problem
2. Describe the system
3. Develop the model
4. Build confidence in the model
5. Use the model for policy analysis
6. Use the model for public outreach

Defining the problem is described by a behavior over time graph of a trend the modeler is trying to explain, also known as the reference mode. I am investigating the dynamics underlying population trends over time, illustrated in Figure 2. Once the modeler understands what is causing the behavior witnessed, he or she can determine how best to intervene and change its trajectory to something more preferable (Sterman, 2001).

Once the problem is defined, the system creating that behavior must be described. Behavior is a function of the structure of the system (Sterman, 2000). Once knowledge of this system has been gathered, a model can be developed. A model is a simplification of reality, taking the knowledge gained about the system, describing the variables involved, and quantifying their relationships.

As John Sterman (2001, p. 10) writes, “just as an airline uses flight simulators to help pilots learn, system dynamics is, partly, a method for developing management flight simulations (often based on formal mathematical models and computer simulations).” Once the model is built, the modeler builds confidence in the model through validity tests to show it can replicate real world behavior for the right reasons (Sterman, 2000). Once it can, it can be used for policy analysis to help decision makers and the public make more informed decisions set in a long term context.
Our ability to understand something as complex as a city to determine its attractiveness or sustainability is limited by the tools we employ. In many cases, the tool used in policy decision is mental models, experiential reasoning, or other imperfect representations of reality (Bagheri and Hjorth, 2006; Sterman, 2001). Urban issues are characterized by dynamic complexity. The conditions of a city are constantly changing, contain time delays and are dictated by feedback. Therefore they cannot be managed with linear cause and effect reasoning (Sterman, 2001). Rather, managers must understand the full effect of their actions, which “alter the state of the world, causing changes in nature and triggering others to act, thus giving rise to a new situation which then influences our next decisions” (Sterman, 2001, p. 12).

System dynamics provides the tools for understanding dynamic complexity. Causal loop diagrams (CLD) help organize mental models and identify feedback loops. There are two types of feedback loops: positive, or reinforcing loops, and negative, or balancing loops. Positive loops amplify behavior while balancing loops correct change (Sterman, 2001). A simulation model takes the structural elements from a CLD and represents them as stocks and flows. A stock is a level of something that the modeler wants to keep track of throughout the course of the simulation (Sterman, 2000). A flow can be material, changing the level of a stock or informational, providing cues and rates of material flows (Sterman, 2000).

As urban areas grow and gain popularity, they then must compete with each other to maintain stability and viability, typically achieved through the
retention of people and capital (Rogerson, 1999). I hypothesize that migrants are looking for economic opportunity, access to services like education and health care, community and diversity. However, quality of life will begin to fall if the resources available are not used at a sustainable rate, causing the environment to become unattractive and motivating the population to move. I predict this will cause a further reduction in investment in other community indicators such as social connections and human health.

To test this hypothesis, I followed the steps detailed above to understand urban systems focusing on the population trend illustrated in Figure 2 as my reference mode. I am seeking to understand the drivers of urban population growth to make policy recommendations for maintaining those attractive qualities without diminishing the city’s capacity to sustain the population.

I have taken inspiration from other system dynamics models of urban sustainability to conceptualize how these forms of capital relate. For example, Jorge A Duran – Encalada and Aberto Paucar-Caceres (2008) published a report on a project to promote urban sustainability in Puebla, Mexico. They used system dynamics modeling to capture the interaction between the social, economic, environmental and institutional dimensions of society. They represent migration rate as a function of education, health, pollutants and gases per capita, inhabitants per household standard level and other service levels. It is also a function of the number of firms opening in this city.

Radzicki and Seville (1993) were asked to build a model of Sterling, Massachusetts to test polices for controlling and sustaining economic growth.
They note the importance of a “holistic approach to socioeconomic analysis” because city committees focus on specific sectors and rarely understand their effects on other areas, despite regular interaction (p. 483). The nature of urban development creates a number of time lags where policy changes today will not be felt for many years. Focusing on the sectors pertinent to Sterling, the authors modeled the interaction between Municipal Light sector, the QOL sector, population and housing, fiscal, commercial and industry, school and land occupied sectors. A full list of the models reviewed and their key stocks is described in Table 1.

Once I understood the structure of urban sustainability from previous models, I determined the most commonly used stocks of capital and performed another literature review on how experts in these fields describe how these stocks are created and depleted. The combination of structural reference and the expertise from the respective disciplines, I constructed a mathematical model of the interconnections that underlie urban sustainability and quality of life. I then use the set of validation tools listed in Sterman’s book, Business Dynamics (2000), to evaluate the robustness of my model.
A major benefit to this approach is simulating policy strategies without the risk associated with real system intervention. Such experiments are not practical in the real world due to the potential drastic costs of implementation and correction (should things go poorly.) This model will help identify leverage points that can be pressed for the most efficient change and clarify why past policies were not as effective as expected.
Table 1: Review of system dynamics literature on sustainability

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CHAPTER 4
THREE CITY HISTORIES

Let’s consider three American pre-industrial cities in the Midwest and compare the factors that contributed to their population growth. Specifically, I am interested in what caused the declines in Milwaukee, Minneapolis – St. Paul and Cleveland, and what was different about Minneapolis that provided greater ability to stabilize and begin to grow its population before the others.

Many Midwestern industrial towns experienced a similar path of growth, maturation and decline. Milwaukee, Minneapolis – St. Paul and Cleveland experienced rapid growth between the 1900s and the 1950s due to booming economies. Abundant and fertile land and easy access via water ways determined the level of success when competing for industry. Heavy machinery, factories and other fixed and inflexible economic capital produced large profits when demand was high which in turn afforded a city many rich amenities. Cities grew in physical size as local governments annexed as much of the outlying areas as possible. But, population growth is often accompanied by growing problems with crowding, crime and poverty. This motivated those with the means to seek kinder surroundings in the suburbs, leaving the poor to dominate the inner core (Hayden, 2004).

Then, in the 1950s and 1960s, the national economy began to shift from a manufacturing to a service-based economy. Much of the remaining industry left these cities for cheaper resources in other cities or for other countries all together. The buildings, machinery and expertise present in these pre-industrial
cities were inflexible (Orum, 1995) and not easy to adapt to new business, adding to their further economic decline. By this time, many cities were also landlocked by the ring of suburbs, meaning growth could not be achieved through increased resource or population revenue from these areas (Orum, 1995). Population continued to drop as people were leaving the inner city for both suburbs and job opportunities in other cities.

According to urban sociologist, Anthony Orum (1995), Minneapolis – St. Paul followed a similar path as Cleveland and Milwaukee, but with a few key differences that have aided in the city’s quicker stabilization and highly regarded standard of living. First, it did not reach the same level of industrialization as Milwaukee and Cleveland. Therefore, it did not have the same high investment in fixed, inflexible economic capital and was therefore more able to adapt to a changing economy at a lower cost.

Also facilitating its adaptability was the presence of a large state research university. This focus and investment in education provided a higher degree of human capital and a stronger job market for white collar workers than Cleveland and Milwaukee. This population was better prepared not only to work in new industries, but were the ones driving and designing the new economy (Orum, 1995).

Finally, Minneapolis - St. Paul was able to form a metropolitan governance structure that served both its suburban and urban development. This reduced the divide and struggle for resources that occurred between the wealthy and poor as suburbs were growing. In doing so, Minneapolis - St. Paul has been more
successful in maintaining their downtowns, which are, to this day, considered highly livable. This level of cooperation was attempted but not achieved in Milwaukee and indicates a greater degree of social cohesion and inclusiveness among the residents of Minneapolis - St. Paul (Orum, 1995).

Do these differences explain why Minneapolis – St. Paul did not experience the same deterioration as Cleveland and Milwaukee, as Orum (1995) suggests? In the following sections, I describe the creation of my model based on the understanding of how the structure of city economics, culture, environment and education lead to its behavior and therefore its attractiveness and viability. I will then use it to test whether these differences in priorities, investment, and social cohesion can account for the differences found between their population trends.
CHAPTER 5
MODEL DEVELOPMENT

My study includes multiple iterations through the system dynamics approach to problem solving. To begin, I evaluated population and capital and described the set of relationships governing their behavior.

I began with the simple representation illustrated in Figure 7 of people's relationship to a generic form of capital using a causal loop diagram (CLD). This conceptual model shows the major feedback loops governing how a population can both add and detract from a given capital stock. As population grows,
capital use will generally increase. This positive relationship is denoted by a “+” at the head of the arrow. If people are very productive, they could create more than they use. If they are wasteful or disregard limits, they will deplete the stock of capital before they can replenish it. As a population grows and shrinks, sustainability will be determined by these rates of production and usage. A population must maintain a high level of productivity in order to provide enough capital for the population. Quality of life can be understood as the capital per person. If the population grows disproportionately to capital, it isn’t going to be a very satisfying place to live and people may leave. Or, if capital is abundant and people are enjoying a high level of capital, it will attract new residents, reducing the capital per person ratio. The key to sustainability is to work at a level that provides enough capital to satisfy the population.

For any city to experience a growing stock of people, it means the population of those areas were able to produce more capital than its people consume, and therefore maintaining a per capital level that satisfies people’s preferences. In this case, the “growth is good” loop dominates. But, if the city encounters a limit which interferes with the production of capital, this value will fall. The dominance shifted to the “resource use” balancing loop, and reduces the attractiveness of the city. When this happens, the population falls as people seek a nicer place to live.

This structure serves as the basis for understanding how the stocks of capital discussed below change with population and add or detract from the attractiveness of a city. Capital, however, is very broad. In the next phase, I
disaggregate the meaning of capital to capture the most relevant sectors driving urban behavior. In my review of the system dynamics literature on urban systems and sustainability since Forrester’s Urban Dynamics (1969), I identified the most relevant capital forms (see Table 1).

The most commonly used stock is population followed by economic capital, human development, housing, land and natural resources. This is consistent with the definitions used of sustainability and informed my choice of capital forms. Figure 8 expands upon the simple population and capital relationship described in Figure 3. Economic capital, natural capital and human capital are frequently included in models of sustainability (refer back to Table 1 and see Appendix A for a more detailed explanation of the studies included). Less frequently included is social capital. It is, however, often included in the theoretical literature on these capital forms and is therefore considered an

![Figure 8 Expanded interaction between people and capital](image-url)
integral form of capital in my urban model. A full description of each form follows below with a causal loop diagram illustrating how it interacts with the population.

5.1 Human Capital

Human Capital (HC) is the accumulation of skills and capabilities that allow people to work more productively (Coleman, 1988; Bourdieu, 1986). Sociologist James Coleman (1988, p. 83) writes, “just as physical capital is created by changes in materials to form tools that facilitate production, human capital is created by changes in persons that bring about skills and capabilities that make them able to act in new ways.” Human capital is often measured by educational achievement and the health of a population. It is similar to embodied cultural capital discussed by French sociologist, Pierre Bourdieu (1986), who used the concept to explain why there was an unequal education attainment of children in different socioeconomic classes. He looked at the range of educational “profits” produced in the academic market by these different classes. His findings did not support the idea that there is a natural aptitude inherent in students, but some are advantaged by the passing down of academic investment by previous generations.

Coleman (1988) approaches the same theory by evaluating the contribution of social capital in the home to the development of human capital. Parents who are engaged and involved in promoting their children’s knowledge formation positively influence those children’s attainment. If parents have a high
level of human capital, but their connection to their children is weak, their influence on that child’s development will be weak as well (Coleman, 1988).

In this way, human capital formation is both a private and social activity, and the benefits expand to each as well. Earning potential increases as people increase their education and skills, and overall labor productively increases as well (Becker, 1964; Schultz, 1961; Birdsal et al, 1999) providing better profits to business and industry. The stock builds upon itself as future generations have a knowledge base to grow and develop. (Vidal, 1998)

The submodel illustrated in Figure 9 shows the relationship between population and human capital. When a population increases, the demand for human services, such as health and education, increases as well. If that demand is met with the necessary support, human capital will increase. As human capital increases, the attractiveness of the community will increase through the spillover

![Figure 9 Causal loop diagram of human capital](image_url)
effects that benefit the entire community (added productivity, innovative and technological achievements, economic growth, etc).

5.2 Natural Capital

Natural Capital (NC) represents “the resources provided by nature that are in some way essential to human well-being” (Beddoe et al, 2009, p. 2488). The most distinguishing feature of natural capital is that it is not human made, and therefore presents a unique set of characteristics and challenges.

First, natural capital is provided by nature and can only be provided by nature (O’Conner, 2000). While humans can modify natural capital, we cannot create a perfect substitute for it with something human-made because human-made capital requires natural capital to create. Therefore they are complements, rather than substitutes for each other (Costanza and Daly, 1992).

Second, natural capital encompasses a set of functions and systems that provide direct and indirect benefits for humans today and into the future. In this way, it represents more than a simple stock (O’Conner, 2000). Ecosystem goods include food and building materials while services include water purification and waste assimilation. The structure of the system drives these behaviors and produces these goods, and is therefore important to understand (Costanza et al 1997). Natural capital is an aggregate of natural resources and their life sustaining services.

Finally, the loss of natural capital is more permanent than human made forms (O’Conner, 2000). When a resource has been degraded, we not only risk
losing it forever, but also may see the life supporting processes discussed above become compromised as well. A chain reaction of instability is likely to follow. For example, the loss of the Great Barrier Reef due to coral bleaching and warmer temperatures would be tragic in that a great natural wonder would be gone, but it means a loss of habit for aquatic life, and would not serve as a wave barrier leaving the shoreline exposed to the full impact of ocean waves.

I represent these dynamics in the causal loop diagram shown in Figure 10. As the population increases, more natural capital is consumed, reducing the stock of raw materials and natural processes that sustain life. This reduces the ecosystem services available per person, making the environment less attractive and motivating more people to move. There is a positive loop between natural capital and regeneration. Nature does naturally restore itself after it has been disturbed. But only if the rate of regeneration is greater than consumption will this loop dominate. (See Woodwell, 1998; Jin et al., (2009); Guan et al., (2011);

5.3 Social Capital

Social Capital (SC) “comes about through changes in the relations among persons that facilitate action” and is a less tangible form than natural or economic capital (Coleman, 1988, p. 83). Personal productivity is increased with social capital because people benefit from the resources and assistance found within networks, norms, trust and other social contracts (Putnam, 1993). As people increase the size of their social networks their personal stock of social capital increases. This is often done through group membership (Putnam 2000). Portes explains, “the consensus is growing in the literature that social capital stands for the ability of actors to secure benefits by virtue of membership in social networks or other social structures” (Portes, 1998, p. 6).

Social capital is a function of trustworthiness, efficient information channels, closure of social networks, the presence of norms and reciprocity. It increases the amount of organized efforts to improve quality of life, and as they increase, the organization is perpetuated, perpetuating these other elements (Coleman, 1988). As Robert Putnam (2000, p. 21) explains, “Trustworthiness lubricates social life. Frequent interaction among a diverse set of people tends to produce a norm of generalized reciprocity.” Social capital is both a result of trust and a cause of trust. Researchers have struggled with the “chicken and the egg”
nature of social capital definitions. However, this is simple a feedback loop of cyclical, rather than linear cause and effect.

There are personal and societal benefits of social capital. For example, communal spaces, such as park and public transit, would be unbearable due to the distrust of others if we felt no connection to feel residents. Also, without social capital, business would be conducted at a much slower pace, increasing transaction costs and efficiency (Jankauskas and Seputiene, 2007; de Blasio and Nuzzo, 2010). Community efforts are much more effective when a group is acting in a mutually beneficial way with common objectives, values, and concerns for one another. The flow of knowledge and ideas is more productive, and reciprocity increases the work done (Bourdieu, 1985).

Studies also find economic benefits to social capital. Robert Putnam (1993) refers to an Italian study from the 1970s where otherwise similar communities varied greatly in their economic stability. The root of success was found to be civic engagement. He writes, “these communities did not become civic simply because they were rich…They have become rich because they were civic” (p. 3). Where norms of trust and reciprocity are strong, cooperation and communication are easier to achieve, and democracy works for the people in an efficient manner. As discussed above, Levett describes the economy as a creation of society. Therefore, it logically follows that a society that works together will also create a stronger economic foundation. As Putnam (1993, p. 10) emphasizes, “social capital is not a substitute for effective public policy but rather a prerequisite for it and, in part, a consequence of it.”
Similar to economic capital, social capital is also complementary to human capital development (Putnam, 1993; Bourdieu, 1986; Coleman, 1988). As discussed in the section on human capital, investing in education will be more effective if social capital is high in the community and in the home.

Too much of a good thing could degrade these benefits, however. Studies of social capital reveal that both very low and very high levels can be detrimental (Robalino, 2000; Florida 2003). High levels may increase benefits to some at the exclusions of others, raising entry barriers and creating high preferential treatment towards only one group (Dudley, 2009).

Figure 11 illustrates the relationship between a population and social capital. “As with conventional capital, those who have social capital tend to accumulate more” (Putnam, 1993, p. 4). Dudley (2009) created a model on the dynamics of people and social capital and helped inform my social capital sub-model. As people move into a community, the total number of connections will increase (assuming every person makes at least one interpersonal connection within the community). The amount of connections per capita gives us a measure of the intensity of social capital in the community. When the intensity increases, the benefits also increase at a diminishing rate. The costs also increase. People can only maintain a certain level of interpersonal connections before the time and energy required is greater than the benefits received from the relationship (Dudley, 2009). On the societal level, the costs also rise, such as the exclusivity and barriers to innovation (Dudley, 2009; Florida, 2003).
Economic Capital (EC) is an important component to a city’s economic productivity. For the purposes of this study, I use economic capital to describe the physical infrastructure necessary to transform natural capital into goods. This definition includes the factories themselves, as well as any machinery and technology used. It also takes into consideration the transportation networks and equipment that is required for processing goods (Bourdieu 1979). Economic capital naturally depreciates with time and the introduction of new technology and will eventually become functionally obsolete.

The degree of flexibility of economic capital determines how readily an industry or company can adapt to changing demands and changing market trends. For example, the heavy machinery involved in steel production was a
“fixed” form of capital, meaning it was highly specialized and difficult to adapt to a new function (Page, 1999). Whereas “flexible” capital is more common in the country’s contemporary, service based economy where most jobs require some form of computing and communications equipment and therefore does not require the same level of investment and retraining to switch job function or industry completely.

![Figure 12 Causal loop diagram of economic capital](image)

In the economic capital sub-model (Figure 12), economic capital is increased by the production of products and services, a portion of which is reinvested into the production of more products and services. A region with more economic capital has the ability to produce more per person, thus the per capita income rises. This leads to a more attractive city to those seeking economic prosperity, and the population rises. If that population maintains a high level of productivity, then they will continue to produce goods and services.

It is also important to mention gross domestic product (GDP) in this section as well. GDP is a widely accepted measure of economic vitality. It is a
measure of an area’s total production of goods and services and is a function of the regions amount and productivity of labor, natural and economic capital (Bureau of Economic Analysis, 2011). Productivity is the output produced from a unit of input, whether that input is a person or form of capital. Therefore, in the final model described below, units of economic, natural and human capital all contribute to an index that captures a more complete look at the economic productivity of the city.

5.5 Complete Causal Loop Diagram

Regardless the form, people interact with capital and the services it provides in roughly the same way. If people are productive, a stock of economic capital will grow. If they are efficient, they can live within the growth of capital. If they interact, social connections grow, and if the supply is there, they can develop greater capabilities. These capital stocks each produce benefits that can satisfy a certain population level, thus as population increases, that stock will be stretched farther, reducing the per capita benefits.
The theory and sub-models described above expanded the relationship between people and capital. The interactions between these forms of capital, however, are the drivers of economic growth, social equity, and environmental degradation/protection. Figure 13 illustrates a causal loop diagram incorporating
population’s relationship with each form of capital. Connecting these “petals” are green arrows that describe the interaction between the social, economic and environmental sectors of society.

Below is a review of the feedback loops between the “petals” of capital. In the structural description that follows, I will discuss which of these loops are included in the final model and which variables are considered exogenous to the system for simplicity.

**NC EC1, balancing:** Natural capital is used in the production of products and services and the more there is the more can be used. The more used, the less natural capital stock remains.

**NC EC2, balancing:** Likewise, when products and services are consumed, it also leads to the consumption of natural capital. This reduces the stock of natural capital with reduces the amount left for the production of products and services. As this reduces economic capital, per capita income will go down, making the area less attractive and reducing the population that wants to live there. But, as the population decreases, demand for products and services will decrease as well.

**NC EC3, reinforcing:** With local revenue, investment in conservation and restoration strategies could increase the availability of natural capital, increasing the material available for the production and economic capital. This is assuming the strategies are effective, and consumption is not outpacing restoration efforts. It may help stabilize the economic growth that would result from using up the natural resources, then crashing as they are depleted completely.
NC EC HC1, reinforcing: A way to make more efficient use of our natural capital in production is to develop better technology. If we can reduce the amount of natural capital we use in production, we can produce more, increase economic capital, and better support human development which leads to more innovation.

EC HC1, reinforcing: The production of products and services is a function of labor productivity which is derived from how capable they are, or their level of human development. As economic capital grows, support for human development can also grow, improving human development, increasing labor productivity, production and increasing economic capital.

EC HC2, reinforcing: As economic capital increases, per capita income increases. As people become richer, they can better afford and access human development services. Accessibility leads to greater human development, more productivity, more production and more economic capital.

EC HC3, reinforcing: Likewise with economic capital directly, innovation helps spur economic growth, leading to better economic support for education and health, better enabling people to be creative and innovative.

NC EC HC2, balancing: As human development increases, labor productivity increases, and production of products and services increases. As consumption of natural capital increases with that production, the stock of natural capital decreases. With this decrease, the ecosystem services per person decreases as well. Ecosystem services include those that improve air and water quality, soil fertility, etc. Thus, as these go down, the health of the community will go down as well, decreasing human development.
**SC HC1, reinforcing:** When social capital per person increases, it helps support human development through more community and family involvement in school and health. As human development increases, it spills over its benefits to the society, making it a more attractive place to live, increasing the population. A larger population leads to more connections, and more connections per person. However, if the connections do not keep pace with the population, the increased population will dilute the social capital/person ratio, decreasing the support for human development.

**EC SC HC1, reinforcing:** As per capital income increases, access to human services increases. As people gain access, the level of human development increases. As human development spillover affects increase, the attractiveness of a healthy community increases, increasing the population. As the population increases, it increases social capital. Social capital helps making business more efficient and profitable by building trust, mutual dependencies, and access to information. Thus it increases economic capital, increasing per capital income. But, that rise in population also directly decreases per capita income, so it is hard to say, at this level of analysis, whether there would be any net change.

**EC SC HC2, reinforcing:** Societies with high levels of social capital run the risk of creating barriers to entry, discouraging creative people from entering (Florida, 2003). Social capital also strengthens rules and norms. If rules and norms become too stringent, they can inhibit creative thinking. Therefore, if social capital increases to a certain threshold it could reduce innovation. As innovation
decreases, economic capital can stagnate and decrease, reducing the area’s economic attractiveness and reducing the population which increases the social capital/person, making the social capital more saturated and further inhibiting outside ideas.

5.6 Structural Description

In the structural model, I am describing and quantifying the relationships summarized in Figure 13 between economic, natural, social and human capital and the population. Below is an illustration and description of the structure of these subsystems. For a full list of equations, see Appendix B.

To reduce complexity at this level of modeling, some of the variables treated endogenously in the causal loop diagram are made constant in the operational model. See Table 2 for a full list of variables by sector.

Table 2 Key variables by sector

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<td>Loss of HC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quality of life</td>
<td>Perceived HC attractiveness</td>
<td>Desired HC attractiveness</td>
<td>More specific QOL indicators, such as:</td>
</tr>
<tr>
<td></td>
<td>Perceived EC attractiveness</td>
<td>Desired EC attractiveness</td>
<td>- Material standard of living achieved</td>
</tr>
<tr>
<td></td>
<td>Perceived SC attractiveness</td>
<td>Desired SC attractiveness</td>
<td>- Economic capital per person</td>
</tr>
<tr>
<td></td>
<td>Perceived NC attractiveness</td>
<td>Desired NC attractiveness</td>
<td>- Income per person</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effects of capital attractiveness on in and out migration</td>
<td></td>
</tr>
<tr>
<td>Population</td>
<td>In migration</td>
<td>Normal in migration rate</td>
<td>Death rate</td>
</tr>
<tr>
<td></td>
<td>Out migration</td>
<td>Normal out migration rate</td>
<td>Birth rate</td>
</tr>
</tbody>
</table>

5.6.1 Economic Capital Subsystem

The economic capital subsystem describes the process of developing the means to production – the machinery, buildings and other infrastructure needed to transport and transform natural capital into goods and services. The building of economic capital requires the use of natural capital, and therefore is a stock connected through and investment flow, representing the extraction of natural capital for the use in economic capital. As with all forms of capital, there is also a depreciation rate which diminishes this stock. Economic capital is used as an input to production, captured in GDP. The structural components are illustrated with natural capital in Figure 13.
Users can manipulate economic capital in the following ways. First, adjusting units per resource will affect how much natural capital is necessary to make a unit of economic capital. Also, the stock of economic capital can be affected by changing the depreciation rate.

5.6.2 Natural Capital Subsystem

To operationalize the natural capital sub-model, my hypothetical city is based on historic ecological footprint data. The earliest national data available on the Global Footprint Network (2011) is for 1961. I used this level as a rough initial level, although my population data is 1900 estimates for the city of Cleveland. Since an urban area is a leaking system, much like the United States is, we can assume that this hypothetical city has access to resources beyond what it available within its boundaries. As Rees (1992) explains, “the total area of land required to sustain an urban region (its "ecological footprint") is typically at least an order of magnitude greater than that contained within municipal boundaries or the associated built-up area.” Therefore, to estimate a resource base, I use the total productive land for the United States, rather than the city specifically (global hectares, abbreviated gha).

I use global population in the model to illustrate the proportion of population against resource consumption as an information piece for the user to consider when making socially equitable and responsible policy for urban sustainability.
Figure 14 illustrates the natural capital and economic stocks. The flows out of natural capital go into economic capital and a stock of products. This is the natural capital in use. This flow is dictated by the amount of people in the city and the resource necessary to sustain them each year at a given level of material demand, or the ecological footprint (Rees, 1992). There are also two inflows to this stock. Growth is a function of how much natural capital is left in the stock, and waste assimilation is the rate at which the waste created by product disposal and economic capital obsolescence gets regenerated or reengineered back into productive natural resources.

Users have the power to control the following aspects of the natural capital system. First, there is the growth rate. Increasing this will increase the rate at which natural capital can reproduce. Similarly, the assimilation rate will affect the rate at which waste can return to usable natural capital. Third, the disposal rate dictates the amount of goods and services sent to the waste stock each year. Finally, the material standard of living (illustrated in the GDP sub model, Figure 17) is a function of resources per person per year, or their ecological footprint. This can be increased or decreased to a user’s preference.
5.6.3 Social Capital Subsystem

The stock of social capital, illustrated in Figure 15, represents how many connections exist between city residents. The rate at which they are added is a function of how easy it is and how willing people are to make new connections. Willingness is a function of the benefits gained through social capital connections. Ability is a function of how close a person is to the per capita max
on production connections. The closer a person gets to the max, the more difficult it is to create new connections.

Investing in social capital is a way to increase residents’ exposure to new people which can lead to a greater degree to interpersonal trust, reciprocity and the exchange of resources and ideas. Doing so increases the normal rate of connections. There is also a normal rate of connection loss, or the depreciation of social capital. This is caused by a natural “losing touch” that happens between people over time. The loss rate is accelerated the more connections a person has.
Figure 15 Social Capital stock and flow diagram
5.6.4 Human Capital Subsystem

The human capital stock (see Figure 16) represents the aggregate level of human capabilities within the community. It is an index of health and education (Qureshi, 2008) and is measured as productivity units. As with the other forms of capital, it is increased based on the level of investment and decreased with the depreciation or loss of capital units.

In my model, investment comes in the form of social support. As social capital increases, it increases the productivity of the people. Bourdieu (1986) found social capital to be the main difference between the academic successes of students from similar economic backgrounds. Therefore, the economic investment is not a lever in my model, but rather it is assumed that if the society is invested, their financial support is present as well. This is assuming the norms of the society are pro education and health, which is not necessarily the case, and thus this relationship can be turned off.

The levers available for user control are productivity units per person per year and the fraction of human capital lost per person due to out migration. Cities are inherently “leaky” systems. One example is in this human capital subsystem. People may leave a city to live, but still work there. In this way, they are contributing some portion of their existence to GDP, but not their everyday living purchases, home taxes, etc. Also, a fraction of the expertise or talent is left behind as people leave, allowing remaining residents and future generations to build upon it.
Figure 16 Human Capital stock and flow diagram
5.6.5 Gross Domestic Product (GDP)

GDP is commonly used as a measure of community health and stability and is used in multiple system models to capture the productivity of people, capital and natural resources (See the table in Appendix A for the models using GDP). It is commonly computed using the Cobb-Douglas formulation, shown in equation 1 (Cobb and Douglas, 1928). I use it here to provide a common economic yardstick for overall productivity of a hypothetical city.

Equation 1: \[ Y = AL^\alpha K^\beta \]

- \( Y \) = total production
- \( L \) = labor input
- \( K \) = capital input
- \( A \) = total factor productivity

In the introductory chapter of Business Dynamics, Sterman (2000) uses GDP as an example of how information is produced and disseminated through filters. Some filters are inherent (such as seeing infrared rays) and others are designed. GDP counts the extraction and consumption of natural capital as production rather than count it as a reduction of the resource stock. In this model, the amount of natural capital that contributes to gross domestic product is the same quantity that determines the rate at which natural capital flows from its original stock to the stock of goods and services.

As mentioned above, a user can change material standard of living desired constant. This reduces resource spent per person and subsequently GDP. Or, a user can change the productivity of resources, which measures how much economic output can be gained per unit of natural capital extracted. A user can also change the total factor productivity variable, used to represent the level
of technology and efficiency in the production sphere. I use GDP per person as a proxy for the average amount of wealth spread among the population.

5.6.6 Quality of Life and Population Subsystems

Quality of life is used as a measure of city competitiveness (Rogerson, 1999) and illustrates whether the city has the amenity package desired by the average resident. Therefore, in my model, in migration and out migration are based on the ratio of existing to desired levels of GDP per capita, natural
resources per capita, connections per capita, and well being per capita. The general structure is illustrated in Figure 18.

Each of these sectors weighs differently on a person’s decision to move in or out of a place. As mentioned above, objective measures of a society and their environment are more robust when compared to the subjective preferences of a resident (Diener and Diener, 1996; Rogerson, 1999; Bognar, 2005). Therefore, the desired levels of each form of capital per person and the relative importance of each sector over in and out migration are constants that a user can change based on their preferences. They include the following variables:

- Normal in migration weights of SC, HC, EC, NC
- Normal out migration weights of SC, HC, EC, NC
- Desired EC/capita
- Desired SC/capital
- Desired HC/capita
- Desired NC/capita

At certain levels, however, the weights will change automatically. If the environment gets too far below people's preference, its effect will take greater precedent over other elements of quality of life, such as social or human capital. These connections are illustrated in Figure 19. This scenario may be the result of water shortages or water quality issues, air quality increasing illness and death, or simply too few resources available to provide the products demanded.
5.7 Assumptions and Simplifications

In order to model the complexity of urban systems, many assumptions and simplifications had to be made. They are listed below and ways to strengthen these components are discussed in the final chapter. A full review of model “look up” tables can be found in Appendix C.

- For simplicity, investments are exogenous to the system. The investment in additional economic capital, social capital, and the required inputs to added productivity come from outside the city.
- Natural capital is drawn from the global supply. There is no competition from other cities included in the availability of natural capital, nor any pricing mechanism feedback to reduce consumption based on availability. It is also realistic to assume that with added wealth, a city could import more natural capital, but this is also excluded from my model. These considerations will be addressed in future iterations.
- I assume an equal age distribution across the population. To reduce complexity, I do not include a labor fraction, but rather have the total population impact GDP.
- Births and deaths are not included in the population dynamics. In some extreme conditions, it can be assumed that out migration is accompanied by increased deaths, but for simplicity, only in and out migration affects the stock of population.

5.8 Validity Testing

My model is the culmination of both theoretical and mathematic relationships and built to represent a hypothetical, developed city. To determine whether the model output can be used to test policies, the model must undergo a series of validity tests. The purpose of model testing is to “uncover errors so you and your clients can understand the model’s limitations, improve it, and ultimately use the best available model to assist in important decisions” (Sterman, 2000, p.
Below is a review of common validity tests and how they were performed, taken from Sterman (2000).

The first test performed is behavior reproduction. If the model is an appropriate representation of reality, it should be able to reproduce behaviors witnessed in the real system. To do this, I referred to the histories provided by Anthony Orum (1999) of Cleveland, Milwaukee and Minneapolis – St. Paul. To summarize the points made in Chapter 4, the story of Minneapolis – St. Paul’s revitalization was due to the following:

1. It did not experience the same extent of industrialization (which indicates a smaller amount of fixed, inflexible economic capital), so there was not the same number of working class residents, but rather more white-collar workers who would be better prepared to work in a post-industrial society.
2. There was less divisiveness between the inner city and suburban areas, aided by the development of the metropolitan council that sustained a more equitable distribution of resources between the two areas. This indicates a higher degree of social cohesiveness and support for fellow community members.
3. There was a long term commitment of wealthy and prosperous families to the Twin Cities that maintained their dedication to the area despite its decline.
4. Minneapolis – St. Paul had a higher degree of human capital investment and development in the form of a major state research university.
In the base run, I parameterized the model to represent the conditions of a city that experience tremendous growth, followed by decline in their population. It is the trend represented by Cleveland in Figure 20. Between the years of 1900 and 2010, the city grew to over twice its size, only to return to almost 1900 levels by the end of the century. The model's base run, labeled “Cleveland” in Figure 21, illustrates a similar growth trend.
To recreate the growth and decline of Minneapolis – St. Paul, I estimated approximate differences in the different capital systems and made the following adjustments:

1. **Decreased the initial level of economic capital by 1/3.** This estimates the degree of industrialization at the turn of the century between the two cities. As Orum (1995) reports, Minneapolis did not industrialize to the same level as Cleveland.
2. **Decreased the annual investment in new economic capital by \( \frac{1}{2} \).** Similar to change number 1, Minneapolis – St. Paul did not have same industrial base which required heavy annual investment to grow and develop that sector of the economy. Rather, Minneapolis - St Paul was already transitioning into more flexible forms of economic capital, represented as more human capital in this model.
3. **Increased the annual investment in human capital by about 10%.** Because Minneapolis – St. Paul had the state university, there was a greater investment in human capital. The population had a higher percentage of white-collar, college graduates than its Midwestern
neighbors like Cleveland, and therefore the model indicates a higher level of annual development of human capital.

4. Increased the annual investment in social capital by .1 people/year. The increase in social capital, quantified by personal connections per person added per year, represents a few different characteristics of Minneapolis – St. Paul’s social structure. First, there was the development of a metropolitan governing body that maintained a more equitable distribution of jobs, finances, and wealth between the city and the suburbs. In other instances, we see a greater divide between political power and wealth as the inner city loses resources to the suburbs. Reducing this divisiveness created a more tolerant and diverse community. Second, there were wealthy family businesses that had profound impacts on the economic development of the city. Those families were loyal to the area and maintained their involvement over generations.

5. Decreased the fraction of human capital lost in outmigration to half the base level. Because the metropolitan area was successful in establishing an overarching governing body, they were able to prevent the leak of business and wealth to the suburbs. Therefore, the downtown area is still highly livable and maintains a healthy economic base where other cities had experienced inner deterioration. In our model, some of the expertise the population develops (counted as human capital) remains as part of systems and best practices.

Outmigration from cities is in large part for outlying suburbs. If people are moving from the city to the suburbs, it is reasonable to believe that Minneapolis – St. Paul’s thriving downtown means more people will remain employed and commute in, reducing the amount of human capital that is lost when a person migrates away from the city.

By making these changes, the model produces the thicker line in Figure 21, where growth is slower than Cleveland’s, a plateau occurs around the same time, but the decline is not as drastic. Minneapolis- St. Paul’s population exceeds Cleveland’s in the 1970s, and increases toward the end of the model run. In future iterations, I would like to see Cleveland’s population dip lower at the end of the run, to recreate the return to 1900 levels as we see in Figure 21.

Next, boundary adequacy analyzes whether the concepts central to the model’s purpose are endogenous to the model. The stocks and flows determine the sustainability of this hypothetical city and are treated endogenously. Because
QOL is determined as a comparison between objective conditions (capital/person) and the degree to which it satisfies subjective preferences (desired capital/person) these elements are endogenous and exogenous, respectively. Variables were omitted that did not support the purpose of the model or where simplifying proxies could be used. Table 2 includes a full review of model boundaries.

Structure assessment was done throughout the preparation of the model through the reviews of theoretical and model studies on how the forms of capital addressed here are formed, depleted and transformed into other capital. Every stage of model development was accompanied by a review of the literature to ensure consistency with the relationships defined by previous researchers. However, for simplicity, the effects of realistic delays were omitted. Therefore, the impacts of policy changes are felt instantly, rather than after the realistic amount of time.

Many of the parameters in this model are estimates based on aggregate data at the national level or thought experiments based on theoretical relationships found in the literature. Therefore, while each of the parameters has real-life meaning, they are occasionally represented by index proxies (for example, human capital as an index of education and health, measured in productivity units. An increase in productivity units per person is developed much the same way as years of education, and effects economic productivity in the same manner as well.) A full list of assumptions is included in Appendix C.
The following chapter includes a discussion on what future research can improve the validity of these parameters.

During a series of tests using extreme values, the model did responded plausibly and did not break any basic, physical logic. When natural capital depletes to zero, no production can occur, and GDP falls to zero as well. There is never a negative value for stocks along the natural and economic system of stocks and flows. Population never falls below zero.
CHAPTER 6
MODEL USE

Though this model is only a preliminary look at the complexities of urban behavior, it shows there is some benefit to understanding a city as a provider of capital for a population of people, and understanding how people interact with that capital and are satisfied by that capital is critical to understanding how likely they are to remain invested in that place. Lessons learned by the changing economy of the 1940s and 1950s should provide insights into how to manage future changes: how to keep economic capital flexible rather than fixed, maintain a high investment in human capital to be prepared for, or even to be the innovators of a new economy.

Under the initial conditions based on Cleveland, OH (for complete list, see Appendix B), the city experiences growth for the first 45 years, followed by a brief plateau as illustrated in Figure 21. The drop in population is caused by a drop in the attractiveness of the economy (GDP/capita) and the human capital sector (HC/capita). When people begin to leave, it takes its toll on the society by the loss of connections which weakens the community’s investment on human capital.

6.1 Policy Analysis

To illustrate the potential of this model for policy analysis, I have included a set of potential city goals and strategies to evaluate with the differences in Cleveland and Minneapolis – St. Paul’s history. I have simulated a series of tests
using key policy scenarios future users could employ. Based on strategies presented in the literature, assumptions about the average person’s idea of effective policy, and my own curiosity, I have created the following list of potential test scenarios. I will then describe the results of two of them in the following section.

1. Goal: Grow the economy (GDP)
   Strategy: Double total factor productivity, double EC investment/year, double people’s material standard of living
   Hypothesis: With the growing economy, new migrants will be attracted and less will want to leave. A stable population will help stabilize the human capital stock, and help reinforce production.

2. Goal: Live within environmental constraints (NC)
   Strategy: Reduce material standard of living by half
   Hypothesis: The society will be able to sustain a greater number of people for longer period of time without significantly reducing the QOL

3. Develop a close community (SC/person)
   Strategy: Invest in social capital, increase the normal connections made per person per year by 50%
   Hypothesis: Greater connections will increase productivity, GDP and HC. This will keep more people in the city fueling consistent growth

6.2 Policy Output

In this thesis, I evaluate the results of these polices based on the output of key indicators of quality of life and sustainability. The results are illustrated in Figures 22 and 23 and preliminary explanations follow.
Policy 1 seeks to increase and maintain gross domestic product. The strategy involved is to increase the means of production (double people’s demand for material well being from 5 to 10) thereby adding more resources into production. Then, there is an added flow of economic capital investment in order to handle the increased desire for material things. Total factor productivity is increased from 50% to 100%. The green line in the first graph, GDP per person,
illustrates that while this strategy initially leads to greater growth than the conditions of Cleveland and Minneapolis – St. Paul, the human capital investment is not sufficient for the population, and that stocks falls faster. Natural capital consumption increases throughout the run of the model, indicating an unsustainable use of resources (indefinite consumption cannot be sustained on a limited stock of resources.) Despite the continued rise in population (Figure 23), the cohesiveness of the community does not continue to grow, as experienced in Cleveland and Minneapolis – St. Paul.

Policy 2 is taken from the recommendations made by the creators of the Ecological Footprint (Wackernagel, et al 2006). They suggest the reduction of natural capital demand by reducing the demand for material items, reducing
population, increasing the supply of natural capital, or increasing the productivity of natural capital thereby requiring less extraction to meet the same demand. This conservation approach can be achieved through denser living, smaller dwellings, less driving and energy consumption. If this is the case, this model city should be able to hold more people than in previous scenarios.

For this run, I did not alter the population rates but only environmental factors. Resources per person is reduced by half to 2.5. The results illustrated in Figures 22 and 23 show that this strategy contributes to more stable growth in GDP and population, suggesting that Wackernagel, et al’s recommendations are sound and more people are able to sustain in an urban area if they require fewer material resources. Social capital stabilizes after the first 20 years and human capital increases throughout the run of the model, with the social capital and financial support available. However, natural capital consumption increases throughout the 100 years projected, indicating that the rise in population will cancel out the natural capital stock conservation of reduced per capital resource demand as population grows.
CHAPTER 7
DISCUSSION

During the writing of this thesis, the Earth’s 7 billionth baby was born (Newcomb, 2011). Global population is at unprecedented levels, and the fraction of that population living in cities is at an all time high and expected to grow (McGranahan et al, 2005). What can we do to ensure a happy, healthy and sustainable population in cities?

As discussed at the beginning of this thesis, sustainability and quality of life are complex issues, highly interconnected, and the product of both objective and subjective measures of society. The goal of this model was to examine the dynamics of population and quality of life in cities. Through the use of a causal loop diagram and structural model, I formed a hypothesis about what causes the behavior seen in declining cities, and looked for way to improve and sustain favorable conditions.

As Egger (2006, p. 1236) writes, “cities do not necessarily require population growth in order to develop. For example, over the past 50 years, cities such as London and Berlin have experienced population decline yet have managed to develop as measured by increases in their metropolitan GDP” (Egger, 2006). This model illustrates that while one important indicator may be flourishing, such as GDP per person, other indicators, such as community cohesion (social capital) or health of the natural environment may be failing. Failing to account for these elements will undoubtedly paint an insufficient and inaccurate portrait of a city.
7.1 Model Limitations

Due to the level of aggregation and the assumptions that define some of the relationships, the model is limited in its capacity to give precise or detailed future trends. The model is not a prediction tool, but for understanding trends, leverage points, tradeoffs, relationships and best places to intervene. Below is a list of limitations and suggestions for improving the model.

This model does not capture the increasing demand for natural capital over time. This is caused by what researchers call the “treadmill of production,” (Schnaiberg and Gould, 1994) which is the continual pursuit of greater profits through increased production and consumption. This is captured by reviewing the trend of total Ecological Footprint over time, which has risen from 2.4 to 2.7 between 1961 and 2007. The feedback between increased development and wealth and an increased desire is not included in this phase of the model, but could be easily incorporated into future versions.

It is also difficult to measure sustainability based on the stock of natural capital computed in this model because it represents the total stock available to a city if the city had unlimited access to it. It does not include competition with other cities. Therefore, natural capital consumption within a city is used as the indicator of environmental sustainability. A stronger understanding of how to represent the environmental conditions within a city relative to the global stock will make this analysis stronger.
Other modelers have been more specific about the source of material for the production of goods and economic capital. The differentiation between renewable and nonrenewable natural capital provides a more accurate account of limits. At this level of aggregation, this difference was not included.

In reality, policies do not immediately take effect. Likewise, changes in the system such as the investment in human capital or social capital would see the impact to their respective stocks years after they are done. Delays in the system are not included in this model.

Another common form of capital included in sustainability discussions is technological capital. Adding this stock and the dynamics of how it changes can better capture how other changes are achieved, for example, a faster growth rate of natural capital and total factor productivity in production.

Sustainability is difficult to define and measure due to the need to assign a time limit and can only be measured in hindsight. The most accurate time frame is measuring whether a stock can sustain indefinitely, but this model only projects 100 years into the future. Extending the run time further would give a more accurate, yet still insufficient estimate of sustainability.

Assumptions and non-linear relationships (full list in Appendix C) are not based on data, but thought experiments and theoretical understanding of how these relationships work. I would like to survey others to see how people’s mental models of these relationships differ from my own.
7.2 Opportunities for Future Research

Once I feel confident in the model’s ability to replicate real world behavior and can address the weakness addressed above, it is my intention to use the model for more thorough analysis of other scenarios and policy options for cities in decline. My focus for this thesis was so heavily placed on learning about city systems and the modeling process that use and analysis is still the weakest part of this paper and my personal skill set. While perhaps weak in execution at this stage, this line of research is rich in potential.

Given the opportunity, I would like to see some of the missing feedback between wealth, technology and natural capital integrated into this model. It currently does not address issues of accessibility associated with wealth distributions and therefore falls short of clearly communicating issues of equity. I would like to see these areas explored, either in ways to integrate them into the model’s computations, or in the development of discussion points to better inform and structure policy formation by the information currently provided in the model.
## APPENDIX 1

### LITERATURE REVIEW TABLE

<table>
<thead>
<tr>
<th></th>
<th>Who/Where</th>
<th>Main Focus</th>
<th>Stocks</th>
<th>Connections</th>
</tr>
</thead>
</table>
| 1 | Qureshi (2009) Pakistan        | Human development, public expenditure and economic growth                   | • Population • Level of human development • Capital • Public debt                         | • Increasing education and health expenditure increase service, increase level of human development, increasing employment and productivity, gdp and income, going to increase taxes and revenue to support these expenditures.  
  • 4Also decreases deaths per year, alters reproductive behavior                                                                                                                  |
| 2 | Qureshi (2008) Pakistan        | Human development and economic growth                                        | • Population • Human development                                                        | • Challenging the trickledown theory, that economic growth will produce universal benefits to all.  
  • Only when human development expenditure in increased is hd increased, even if the economy grows a relatively lower rate |
| 3 | Dangerfield (2007) Sarawak      | Human dev. & economic growth – managing the transition from goods passed economy to knowledge based | • Population • Education/HC • Manufacturing • Services and GDP • State products • State revenue and spending | • Require investment in R&D to attract and retain knowledge based firms, while also providing the skills necessary for the population to work in those industries |
| 4 | Radzicki & Seville (1993) Sterling, MA | Bring together the various institutions governing the city to better inform policy decisions | • (Sectors): municipal light • Quality of life • Population and housing • Fiscal • School • Land fraction • Commercial and industry | • Started with URBAN1, simplified version of Forrester's Urban Dynamics model  
  • One example: in-migration formulations influenced by the labor force-to-jobs ratio, low, in migration increases, but in Sterling, most people work elsewhere, migration forces had to be adapted appropriately  
  • QOL was a main in migration mechanism, influenced by crowding from pop and structures, ratio of commercial and industrial structures, tax rates.  
  • 2 main components of QOL: tax satisfaction (ration
### Table: Examples of Urban Sustainable Development

<table>
<thead>
<tr>
<th>Source</th>
<th>Case Study</th>
<th>Urban Sustainable Development</th>
<th>Social Indicators</th>
<th>Economic Indicators</th>
<th>Environmental Indicators</th>
<th>Institutional Indicators</th>
<th>Model Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Duran-Engalada &amp; Paucar-Caceres (2008) Puerto Aura in Puebla, Mexico</td>
<td>Urban sustainable development: futurity, environment, public participation, equity</td>
<td>Social (population and employment, housing, education and health)</td>
<td>Economic (transport, economic)</td>
<td>Environmental (Water, air pollution, solid waste)</td>
<td>Institutional (land)</td>
<td>Model tracks people through different age groups and working status, in migration function of pollutants per capita, gases per capita, opening firms, in habitants per household standard, education service level, health services level, other services level. Transport: firms opening and new jobs affects # cars on the road, affecting congestion and noise. Water available is a function of what's being consumed by homes, firms, schools, and health care facilities and the supply is decreased by the amount of ground coverage these buildings take up, reducing infiltration of rainwater.</td>
</tr>
<tr>
<td>7</td>
<td>Alfeld (1995) Boston</td>
<td>Managing urban aging, specifically the gap between high priced jobs and low-priced housing</td>
<td>Urban aging:</td>
<td>Housing by age</td>
<td>Business structures by age</td>
<td>Population by socioeconomic class</td>
<td>Model called for the need for stabilizing and expanding the lower-income employment base, emphasis on education and that the old housing sock needed to be conserved and rehabilitated so that it still looked attractive to affluent residents. Finance happened. Instead, the affluent fled to the suburbs and commuted.</td>
</tr>
</tbody>
</table>

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Often tax satisfaction falls when rates go up, but service satisfaction rises because the taxes are going to something the people want, so overall QOL increases.
<table>
<thead>
<tr>
<th>#</th>
<th>Author (Year)</th>
<th>Location</th>
<th>Study Description</th>
<th>Impact</th>
</tr>
</thead>
</table>
| 8  | Alfeld (1995) Concord | Controlling population growth to maintain historic charm of the city | • Population  
• Community attractiveness | • Attracting more people than a place can sustain causes an overshoot and collapse, potentially ruining its original charm for good  
• Need a set of pressures that the outside community perceive as sufficiently negative (like the water prices for Qureshi) to counter the attractiveness |
• Housing  
• Jobs | • “trading what little remained of its declining economic base for new apartments could only lead to more people, increased traffic, higher unemployment and more problems… move the city toward a long-term balance between pop and employment.”  
• “city’s investment in its neighborhoods also encouraged private re-investment… helped to stabilize both the population turnover and the property tax base.” |
| 10 | Alfeld (1995) Palm Coast | Managing projected growth of a small community to a city | • Housing  
• Target population, families vs. retirees preferences | • spacing our affordable housing development overtime, avoid filter down after 50 years to large slum |
| 11 | Chen, HO, Jan (2006) Taipei City | Air pollution caused by increased transportation from population, reduction in open space from greater land development demands | • green land  
• population  
• urban development for building  
• transportation  
• economic growth | • |
|    | Guan et al. (2011) Chongqing, China | Addresses the spatial constraints of SD with GIS, | • Stocks:  
• R. Resources  
• Discharged volume of solid waste | • |
<table>
<thead>
<tr>
<th>12</th>
<th>Jin, Xu, &amp; Yang</th>
<th>Integrating system dynamics and ecological footprint</th>
<th>Capital</th>
<th>Neoclassical economic theory: capital stock plus investment minus depreciation * depreciation rate (what I have)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>China</td>
<td>Part one – economic capital growth</td>
<td>Population</td>
<td>GRP = total factor productivity * Cap * labor force inputs * energy inputs (abbreviated Cobb Douglas production function)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Part two - Land use and consumption</td>
<td>Multiple land uses (part two)</td>
<td>Population includes in migration and births/deaths</td>
</tr>
<tr>
<td>13</td>
<td>Bagheri &amp; Hjorth (2005) Tehran</td>
<td>Monitoring sustainable development in terms of carrying capacity, as applied to an urban water system in Tehran</td>
<td>Problem symptoms, fixes, consequences, backfires</td>
<td>Water shortages lead the city to acquire water from other places, so that the stock of provided water goes up, this makes makes the attractiveness of Tehran increase while making the attractiveness of the places where they got the water from less attractive. This increases in migration and water demand, putting the city in the same supply problem</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Loops need to added to balance this trend – cost of water services to deter population growth, water efficiency measures to reduce demand</td>
</tr>
<tr>
<td>14</td>
<td>Dudley (2004)</td>
<td>Modeling social capital – defining it as the system, not just a simple stock (circularity of the definition)</td>
<td>Connections/person</td>
<td>SC yields communal obligations, leads to higher expected level of norms, rules and procedures</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Benefits</td>
<td>Rules ratio can increase to make a stable environment and stifle creativity/innovation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Value of SC</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Current benefits from initiative</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Current benefits from stable operating</td>
<td></td>
</tr>
</tbody>
</table>
| 15 | Hjorth & Bagheri (2006) | Understanding urban sustainability as process of maintaining strong viability loops rather than an ideal state as a goal | Environment  
- Strength and stability of community norms  
- Trust/useful information?  
- Benefits of successful initiatives and stability feed back to encourage or balance the level of SC  
- Reciprocity, reputation, trust, reciprocity |
|---|---|---|---|
| 16 | Senge, Seville, Lovis & Lotspeich (2000) | Modeling the components of the shift to natural capitalism | Natural capital (biotic and abiotic resources)  
- Resources used in manufacturing  
- Products in use  
- Waste  
- Must increase productivity so we get more product out of capital extracted  
- Close the loop so waste becomes food to another system  
- Manufactures take back goods when consumers are done, rather than discarding them  
- Business must reinvest in natural capital to sustain and...
| 17 | Pretty (2003) | The use of social capital to manage natural resources | • 4 important features:
  - Relations of trust
  - Reciprocity and exchanges
  - Common rules, norms and sanctions
  - Connectedness in networks and groups
  - Letting people govern themselves towards what’s best for the society, rather than the pursuit of individual gain as discussed by Hardin in “ToFC”
  - Social capital lowers transaction costs of working together, facilitates cooperation, confident to invest in collective activity knowing that others will also do so, less likely to engage in unfettered private actions with negative outcomes, such as resource degradation |
| 18 | Forrester (1969) | Urban dynamics | • Land available
  - Business growth
  - Population
  - Housing
  - Theory of relative attractiveness: “given free migration, no place can long remain more attractive than any other place” (A, 1995). “lifeboat” analogy
  - Cities naturally go through periods of growth, decline, and stagnation |
| 19 | Woodwell (1998) | Economic growth, resources depletion – experimenting with the theory of Limits to Growth and its critics resource consumption, production, factors of production | • 7 sectors to the model:
  - Technology in production
  - Production
  - Renewable natural capital
  - Non renewable natural capital
  - Human capital
  - Man made capital
  - population
  - all equations provided
  - "various combinations of rapid population growth, excessive depletion of natural capital, and stagnation in technological development can cause overshoot and collapse”
  - “this model has not been calibrated to the data of a single country or region and is not a tool to predict future trends.”
  - Cobb Douglas Production function – exponents all add up to one, so a decline in one factor will be mad up by another. Investments in tech, man-made cap and human cap are subtracted from production
  - Investments in ed and skill increase productivity of HC, yield diminishing returns, impacts of increases and decreases realized immediately
  - Man-mad cap growth |
<table>
<thead>
<tr>
<th></th>
<th>Levett</th>
<th>Urban sustainability -</th>
<th>Renewable natural capital grows in a logistic curve (S shaped?)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Campbell (1996)</td>
<td>Sustainable development – resolving the 3 conflicts of the planners triangle</td>
<td>Non systems, Russian doll rather than a 3 ring circus framework</td>
</tr>
</tbody>
</table>

- Changes linearly with investment, deprecation is an exponential decay function, limited by natural capital, RRes consumption + NR Res consumption + land = limit on growth of manmade cap
- Renewable natural capital
grows in a logistic curve (S shaped?)
- Non renewable – land and others. Upper limit on consumption depletion = exponential decay function for each compartment.
- Production increases more non renewable natural capital taken.
- Tech in production is a scaling factor, sets efficiency, growth is exponential in base run, can be switched to linear

- Tensions between each

- Happiness “the best society is one where the citizens are happiest.” Bentham 1789. Measured on a scale 1-10
- Authors use it synonymous with SWB
- Things money can buy & things money can’t buy. Expectations in the drivers for things money can by adapt faster
- Models the interdependence of happiness and happiness drivers
- Questions the assumption that financial prosperity leads to happiness – cites a study that found that GDP and happiness were not correlated
- Understand happiness is measured from a number of different fields, call for a holistic approach with SD
- Happy people tend to have more friends, find jobs easier, find partners easier – things that also drive happiness
- Psychic income: when constant at any level, a change in happiness doesn’t occur, only when the level deviates
- Csikszentmihalyi flow: “people are happiness in situations where they’re
| 23 | Franck (2007) | Applied to climate change mitigation | Utility functions – consumption, GDP, population | Subjective well being – how people evaluate their own lives | Consumption per capita | Consumption per capita reference | • Traditional – desire is never satiated, more is always better, growth at all costs: per capital consumption * population | • SWB – utility doesn’t rise permanently with increased consumption, because peoples habituation to their actual consumption levels: current consumption/reference consumption* population | • Habituation balancing loop: when SWB utility is used, if the current is larger than the reference consumption, a person eventually gets used to it, adjusting their reference |
| 24 | Cox, Johnstone, & Robinson (2006) | Theory applied to Queensland, Australia | Quality of natural areas effect on human social well being | • Time spent recreating | • Quality of life | • Health | • Social capita | • Structure could replace “waterway recreation” with other more relevant items, perhaps neighborhood, Red Rock, Lake Mead, public parks? | Hypotheses: perceived condition of natural areas affect amt of recreation | • Natural areas promote more common space usage, more contact, more trust/social capital | • More social support, better health, better QOL | • Sense of place increases QOL, increased with better natural areas, social component as well | • Didn’t find statistical support based on survey done of different natural areas to support all of these hypotheses. |
| 25 | Ostrom, 1997 | Collective norms as a means to govern the commons | • Reciprocity, reputation, trust (positive feedback loop) | • Increases levels of cooperation | • Benefits, which can include better use of common pool resources | Promoting mutually beneficial habits by making it the norm, and collectively enforcing the rules and norms |
### APPENDIX 2

#### MODEL EQUATIONS

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Units</th>
<th>Equation</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic Capital</td>
<td>Gha</td>
<td>INTEG(NC consumed for EC-disposal)</td>
<td>Stock of EC, the means to production</td>
<td></td>
</tr>
<tr>
<td>Initial Economic capital</td>
<td>Gha</td>
<td>1000</td>
<td>At start of sim, initial value of EC</td>
<td></td>
</tr>
<tr>
<td>EC Depreciation Rate</td>
<td>1/year</td>
<td>.025</td>
<td>Proportion of economic capital depreciated each year</td>
<td>BEA, 1997 (Woodwell uses .045, but does not include a source or justification.)</td>
</tr>
<tr>
<td>EC disposal</td>
<td>Gha/year</td>
<td>EC depreciation rate * economic capital</td>
<td>Amount of EC depreciated and obsolete</td>
<td></td>
</tr>
<tr>
<td>Normal Investment Rate</td>
<td>Gha/year</td>
<td>EC disposal</td>
<td>Normal investment rate is equal to the amount depreciated</td>
<td></td>
</tr>
<tr>
<td>NC consumed for EC</td>
<td>Gha/year</td>
<td>IF THEN ELSE(EC growth for population increase * TIME STEP * normal investment rate &lt; natural capital / TIME STEP, EC growth for population increase * TIME STEP * normal investment rate, 0)</td>
<td>The amount of natural capital extracted and used in the building of EC</td>
<td></td>
</tr>
<tr>
<td>EC growth for population increase</td>
<td>1/year</td>
<td>MAX(population growth, 1)</td>
<td>The normal rate of EC investment is increased proportionally to population growth</td>
<td>Capital investment is typically modeled as a percent of gross regional product, which increases with population. This is a simplification of that dynamic (Jin et al, 2009)</td>
</tr>
<tr>
<td>Capital units</td>
<td>Capital units</td>
<td>capital units per resource * economic capital</td>
<td>Input to GDP, capital units, developed by NC</td>
<td></td>
</tr>
<tr>
<td>Capital units per resource</td>
<td>Capital units/gha</td>
<td>0.1</td>
<td>It requires 10 gha to produce 1 capital unit</td>
<td></td>
</tr>
<tr>
<td>Variable Name</td>
<td>Units</td>
<td>Equation</td>
<td>Description</td>
<td>Source</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>---------</td>
<td>--------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Initial NC</td>
<td>Gha</td>
<td>6.7e+006</td>
<td>Initial stock available</td>
<td>Scaled level of productive land in 1961 ecologicalfootprint.org</td>
</tr>
<tr>
<td>NC growth</td>
<td>Gha/year</td>
<td>MAX(natural capital*NC growth rate, 0)</td>
<td>Number of gha added each year</td>
<td>Structure adapted from Senge, P., Seville, D., Lovins, A., and Lotspeich, C. (2000)</td>
</tr>
<tr>
<td>NC growth rate</td>
<td>1/year</td>
<td>0.000675</td>
<td>Percent of NC stock added each year</td>
<td></td>
</tr>
<tr>
<td>NC used in products and services</td>
<td>Gha/year</td>
<td>IF THEN ELSE(natural capital/TIME STEP&lt;NC consumption/TIME STEP, IF THEN ELSE(natural capital/TIME STEP&gt;0, natural capital/TIME STEP, 0), NC consumption/TIME STEP)</td>
<td>Amount of NC stock used by population in products and services</td>
<td>Structure adapted from Senge, P., Seville, D., Lovins, A., and Lotspeich, C. (2000)</td>
</tr>
<tr>
<td>NC in products and services</td>
<td>Gha</td>
<td>INTEG(NC used in products and services-waste from products and services)</td>
<td>The NC that are in use</td>
<td>Structure adapted from Senge, P., Seville, D., Lovins, A., and Lotspeich, C. (2000)</td>
</tr>
<tr>
<td>Product disposal rate</td>
<td>1/year</td>
<td>.8</td>
<td>Rate of disposal</td>
<td>Hawken, 2008</td>
</tr>
<tr>
<td>Waste to NC ratio</td>
<td>dmnl</td>
<td>waste/natural capital</td>
<td>Amount of waste relative to productive gha</td>
<td>Based on relationship found in Jin et all 2009. They model pollution as result of energy use increasing death rate. I attribute it to out migration.</td>
</tr>
<tr>
<td>Effect of waste on human health</td>
<td>dmnl</td>
<td>([(0,0)-(2,0.5)],(0.5,0), (0.574924,0.0328947), (0.691131,0.0657895), (0.844037,0.111842), (1,0.15), (1.15596,0.188596), (1.33333,0.221491), (1.52905,0.256579), (1.76758,0.289474),(2,0.3)]</td>
<td>If the waste to NC ration is under 50%, no impact on HC. If greater than 50% decreases HC. If 100%, 15% reduction in HC, when it begins to exceed 100%, it degrades up to 30% /year</td>
<td></td>
</tr>
<tr>
<td>Effect of waste on human health</td>
<td>dmnl</td>
<td>effect of waste on human health (0)(waste to NC ratio)</td>
<td>Computes the effect from the lookup table</td>
<td></td>
</tr>
<tr>
<td>Effect of waste on human health</td>
<td>Gha/people</td>
<td>5</td>
<td>Figure based on 1961 average ecological footprint of a US resident</td>
<td></td>
</tr>
<tr>
<td>Resources per person</td>
<td>Gha</td>
<td>resources per person*island population</td>
<td>Total NC consumed each year</td>
<td></td>
</tr>
<tr>
<td>NC consumption</td>
<td>Gha</td>
<td>5</td>
<td>How many gha a person consumes each year</td>
<td></td>
</tr>
<tr>
<td>Variable Name</td>
<td>Units</td>
<td>Equation</td>
<td>Description</td>
<td>Source</td>
</tr>
<tr>
<td>------------------------</td>
<td>------------------</td>
<td>--------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>Social Capital</td>
<td>Connections</td>
<td>INTEG(SC added-SC removed)</td>
<td>Number of connections between the population</td>
<td>Structure adapted from Dudley, 2004</td>
</tr>
<tr>
<td>Initial social capital</td>
<td>Connections</td>
<td>20000</td>
<td>Initial number of connections</td>
<td></td>
</tr>
<tr>
<td>SC removed</td>
<td>Connections/year</td>
<td>IF THEN ELSE(social capital/TIME STEP&gt;social capital/(natural depreciation rate<em>Loss rate MULTIPLIER), social capital/natural depreciation rate</em>(Loss rate MULTIPLIER) , MAX(social capital/TIME STEP, 0))</td>
<td>Connections lost each year</td>
<td>Structure adapted from Dudley, 2004</td>
</tr>
<tr>
<td>SC added</td>
<td>Connections/year</td>
<td>IF THEN ELSE(social capital&gt;max social capital, 0, normal connections added each year*(1+effect of value on people’s desire to create connections)*(1+people’s ability to make new connections))</td>
<td>Connections added each year</td>
<td>Structure adapted from Dudley, 2004</td>
</tr>
<tr>
<td>social capital per person</td>
<td>Connections/people</td>
<td>social capital/island population</td>
<td>Average number of personal connections</td>
<td></td>
</tr>
<tr>
<td>ratio of SC/person to max SC/person</td>
<td>Dmnl</td>
<td>social capital per person/links per person max</td>
<td>Percent of maximum connections</td>
<td></td>
</tr>
<tr>
<td>Links per person max</td>
<td>Connections/person</td>
<td>150</td>
<td>Maximum number of connections a person can maintain</td>
<td>Gladwell, 2000; Dudley, 2004</td>
</tr>
<tr>
<td>People’s ability to make new connections</td>
<td>Dmnl</td>
<td>saturation effect on ability to make new connections</td>
<td>Ability is based on the existing number of connections a person has, as they approach the max, it becomes more difficult to</td>
<td></td>
</tr>
<tr>
<td>saturation effect on ability to make new connections</td>
<td>Dmnl</td>
<td>Look up table for relationship between ratio of connections to max connections and ability to make new connections</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
<td>------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dmnl [0.0,0.0),(0.140673,0.986842), (0.281346,0.960526), (0.40367,0.925439), (0.538226,0.872807), (0.672783,0.828947), (0.776758,0.780702), (0.856269,0.70614), (0.911315,0.631579), (0.98471,0.473684), (1.03976,0.372807), (1.12538,0.285088), (1.20489,0.245614), (1.3211,0.214912), (1.46789,0.188596), (1.57798,0.162281), (1.77982,0.157895), (1.99388,0.153509)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Net benefit of social capital</th>
<th>Dmnl</th>
<th>Benefits gained through social capital</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dmnl value of SC LOOKUP(ratio of SC to max SC)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Value of SC LOOKUP</th>
<th>Dmnl</th>
<th>Look up table for computing benefits based on ratio of SC to max SC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dmnl [(0.0),(5.2)],(0.0), (0.122324,0.0175439), (0.275229,0.0789474), (0.412844,0.166667), (0.519878,0.385965), (0.657492,0.701754), (0.795107,0.877193), (0.978593,1), (1.34557,1.03509), (1.6055,1.03509), (1.98777,1), (2.27829,0.850877), (2.49235,0.622807), (2.69113,0.403509), (2.95107,0.22807), (3.19572,0.105263), (3.50153,0.0526316), (3.88379,0.0350877), (4.38838,0.0175439), (5.0,0.0001)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total benefit</th>
<th>Connections</th>
<th>Total societal benefits from SC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connections * net benefit of social capital</td>
<td>Total benefit</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Max benefit</th>
<th>Connections</th>
<th>Maximum benefit based on max per capita benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connections</td>
<td>per capita benefit max*social capital</td>
<td>Maximum benefit</td>
</tr>
</tbody>
</table>

<p>| Ration of 1 | ratio of benefit to max | Percent of |</p>
<table>
<thead>
<tr>
<th>Benefit to max benefit</th>
<th>Benefit</th>
<th>Max benefits realized</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC effect on HC LOOKUP 1</td>
<td>[(0,0)-(1,2)],(0,0), (0.0795107,0.0263158), (0.122324,0.0789474), (0.183486,0.114035), (0.250765,0.219298), (0.327217,0.377193), (0.409786,0.640351), (0.464832,0.850877), (0.5,1), (0.501529,0.991228), (0.559633,1.31579), (0.593272,1.48246), (0.642202,1.64035), (0.718654,1.73684), (0.785933,1.81579), (0.834862,1.87719), (0.923547,1.92105),(1,2)</td>
<td>Relationship table between benefits and increase of HC added</td>
</tr>
<tr>
<td>SC effect on HC development MULTIPLIER 1</td>
<td>SC effect on HC LOOKUP(ratio of benefit to max benefit)</td>
<td>Effect on HC based on benefits</td>
</tr>
<tr>
<td>Effect of value on people’s desire to create connections Dmnl</td>
<td>benefit effect on desire LOOKUP(net benefit of social capital/per capita benefit max)</td>
<td>Benefits effect of motivation to make new connections Based on Putnam, 1993, Dudley, 2004</td>
</tr>
<tr>
<td>Per capita benefit max Dmnl</td>
<td>5</td>
<td>Max benefits a person can realize in a year</td>
</tr>
<tr>
<td>Benefit effect on desire LOOKUP Dmnl</td>
<td>[(0,0)-(1,1)],(0,0.9), (0.0764526,0.973684), (0.2,1),(0.302752,0.95614), (0.400612,0.807018), (0.470948,0.622807), (0.556575,0.482456), (0.669725,0.394737), (0.764526,0.315789), (0.874618,0.22807),(1,0.2)</td>
<td>Table of relationship between benefits and desire</td>
</tr>
<tr>
<td>Loss rate MULTIPLIER Dmnl</td>
<td>speed of loss LOOKUP(ratio of SC per person to max SC per person)</td>
<td>As people approach the max number of connections, it becomes easier to lose touch, thus multiplying the natural depreciation</td>
</tr>
<tr>
<td>Connections added each year</td>
<td>Connections/year</td>
<td>island population*connections per person/TIME STEP</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>Connections per person</td>
<td>Connections/person</td>
<td>normal connections per person*SC investment LOOKUP(investment in social capital)</td>
</tr>
<tr>
<td>normal connections per person</td>
<td>Connections/person</td>
<td>2</td>
</tr>
<tr>
<td>SC investment LOOKUP</td>
<td>dmnl</td>
<td>[(0,0)-(1,4)], (0.00611621,0.45614), (0.0764526,0.508772), (0.137615,0.578947), (0.189602,0.631579), (0.256881,0.701754), (0.327217,0.789474), (0.397554,0.877193), (0.5,1), (0.562691,1.08772), (0.614679,1.21053), (0.64526,1.38596), (0.697248,1.7193), (0.752294,2.03509), (0.816514,2.47368), (0.859327,2.7193), (0.896024,2.85965), (0.948012,2.94737), (1,3)</td>
</tr>
<tr>
<td>Investment in social capital</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Max social capital</td>
<td>Connections</td>
<td>(island population*(island population-1)/2)*connections modifier</td>
</tr>
<tr>
<td>Connections modifier</td>
<td>connections/(person*person)</td>
<td>1</td>
</tr>
<tr>
<td>Variable Name</td>
<td>Units</td>
<td>Equation</td>
</tr>
<tr>
<td>---------------</td>
<td>-------</td>
<td>----------</td>
</tr>
<tr>
<td>Human Capital</td>
<td>Productivity units</td>
<td>INTEG(HC developed-HC lost)</td>
</tr>
<tr>
<td>HC developed</td>
<td>Productivity units/year</td>
<td>adjusted rate of HC added</td>
</tr>
<tr>
<td>HC lost</td>
<td>Productivity units/year</td>
<td>IF THEN ELSE((human capital/TIME STEP&gt;(human capital<em>effect of waste on human health/TIME STEP)+total HC out migration), ((human capital</em>effect of waste on human health/TIME STEP)+total HC out migration), human capital /TIME STEP)</td>
</tr>
<tr>
<td>normal rate of HC added*SC effect on HC development MULTIPLIER</td>
<td>Productivity units/year</td>
<td>normal rate of HC added*SC effect on HC development MULTIPLIER</td>
</tr>
<tr>
<td>Normal rate of HC added</td>
<td>Productivity units/year</td>
<td>island population*productivity units gained per person per year</td>
</tr>
<tr>
<td>Adjusted rate of HC added</td>
<td>Productivity units/year</td>
<td>normal rate of HC added*SC effect on HC development MULTIPLIER</td>
</tr>
<tr>
<td>Total HC out migration</td>
<td>Productivity units/year</td>
<td>fraction of HC lost per person<em>HC per person</em>out migration</td>
</tr>
<tr>
<td>Fraction of</td>
<td>1</td>
<td>.05</td>
</tr>
<tr>
<td>HC lost per person</td>
<td>Productivity units/person</td>
<td>human capital/island population</td>
</tr>
<tr>
<td>---------------------</td>
<td>--------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Labor productivity</td>
<td>LOOKUP 1</td>
<td>[(0,0)-(2,3)],(0,0), (0.5,1),</td>
</tr>
<tr>
<td>HC per person</td>
<td></td>
<td>(0.7,1.4),(0.9,1.8), (1.2),(1.11927,2.18421), (1.21713,2.28947), (1.3737,2.42105), (1.5,2.5),(1.71621,2.68421), (1.84343,2.81579),(2,3)</td>
</tr>
</tbody>
</table>
Table 8. GDP Subsystem Equations

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Units</th>
<th>Equation</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDP</td>
<td>Dollars/year</td>
<td>(capital units<em>island population</em>labor productivity)*(IF THEN ELSE(resource shortage =1, NC used in products and services <em>NC productivity, NC consumption</em>NC productivity))/TIME STEP</td>
<td>Total production for the year. Complaint about its lack of dimensional analysis</td>
<td>Qureshi, 2008 &amp; 2009; Woodwell,1998; Guan et al, 2011; Dangerfield, 2007;</td>
</tr>
<tr>
<td>NC productivity</td>
<td>Dollar/gha</td>
<td>.05</td>
<td>Normal productivity of a gha</td>
<td></td>
</tr>
<tr>
<td>Total factor productivity</td>
<td>Dollars/capital units</td>
<td>.05</td>
<td>Normal productivity of an capital unit</td>
<td></td>
</tr>
<tr>
<td>Variable Name</td>
<td>Units</td>
<td>Equation</td>
<td>Description</td>
<td>Source</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>------------------------</td>
<td>--------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td><strong>Human Capital</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perceived attractiveness of HC</td>
<td>Productivity units/person</td>
<td>human capital/island population</td>
<td>Average HC per person – proxy for how good the schools are, how invested the community is, the health care available</td>
<td></td>
</tr>
<tr>
<td>Desired attractiveness of HC</td>
<td>Productivity units/person</td>
<td>1</td>
<td>Desired average HC/person</td>
<td></td>
</tr>
<tr>
<td>effect of HC attractiveness on In migration</td>
<td>LOOKUP</td>
<td>1</td>
<td>[(0,0)-(5,5)],(0.0),(0.5,0.7), (0.6,0.8),(0.7,0.9),(0.8,0.95), (1,1),(1.3,1.1), (1.6208,1.11842), (1.91131,1.14035), (2.30887,1.22807), (2.67584,1.31579), (3.16514,1.40351), (3.63914,1.51316), (4.05199,1.62281), (4.48012,1.79825), (5,2)</td>
<td></td>
</tr>
<tr>
<td>Effect of HC attractiveness on in migration</td>
<td>1</td>
<td>lookups[(0,0)-(5,2)],(0.2), (0.183486,1.97368), (0.29052,1.92982), (0.382263,1.84211), (0.6,1.6),(0.703364,1.34211), (0.795107,1.18421), (0.88685,1.05263), (1.1),(1.14679,0.921053), (1.3,0.9),(1.46789,0.885965), (1.65138,0.868421), (1.85015,0.77193), (2.03364,0.561404), (2.23242,0.377193), (2.44648,0.254386), (2.79817,0.157895), (3.40979,0.0877193), (4.98471,0.0526316)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>effect of HC attractiveness on outmigration</td>
<td>LOOKUP</td>
<td>1</td>
<td>effect of HC attractiveness on outmigration LOOKUP(ratio of desired and perceived attractiveness of HC benefits)</td>
<td></td>
</tr>
</tbody>
</table>

**Economic Capital**
<table>
<thead>
<tr>
<th>GDP/person</th>
<th>dollar/(Year*person)</th>
<th>GDP/island population</th>
<th>GDP per person</th>
</tr>
</thead>
<tbody>
<tr>
<td>perceived economic attractiveness</td>
<td>dollar/(Year*person)</td>
<td>GDP per person</td>
<td></td>
</tr>
<tr>
<td>desired economic attractiveness</td>
<td>dollar/(Year*person)</td>
<td>100000</td>
<td></td>
</tr>
<tr>
<td>ratio of desired and perceived economic attractiveness</td>
<td>1</td>
<td>perceived economic attractiveness/desired economic attractiveness</td>
<td></td>
</tr>
<tr>
<td>effect of EC attractiveness on In migration</td>
<td>1</td>
<td>[(0,0)-(5,2)],(0,0), (0.030581,0.350877), (0.107034,0.631579), (0.229358,0.789474), (0.382263,0.885965), (0.556749,0.947368), (0.749235,0.991228), (1,1),(1.26911,1.00877), (1.66667,1.01754), (2.07951,1.03509), (2.43119,1.08772), (2.85933,1.24561), (3.2263,1.38596), (3.65443,1.54386), (4.02141,1.70175), (4.40367,1.84211), (4.61774,1.90351),(5,2)</td>
<td></td>
</tr>
<tr>
<td>effect of EC attractiveness on Out migration</td>
<td>1</td>
<td>effect of EC attractiveness on In migration LOOKUP(ratio of desired and perceived economic attractiveness)</td>
<td></td>
</tr>
<tr>
<td>effect of EC attractiveness on Out migration</td>
<td>1</td>
<td>[(0.0)-(5,6)],(0.0152905,2), (0.183486,1.89474), (0.382263,1.73684), (0.489297,1.57895), (0.611621,1.39474), (0.779817,1.13158), (1.00917,1), (1.22324,1), (1.39144,0.973684), (1.59021,0.947368), (1.789899,0.815789), (2.04893,0.631579), (2.263,0.473684), (2.44648,0.394737), (2.76758,0.263158), (3.1043,0.210526), (3.8685,0.131579), (4.98471,0.0526316)</td>
<td></td>
</tr>
</tbody>
</table>

**Social Capital**
<table>
<thead>
<tr>
<th>desired social capital attractiveness</th>
<th>connections/people</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>effect of SC attractiveness on In migration</td>
<td>LOOKUP</td>
<td>[(0,0)-(5,5)],(0,0),(0.5,0.7), (0.6,0.8),(0.7,0.9),(0.8,0.95), (1.02446,1.0307), (1.26911,1.14035), (1.54434,1.40351), (1.80428,1.73246), (2.04893,2), (2.32416,2.03947), (2.59939,2), (2.85933,1.75439), (3.0581,1.33772), (3.3945,0.789474), (3.73089,0.482456), (4.28135,0.175439), (4.98471,0.0438596)</td>
</tr>
<tr>
<td>effect of SC attractiveness on In migration</td>
<td>LOOKUP</td>
<td>[(0,0)-(5,4)],(0,2), (0.183486,1.80702), (0.30581,1.63158), (0.443425,1.47368), (0.642202,1.31579), (0.795107,1.18421), (0.88685,1.05263), (1.1),(1.14679,0.921053), (1.3,0.9),(1.4,0.85), (1.5,0.75),(1.7,0.6), (1.9419,0.421053), (2.17125,0.289474), (2.40061,0.157895), (2.75229,0.0789474), (4.98471,0.0526316)</td>
</tr>
<tr>
<td>effect of SC attractiveness on Outmigration</td>
<td>LOOKUP</td>
<td>[(0,0)-(5,4)],(0.2), (0.183486,1.80702), (0.30581,1.63158), (0.443425,1.47368), (0.642202,1.31579), (0.795107,1.18421), (0.88685,1.05263), (1.1),(1.14679,0.921053), (1.3,0.9),(1.4,0.85), (1.5,0.75),(1.7,0.6), (1.9419,0.421053), (2.17125,0.289474), (2.40061,0.157895), (2.75229,0.0789474), (4.98471,0.0526316)</td>
</tr>
</tbody>
</table>

**Natural Capital**

<table>
<thead>
<tr>
<th>natural capital per person</th>
<th>Gha/person</th>
<th>natural capital/island population</th>
</tr>
</thead>
<tbody>
<tr>
<td>perceived environmental attractiveness</td>
<td>gha/person</td>
<td>natural capital per person</td>
</tr>
<tr>
<td>desired environmental attractiveness</td>
<td>gha/people</td>
<td>1000</td>
</tr>
</tbody>
</table>

This is enough for an individual’s children to sustain at a constant or slightly increased rate of
<table>
<thead>
<tr>
<th>ratio of desired and perceived environmental attractiveness</th>
<th>1</th>
<th>perceived environmental attractiveness/desired environmental attractiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>effect of NC attractiveness on in migration</td>
<td>1</td>
<td>[(0.0)-(5.5)],(0.0), (0.152905,0.0004386), (0.29052,0.001096), (0.443425,0.006579), (0.611621,0.109649), (0.764526,0.285088), (0.902141,0.438596), (1.05505,0.635965), (1.19266,0.877193), (1.39144,0.921053), (1.69725,0.986842), (2.07951,1.09649), (2.4159,1.20614), (2.82875,1.33772), (3.28746,1.4693), (3.76147,1.57895), (4.31193,1.75439), (5,2)</td>
</tr>
<tr>
<td>effect of NC attractiveness on in migration</td>
<td>1</td>
<td>effect of NC attractiveness on Immigration LOOKUP(ratio of desired and perceived environmental attractiveness)</td>
</tr>
<tr>
<td>effect of NC attractiveness on outmigration</td>
<td>1</td>
<td>[(0.0)-(5.2)],(0.0152905,2), (0.107034,1.89474), (0.229358,1.73684), (0.351682,1.57895), (0.489297,1.34211), (0.626911,1.15789), (0.795107,1.05263), (1,1),(1.22324,1), (1.4526,1), (1.69725,0.964912), (1.85015,0.877193), (1.97248,0.736842), (2.20183,0.570175), (2.49235,0.403509), (2.82875,0.298246), (3.18043,0.210526), (3.51682,0.166667), (3.8685,0.131579), (4.34251,0.0964912), (4.98471,0.0526316)</td>
</tr>
<tr>
<td>effect of NC attractiveness on outmigration</td>
<td>1</td>
<td>effect of NC attractiveness on outmigration LOOKUP(ratio of desired and perceived environmental attractiveness)</td>
</tr>
<tr>
<td>Variable Name</td>
<td>Units</td>
<td>Equation</td>
</tr>
<tr>
<td>-----------------</td>
<td>------------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Population</td>
<td>People</td>
<td>INTEG(in migration-out migration)</td>
</tr>
<tr>
<td>In migration</td>
<td>People/year</td>
<td>((effect of EC attractiveness on in migration<em>economic capital's weight on IM)+(effect of HC attractiveness on in migration</em>human capital's weight on IM)+(effect of NC attractiveness on in migration<em>natural capital's weight on IM)+(effect of SC attractiveness on in migration <em>social capital's weight on IM))</em>(normal in migration</em>island population)</td>
</tr>
<tr>
<td>Out migration</td>
<td>People/year</td>
<td>MIN(island population/TIME STEP, ((economic capital's weight on OM*effect of EC attractiveness on out migration)+(effect of HC attractiveness on out migration <em>human capital's weight on OM)+(effect of NC attractiveness on out migration</em>natural capital's weight on OM)+(effect of SC attractiveness on out migration *social capital's weight on OM))<em>normal out migration</em>island population)</td>
</tr>
<tr>
<td>normal in migration</td>
<td>1/year</td>
<td>.07</td>
</tr>
<tr>
<td>Normal EC in weight</td>
<td>1</td>
<td>.4</td>
</tr>
<tr>
<td>Economic Capital's Weight on IM</td>
<td>Max(normal EC in weight - natural capital's influence on other migration rates, 0)</td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Social Capital's Weight on IM</td>
<td>Max(normal SC in weight - natural capital's influence on other migration rates, 0)</td>
<td></td>
</tr>
<tr>
<td>Human Capital's Weight on IM</td>
<td>Max(normal HC in weight - natural capital's influence on other migration rates, 0)</td>
<td></td>
</tr>
<tr>
<td>Natural Capital's Weight on IM</td>
<td>(3 * natural capital's influence on other migration rates) + normal NC in weight</td>
<td></td>
</tr>
<tr>
<td>Natural Capital's Influence on Other Migration Rates</td>
<td>If then else(effect of NC attractiveness on in migration &lt; 0.25, 0.1, 0)</td>
<td></td>
</tr>
</tbody>
</table>

<p>| Normal Out Migration | 1/year | .05 |
| Normal EC Out Weight | 1 | .4 |
| Normal SC Out Weight | 1 | .1 |
| Normal HC Out Weight | 1 | .1 |
| Normal NC Out Weight | 1 | .4 |
| Economic Capital's Weight on OM | Max(normal social capital out weight - natural capital's influence on out migration rates, 0) |
| Economic Capital's Weight on OM | Max(normal EC weight - natural capital's influence on out migration rates, 0) |
| Normal EC Weight | normal EC out weight-economic |</p>
<table>
<thead>
<tr>
<th>Condition</th>
<th>Weight</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic condition on EC outmigration</td>
<td>1</td>
<td>IF THEN ELSE(effect of EC attractiveness on out migration&lt;0.3, 0.3, 0)</td>
</tr>
<tr>
<td>Human capital's weight on OM</td>
<td>1</td>
<td>MAX(normal HC out weight + natural capital's influence on out migration rates, 0)</td>
</tr>
<tr>
<td>Natural capital's weight on OM</td>
<td>1</td>
<td>MAX(normal NC out weight + (3 * natural capital's influence on out migration rates), 0)</td>
</tr>
<tr>
<td>Natural capital's influence on out migration rates</td>
<td>1</td>
<td>IF THEN ELSE(effect of NC attractiveness on out migration&gt;1.5, 0.1, 0)</td>
</tr>
<tr>
<td>Global population</td>
<td>people</td>
<td>INTEG(population added)</td>
</tr>
<tr>
<td>Population added</td>
<td>People/year</td>
<td>0.011 * global population / TIME STEP</td>
</tr>
<tr>
<td>Island population fraction of total population</td>
<td>1</td>
<td>island population / global population</td>
</tr>
<tr>
<td>Fraction of biocapacity consumed</td>
<td>1/year</td>
<td>NC used in products and services / natural capital</td>
</tr>
</tbody>
</table>
BIBLIOGRAPHY


Degrees:
Bachelors of Science, Business Administration
University of Illinois, Urbana- Champaign

Conference Presentations:
**Beck, Abby.** (March 17, 2012). Understanding Sustainability and Quality of Life. Poster presentation at the 2012 Graduate and Professional Student Association Research Forum, Las Vegas, NV.


Encyclopedia Entries:


Thesis Title:
Understanding Urban Sustainability and Quality of Life: A System Dynamics Approach

Thesis Committee:
Chairperson, Krystyna Stave, Ph.D.
Member, Robert Futrell, Ph.D.
Member, Alfredo Fernandez- Gonzalez
Graduate College Representative, Sajjad Ahmad, Ph.D.