Predicting and Measuring Systems Thinking about Climate Change among University Students

Thesis

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Abstract

Complex interactions among biophysical and social systems present challenges for environmental problem-solving. Addressing climate change is a prime example. Climate change can be described as a systems problem characterized by a highly interconnected system structure that produces undesirable outcomes. This complexity highlights the importance of employing systems thinking. Systems thinking departs from the traditional approach of breaking down a system into its separate components, and instead accounts for the complex and dynamic interactions between them, enabling the evaluation of outcomes of decisions and interventions at multiple scales. Accordingly, higher educational institutions are increasingly incorporating systems thinking in their curriculum and pedagogy to produce a qualified cadre of systems thinkers capable of addressing the complex problems they will encounter in their careers. More specifically, systems thinking has been identified as a fundamental element of environmental education as it trains students to integrate information across multiple scales, allowing them to develop effective solutions for today's multidimensional environmental challenges. However, there are still significant knowledge gaps on how to promote and assess systems thinking in formal educational settings.

This thesis contributes to the literature in several ways. In chapter two, I apply a systems approach to identify network-derived indicators of systems thinking by analyzing 35 cognitive maps of university students. The key contribution of this work is the development of a novel conceptual framework that integrates three fundamental

dimensions of systems thinking – system components, system structure, and system function. Using hierarchical clustering, I identify and distinguish between simple versus complex systems thinking based on how cognitive maps with similar results cluster together. Subsequently in chapter three, I examine how different factors pertaining to a student's academic background and training predicts them having more complex systems thinking. An understanding of the predictors of systems thinking can in turn guide the development of curricula, course material, and teaching strategies that foster systems thinking in a classroom.

The study's results reveal that most students are unable to produce a cognitive map that incorporates different aspects of climate change (dimension one) and fail to include substructures that indicate higher cognition of complex causality (dimension two). However, many students were able to connect the identified components in a logical manner suggesting understanding of system function (dimension three). Moreover, the results show that there is often a trade-off between the different systems thinking dimensions. Furthermore, the findings suggest that increased climate change knowledge positively predicted a student's ability to identify the different components of climate change while it negatively predicted their ability to connect them in a logical manner. More surprisingly, as students advance in their studies, they are less capable of identifying system function. Taken together, these findings highlight the value of using the multidimensional framework for measuring systems thinking which can serve as an evaluation tool for educational programs to identify gaps in students' systems thinking abilities and inform formal systems thinking teaching in higher education.

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Chapter 1: Introduction

1. What are Complex Systems?

In today's society, it doesn't take much for one to encounter a complex system. For example, the food and agricultural sector can be conceptualized as a complex system that is comprised of diverse groups of actors such as pathogenic bacteria, agricultural pests, consumers, farmers, and governments that interact across multiple scales creating feedback and interdependence between natural resources and human systems (IOM and NRC, 2015). Another example of a complex system is the healthcare industry which consists of evolving connections between individual agents and where rare and nondeterministic events take place leading to disruptions in the whole system, as was clearly demonstrated with the Covid-19 pandemic (Stevens et al., 2020). On a larger scale, interconnections between physical, biological, and social processes create complex subsystems within larger global complex systems (Donner et al., 2009).

A complex system is a "system composed of many interacting parts, often called agents, such that the collective behavior of those parts together is more than the sum of their individual behaviors" (Newman, 2011, p.1). The system's structure, the types of interactions and the emerging patterns that arise from these interactions define the system's collective behavior, also known as emergent behavior, and makes it challenging to understand, predict and manage the system (Herbert, 2006; Magee and de Weck, 2004). Complex systems science provides an approach of addressing complex systems by examining the interconnections between the system's components and their interactions with their environment, which helps to explain the collective behavior of the system (Bar-Yam, 2002). As a broadly interdisciplinary field, complex systems science is not a “monolithic body of knowledge” but rather consists of numerous theoretical and conceptual frameworks used for modeling and analyzing complex systems derived from a variety of disciplines, including computer science, mathematics, and ecology (Newman, 2011). However, as researchers applied a wide range of models and tools to understand complex systems, a core set of commonalities has emerged, which describe the fundamental tenets of complex systems including self-organization, emergence, non-linear dynamics, feedback, and adaptation (Turner and Baker, 2019).

Table 1.1: Characteristics of Complex Systems

Characteristic	Definition
Self-organization	“Individuals act in similar ways in proximity to and in concert with each other.” (Aritua et al., 2009, pp. 76–77)
Emergence	“Each organization’s internal dynamics affect its ability to change in a manner that might be quite different from other organizations.” (Lindberg and Schneider, 2013, pp. 231)
Non-linearity	“Small changes in the initial conditions or external environment can have large and unpredictable consequences in the outcomes of the system.” (Aritua et al., 2009, pp. 76–77)
Feedback	“Information is circulated, modified, and returned.” (Aritua et al., 2009, pp. 76–77)
Adaptation	“Open systems affect, and are affected by, external environmental systems. Open systems must be capable of reacting to changes in external environmental systems.” (Aritua et al., 2009, pp. 76–77)

2. The Complexity of Social-Ecological Systems

Over the last two decades, complex systems perspectives and insights are increasingly being applied to the study of social-ecological systems (Berkes and Folke, 1998; Holling, 2001; Liu et al., 2007; Levin et al., 2013). Social-Ecological Systems (SESs) are "ecological systems intricately linked with and affected by one or more social systems" (Anderies et al., 2004, p.2). Examples of social-ecological systems include coral reefs (e.g., Cinner et al., 2012), forests (e.g., Kalaba, 2014), and lake ecosystems (e.g., Nagendra and Ostrom, 2014). In each of these examples, the system is composed of many diverse natural systems (consisting of both biotic and abiotic components) and human systems (e.g., resource users, governments, organizations, etc.), which interact on multiple scales giving rise to the system producing and maintaining its own behavioral patterns (Preiser et al., 2018). In their seminal paper, Liu et al. (2007) highlight the key characteristics of complex social-ecological systems: nonlinear dynamics with spatial and temporal thresholds, reciprocal feedback between social and ecological processes, legacy effects and time delays, heterogeneity, resilience, and surprises.

The recognition of social-ecological systems as complex systems is critical to understanding macro-level system behavior which emerge from the local interactions between components on the micro-level. Moreover, understanding the complex systems characteristics of social-ecological systems and the ways in which these systems behave enables us to evaluate the outcomes of different management and policy interventions (Levin et al., 2013). While evident in many aspects of society, this is especially important as climate change leads to disruptions across a diverse set of systems. In Chapter 2, I describe how different social-ecological systems contribute to and are impacted by climate change, as well as how this phenomenon itself may be viewed as a complex system.

3. Systems Thinking – A Model for Managing Complexity

Conventional and reductionist frameworks, which have predominately been used in traditional sciences in the past, focus on understanding and managing a system's function by breaking it down into its smaller constituents (Zhang and Ahmed, 2020). Despite the former success it has had (e.g., understanding the chemical basis of biological processes), this approach falls short of solving today's most pressing issues as complex systems become more prevalent (Turner and Baker, 2019). In their paper, Zellner and Campbell (2015) argue that complexity is both the root of seemingly unsolvable problems and a mechanism to find a solution. Many scholars define this mechanism as systems thinking (e.g., Richmond, 1997; Maani and Maharaj, 2004; Meadows, 2008). Instead of looking at the individual components in isolation, systems thinking examines the system holistically to consider the interconnections between components, their interactions, and properties that emerge (Meinke et al., 2009).

The concept of "thinking in systems" began to gain popularity as early as the start of the 20th century when Ludwig von Bertalanffy, an Austrian biologist, proposed General System Theory (GST) to explain biological processes as more than the function of individual parts (Zhang and Ahmed, 2020). Since then, many scholars have applied systems thinking approaches to other disciplines including computer science, management, and environmental science. For example, in his book "The Fifth Discipline", Peter Senge (1990) identified systems thinking as an important discipline that organizations could adopt to create a learning organization, where employees continuously improve their ability to create the desired outcomes. In the context of environmental management, Donella Meadows, who identified herself as a systems thinker, used systems thinking approaches such as system dynamics modelling to examine the relationship between human populations, economic growth, and natural resources (Zhang and Ahmed, 2020).

With the application of systems thinking in many fields, a plethora of research focused on examining what systems thinking entails emerged in the literature. For example, Richmond (1997) identified seven thinking skills that are crucial for engaging in systems thinking: dynamic thinking, system-as-cause thinking, forest thinking, operational thinking, closed-loop thinking, quantitative thinking, and scientific thinking. Moreover, Goodman (2002) developed the Iceberg Model as a systems thinking tool for understanding the root cause of a specific problem. The model, which consists of 4 levels, assesses a particular event by examining the underlying patterns of behavior, system structure, and mental models.

With many different conceptualizations of systems thinking emerging in the literature, it has become a difficult concept to define and measure. Researchers have used a wide range of approaches and methods ranging from scenario-based assessments (e.g., Grohs et al., 2018) to using network analysis tools (e.g., Levy et al., 2018) to measure systems thinking. Yet, systems thinking assessment tools remain scarce and limited in the literature. This methodological gap in the literature is the motivation for Chapter 2.

4. Systems Thinking in Higher Education

The primary objective of education, particularly higher education, is to produce informed and responsible citizens who can make meaningful contributions to the betterment of society (Keniston, 1960). Higher education institutions are tasked with training the next generation of decision makers and problem solvers to advance frontiers of knowledge, perform effectively in the workforce, and become active members of their communities (Kromydas, 2017). However, to better prepare students for the complexity of the modern world, universities must now reconsider their academic goals in light of the challenging conditions that exist today. As a result, many institutions are now moving away from the traditional science curricula (with an emphasis on reductionist approaches) to incorporate formal systems thinking pedagogy into their educational programs and curriculum development (Elsawah et al., 2021).

Conventional science education emphasizes reductionist methods and simplistic thinking as means to reduce complexity (Forrester, 1993). Moreover, knowledge acquisition is usually fragmented whereby students learn concepts from different science subjects at varying stages throughout their academic journey without making connections between them (Zhang and Ahmed, 2020). However, natural processes are often explained by the same scientific laws and can relate to different scientific disciplines (e.g., physics, biology, chemistry). Furthermore, many of today's issues are multifaceted and interconnected, which requires students to integrate knowledge across multiple disciplines to understand and address the complex nature of real-world problems (Bililign, 2013). In that sense, it is essential for universities to equip students with interdisciplinary knowledge that combines a wide range of perspectives and approaches across different disciplines.

Achieving this goal may require a shift from fragmented learning approaches to those that emphasize interconnections and are consistent with systems thinking. Fostering systems thinking among students enhances their participation and engagement in the learning process, improves their decision-making and problem-solving skills, and enables them to integrate knowledge from different disciplines (Gray et al., 2019). The knowledge and skills gained through formal systems thinking can make students more competitive in the labor market, as companies are increasingly searching for qualified professionals capable of tackling complex challenges (Jaradat et al., 2020).

However, there are still knowledge gaps regarding how to develop and measure systems thinking among university students in formal education programs (Arnold and Wade, 2015). Questions remain on how to incorporate systems thinking pedagogy in curricula and course content, as well as how to support educators in teaching systems thinking. Moreover, there is limited understanding of what factors predict student engagement in systems thinking.

5. Research Overview

Guided by the several knowledge gaps highlighted above, the main research objective was to develop a multidimensional framework for measuring systems thinking that can be utilized as an evaluation tool in educational settings. Drawing on existing literature that uses network science and cognitive mapping, I identified network-derived indicators of systems thinking and organized them in a conceptual framework that incorporates three fundamental tenets of systems thinking: system components, system structure, and system function. By measuring systems thinking across different dimensions, it becomes possible to identify gaps in students' thinking skills which can then guide curriculum development and course content.

In Chapter 2, I delve deeper into why individuals struggle to grapple with complexity and further consider the benefits of engaging in systems thinking to understand complex systems and improve decision making. Furthermore, I examine existing systems thinking assessment tools and describe the proposed multidimensional framework for measuring systems thinking. I then apply the framework to measure systems thinking among university students, using climate change as a model.

In the subsequent chapter (Chapter 3), I shift my focus to the topic of systems thinking in higher education. I describe in greater detail the value of developing systems thinkers and examine current efforts to teach and assess systems thinking in a classroom. I then set out to examine how several factors pertaining to a student's academic training predicts their engagement in systems thinking.

Chapter 2: A Multi-Dimensional Framework to Assess Systems Thinking about Climate Change: A Cognitive Mapping Approach

1. Introduction

Increased temperatures, changes in precipitation patterns, and extreme weather events are just some of the significant climate change impacts facing societies today (IPCC, 2021). Significant barriers persist in mitigating and adapting to climate change, despite the increasing number of initiatives being carried out locally and globally to lessen its effects. These barriers can be attributed in part to the complex nature of climate change, which arises due to the interactions between the natural, built, and social systems that produce unpredictable behaviors and outcomes (Ingwersen et al., 2013). To better assess the risks associated with climate change and develop effective intervention measures on local and global scales, it is necessary to not only consider the individual systems in isolation but to account for how these systems interact and depend on each other (USGCRP, 2018).

So how does one even begin to grapple with the complexity of climate change? Although research has revealed numerous factors that influence climate change perception, including political orientation and knowledge (Smith and Mayer, 2019; Stevenson et al., 2018), recognizing the complex systems nature of climate change is essential for developing coherent understanding (McNeal et al., 2014).

Systems thinking has been proposed as a model for understanding and managing complex systems because it places equal importance on understanding the complex interactions between the system components as it does on understanding the components themselves (Sterman, 2000; Meadows, 2008; Meinke et al., 2009). In doing so, it becomes possible to holistically evaluate and predict system outcomes. Although numerous prior studies have analyzed systems thinking (e.g., Levy et al., 2018; Grohs et al, 2018; Gray et al., 2019; Dayarathna et al., 2021), there is limited consensus on how to evaluate systems thinking (Levy et al., 2018).

To address this gap, I build on emerging literature that uses network approaches, and more specifically cognitive mapping, to assess systems thinking. The study aims to achieve the following:

- Identify network-derived indicators of systems thinking.
- Develop a conceptual framework that organizes these indicators into qualitatively distinct dimensions of systems thinking.
- Illustrate the utility of the conceptual framework through application to assess systems thinking about climate change.

In the following sections, I provide an overview of the complex nature of climate change (Section 2.1) and the cognitive barriers to comprehension of its complexity (Section 2.2). I then introduce systems thinking and its benefits (Section 2.3), as well as review existing assessment tools that use a wide range of approaches for assessing systems thinking (Sections 2.4 and 2.5). Subsequently, I describe the multidimensional framework for measuring systems thinking using cognitive mapping (Section 3), present the methodology and results of its application (Sections 4 and 5 respectively), and discuss theoretical and practical implications of my research (Section 5).

2. Background

2.1 Climate Change as a Complex System

Climate change is the long-term change in average global weather patterns such as temperature and precipitation as a result of both biophysical and anthropogenic processes interacting across different spatial and temporal scales (IPCC, 2007). From an ecological perspective, the climate system is a complex system that consists of interconnected subsystems: the atmosphere, hydrosphere, biosphere, cryosphere, and lithosphere. Each subsystem is a complex system in and of itself with many components interacting together within and across system boundaries forming complex feedback loops (Donner et al., 2009). There is substantial evidence that the main driver of climate change in the last century is the increased emission of greenhouse gases resulting from human activities within different sectors (e.g., food industry, transportation, consumerism) (IPCC, 2021). Climate change has led to wide range of impacts on both components of social-ecological systems: the natural systems (e.g., land and soil, water resources, forests), and the social systems (e.g., agriculture). In addition to being impacted by climate change, these systems are interdependent and are also subjected to non-climate stressors (e.g., population growth, urbanization) (USGCRP, 2018). Collectively, these stressors reduce the resilience of social-ecological systems and impede their ability to adapt (Folke et al., 2016). In response to these impacts, policies and interventions that seek to reduce the negative impacts of climate change have been implemented at the micro- and macro-levels often requiring collaboration and coordination between different levels of stakeholders and sectors. Adding to the complexity of climate change are the temporal dynamics at play. For example, research shows that carbon dioxide accumulates in the atmosphere over time with emissions released today having the potential to have impacts multiple years into the future; it can take decades for warming and associated changes in weather patterns to occur (Zickfeld and Herrington, 2015). Furthermore, there is a time lag between the implementation of mitigation measures and the decrease in greenhouse gas concentrations (Tebaldi and Friedlingstein, 2013).

2.2 Cognitive Dimensions of Complexity

As complexity of a system increases, it becomes challenging for individuals to understand every aspect of the system. This is compounded by the fact that we live in a world with increasing dynamic complexity. Dynamic complexity describes the scope of unpredictable system-level behavior that results from the interactions of the system's components over time (Sterman, 2001). Grappling with this complexity is difficult for the human mind. As 'boundedly rational' individuals (Simon, 1972), we often operate with limited and/or imperfect information and poor scientific reasoning skills that hinder our ability to comprehend the structure and behavior of complex systems (Sterman, 2000). Moreover, we often rely on cognitive biases and heuristics to assess causal interactions which results in overlooking fundamental elements of dynamic complexity such as feedbacks, nonlinearities, and time delays (Sterman, 2001).

Climate change provides an excellent illustration of how cognitive biases and heuristics limit understanding of complex systems. When dealing with phenomena that involve stocks and flows, people typically use heuristics to identify correlations between variables and predict future outcomes (Chen, 2011). Because of the complex system characteristics of climate change, adopting these heuristics to understand climate change often leads to misconceptions. Research on climate change perception reveals that people struggle with understanding the phenomenon of accumulation (Sterman and Booth Sweeney, 2007; Pala and Vennix, 2005), which results in the common misassumption that a decline in emissions of greenhouse gasses results in a concomitant decline in concentrations of these gasses in the atmosphere and consequently an immediate decline in global temperature. Furthermore, construal level theory proposes that the more psychologically distant an object or event is from an individual's experience, the more abstract it becomes to them (Trope and Liberman, 2010). The use of temporal and spatial proximity cues to understand climate change has been shown to contribute to a common perception of climate change as an abstract threat that is more likely to impact distant regions and/or future generations (Sullivan and White, 2019).

The discrepancy between the nature of complex system dynamics and our cognition of them gives rise to policy resistance, which is when policies and interventions fail to achieve the desired outcome (Meadows, 2008), highlighting the need for fundamentally new ways of thinking and acting (Sterman, 2001; LeFay, 2006).

2.3 Systems Thinking

In response to the call for more effective approaches for addressing complex problems, systems thinking has emerged as a more holistic way of thinking that enables us to understand complex systems as more than the sum of their parts (Senge, 1990). Using systems thinking allows for greater understanding of the system components and their interactions to better predict and alter system behavior and outcomes (Meadows, 2008). Systems thinking has been applied in a wide range of disciplines and settings to improve decision-making processes. For example, in the field of organizational management, systems thinking is conceptualized as a problem-solving framework that can assist managers in understanding and evaluating organizational processes and outcomes by considering multiple and interacting root causes of complex managerial problems (Mehrjerdi, 2011). Moreover, systems thinking principles have been applied to and integrated with systems engineering, which focuses on the design and management of complex systems over their entire life cycles to produce superior systems and avoid catastrophic design failures (Monat and Gannon, 2018).

In the field of environmental management, the use of systems thinking facilitates better understanding and navigation of complex social-ecological systems (Assaraf and Orion, 2005; Hmelo-Silver et al., 2007). On a macro scale, applying systems thinking approaches allows for the evaluation of interdependencies among system components to assess how system behavior at one level can have cascading effects on natural and social systems across local and global levels (Levy et al., 2018). For example, Lawrence et al. (2020) apply critical systems thinking to assess the effect of cascading climate change impacts across various sectors including infrastructure and financial services and the resulting implications on their governance. On a more micro-level, research has revealed that understanding of system interconnections and function is necessary for individuals to engage in environmental conservation and adopt pro-environmental behaviors (Orion, 2002).

2.4 Measuring Systems Thinking

Despite growing interest in the application of systems thinking to guide problem-solving, there is no universal definition of systems thinking (Arnold and Wade, 2015) and no clear guidance on how systems thinking can be implemented (Monat and Gannon, 2018). Furthermore, methodological tools and approaches to measure systems thinking are underdeveloped and sparse in existing literature as measuring 'thinking' is a difficult task (Grohs et al, 2018). Rather, a diverse set of tools and methods have been used in attempt to assess systems thinking skills.

One category of methods is the use of self-assessment tools. For example, the Systems Thinking Scale (STS), widely administered to healthcare professionals to improve patient safety and care, is a 20-item instrument that uses a 5-point Likert scale (0=Never and 4=Most of the time) in questions about sequence of events, cause-effect relationships, and interactions among factors, resulting in a final score ranging between 0 and 80 with higher scores indicating more systems thinking (Dolansky et al., 2020). Moreover, the Systems Thinking Scale Revised (STSR) developed by Randle and Stroink (2012) is a 15-item instrument used to measure an individual's ability to acknowledge and understand complex adaptive systems and more specifically the interconnectedness of social-ecological systems. Since its development, STSR has been used in multiple studies (e.g., Davis and Stroink, 2015; Thibodeau et al., 2016).

Another approach to measuring systems thinking is the use of scenario-based assessment tools. In their study, Grohs et al. (2018) developed a community-level problem scenario and scored participant's written responses according to a scoring rubric that was iteratively produced from the responses. Scenario design was guided by a framework established by the authors that includes three dimensions – problem, perspective, and time. The rubric scored responses across seven constructs: problem identification, information needs, stakeholder awareness, goals, unintended consequences, implementation challenges, and alignment. In another study, the participants responded to a survey after taking part in an immersive real-word case scenario of large retail supply chain using virtual reality (Dayarathna et al., 2021). Responses were scored according to one scale (level of complexity) of a systems thinking skills instrument (Jaradat, 2015) that is composed of seven scales: level of complexity, level of interaction, level of independence, level of change, level of uncertainty, level of systems worldview, and level of flexibility.

2.5 Network Science and Cognitive Mapping

There is a growing body of literature that applies network analysis tools to measure systems thinking. Complex systems are often conceptualized as networks composed of many agents and are characterized by complex interactions and topology (Newman, 2011). Therefore, the use of network-derived tools such as cognitive mapping to measure systems thinking enables the assessment of one's understanding of system components and their interactions – key tenets of engaging in systems thinking. Cognitive maps are graphical representations of mental models through which an individual filters, processes and stores information which are then used to form understanding of the world and make decisions based on internal processing of this information (Gray et al., 2014). A cognitive map consists of system components represented as nodes and directed links between the nodes representing causal interactions (Levy et al., 2018).

In existing literature, systems thinking has been operationalized using cognitive mapping in two ways. The first approach analyzes a cognitive map based on its qualitative composition which relates to the different system components being represented in the map. For example, Attari et al. (2017) measured university students' systems thinking skills by comparing the students' cognitive map of their perception of water systems with an accurate diagram developed through expert elicitation. Each map was scored based on how many of the major categories identified by the experts were included in the student's map. A higher score revealed more understanding of system components and thus higher systems thinking skills.

Cognitive maps can also be analyzed in terms of their structural characteristics. Previous studies use network metrics (e.g., number of nodes, network density) to measure systems thinking (e.g., Gray et al., 2019; Olazabal et al., 2018). For example, Platt (2010) developed the Cognitive Mapping Assessment of Systems Thinking (CMAST) as a tool that allows researchers to evaluate individuals' cognitive maps in terms of number of components and patterns of causal connections between these components. Moreover, researchers have examined cognitive maps at a micro-level by looking at substructures within a cognitive map that embody complex causal connections (e.g., feedback loops) which reveal higher cognition of complex causality (Levy et al., 2018; Aminpour et al., 2021).

3. Conceptual Framework for Measuring Systems Thinking

With no consensus on how to conceptualize or evaluate systems thinking in the literature, methodological approaches are wide-ranging and diverse, as previously demonstrated. In their review of the systems thinking literature, Arnold and Wade (2015) state that a definition of systems thinking must encompass three fundamental tenets: elements, interconnections and a goal or function. I propose that this be extended not only to the definition of systems thinking, but also to its measurement. Therefore, I developed a Framework for Measuring Systems Thinking that includes three dimensions – System Components, System Structure, and System Function (Figure 2.1). Through the use of this multidimensional framework, we are able to capture qualitatively distinct aspects of systems thinking. Specifically, we gain insight into an individual's ability to identify and conceptualize the numerous components of a system (i.e., breadth of knowledge), to recognize the structural characteristics of complex interactions that are inherent to complex systems, and to conceptualize relationships among causal factors in a way that demonstrates in-depth understanding of how a system functions.

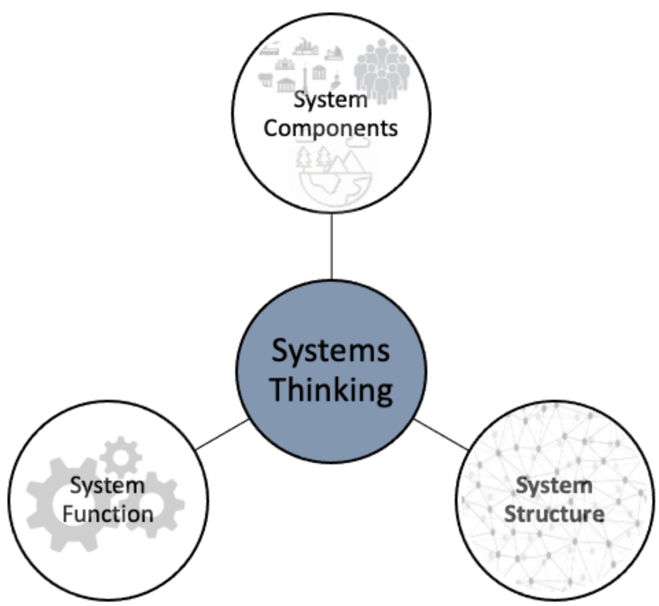

Figure 2.1: Conceptual Framework for Measuring Systems Thinking

3.1 Dimension One: System Components

Recognizing the diversity of components that make up the system is an important first step in engaging in systems thinking (Dugan et al., 2021). Research reveals that individuals who can identify a larger number of system components – for example, number of nodes in a cognitive map – are better able to comprehend the complexity of the system (Eden, 2004; Gray et al., 2019). I propose taking this idea a step beyond just counting the number of factors in a cognitive map by considering the domains within which these components fall under (e.g., natural, social, economic, political). This closely relates to the psychological construct of cognitive complexity, which describes an individual's ability to differentiate and integrate multiple perspectives when describing a topic (Bieri, 1955; Chen and Unsworth, 2019). When it comes to climate change perception, for example, a person with low cognitive complexity may consider only one perspective (anthropogenic activities or natural factors), while a person with high cognitive complexity considers the interaction of multiple types of factors (Chen and Unsworth, 2019).

Previous studies have examined the breadth of cognitive maps in terms of the number of domains or categories of the factors identified in the cognitive map. Examples include consideration of ecological and social factors in fisheries ecosystems (Aminpour et al., 2021), categories of processes in water systems (Attari et al., 2017), and types of issues in engineering problems (engineering, environmental, business, social, ethical, cultural, and political issues) (Rehmann, 2011). Some scholars have suggested that cognitive complexity (illustrated by an increased number of factors perceived to be associated with a topic) is synonymous with systems thinking (Cabrera et al., 2022), I believe that it is necessary for systems thinking but is only one part of the equation since systems thinking moves beyond just looking at the factors to consider the interactions between them.

3.2 Dimension Two: System Structure

Engaging in systems thinking also requires understanding of the system structure in terms of identifying specific dynamics and interactions between the various components (Levy et al., 2018). The second dimension is structural in nature as it considers the topology of causal connections in a cognitive map irrespective of its qualitative composition. Although there are many ways to analyze the structural characteristics of a cognitive map (e.g., density, centralization, transitivity, etc.), I examine the structure of a map at a micro-level by measuring the extent to which it incorporates specific network motifs. Motifs are the building blocks of complex networks and are specific patterns of connections between a small number of nodes (Milo et al., 2002). Existing literature identifies several motifs that indicate higher cognition of complex causality, including bidirectionality, feedback loops, multiple effects, and indirect effects (Figure 2.2) (Levy et al., 2018; Aminpour et al., 2021).

Complex systems, and more specifically complex social-ecological systems, are governed by nonlinear system dynamics (Liu et al., 2007). Comprehending this complexity is challenging as individuals tend to interpret processes using linear and hierarchical causal structures which leads to a failure in recognizing more complex causal relationships (Plate, 2010). One example is the lack of understanding of feedback processes within a system. Feedback loops are the basic operating unit of a system through which long-term consistent system behavior is maintained (Meadows, 2008). According to research, people consistently overlook feedback processes in their mental models, therefore cognitive maps that incorporate feedback loops exhibit more complex causal thinking (Levy et al., 2018; Aminpour et al., 2021). While incorporating more complex motifs in a cognitive map does not necessarily translate into better understanding of system outcomes, it does indicate more complex thinking.

Moreover, adopting linear causal models leads to the assumption that single causes produce single effects, however in complex systems, causes often join together to produce multiple effects (Meadows, 2008). In their study, Levy et al. (2018) apply construal level theory to argue that effects are often few and abstractly defined in cognitive maps compared to causes which are numerous and more concretely depicted. Hence constructing a 'causal web' in which one cause might have multiple effects is more suitable for grappling with complexity (Plate, 2010).

Through rational thinking, we learn to follow direct relationships from cause to effect, neglecting the influence of indirect effects in the process, and as a result, indirect effects are frequently underrepresented in cognitive maps (Meadows, 2008; Levy et al., 2018). Indirect effects, defined as the effect of one causal variable on an outcome variable mediated by a third variable (Thrash et al., 2019), are common in complex social-ecological systems (Li et al., 2020b). For example, a reduction in abundance of one plant species because of climate change, may lead to an increase in another plant species due to reduced competition (Li et al., 2020a). Therefore, it is imperative to understand indirect interactions among and between natural and social processes to improve the effectiveness of conservation and management initiatives (Li et al., 2020b).

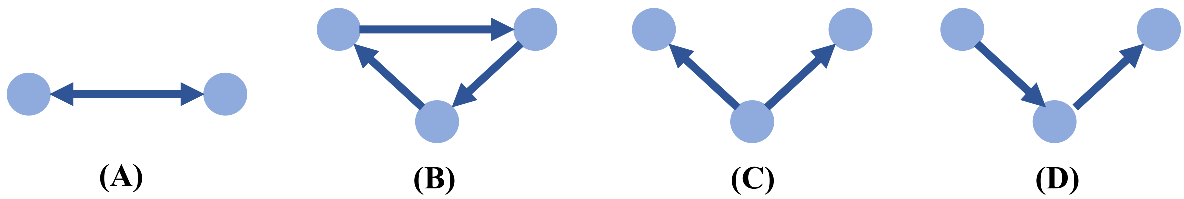

Figure 2.2: Micro-level network motifs that signify complex patterns of causality.
(A) Bidirectionality (reciprocal pair), (B) Feedback Loops (cyclic triple), (C) Multiple Effects (out star), and (D) Indirect Effects (two path)

3.3 Dimension Three: System Function

A system's function is the most essential determinant of its behavior, despite being the most difficult component to detect (Meadows, 2008). Functions can be understood as the outcomes of the system depending on its components and the interactions among these components (Gray et al., 2019). In their paper, Gray et al. (2019) operationalize system function as the system's dynamic behavior by testing 'what if' scenarios using fuzzy cognitive mapping, a semi-quantitative cognitive mapping method in which systems are depicted as directed and weighted networks. However, I conceptualize system function as the ability to predict system outcomes by identifying cause-effect relationships in a logical way, a fundamental step in understanding system dynamics (Lagnado et al., 2007), with the assumption that the logical arrangement of relationships is suggestive of systems thinking. For example, industrial agriculture significantly contributes to the emission of greenhouse gases leading to rising temperatures and anthropogenic climate change, which ultimately reduces crop yields and exacerbates food insecurity (Moore et al., 2017; Lynch et al., 2021). In response to low food security, advocacy groups can mobilize to promote policy change to limit greenhouse gas emissions by engaging in policy debates. Engaging in systems thinking means understanding how different system components (both causes and effects) interact to produce a system behavior that leads to desirable or undesirable outcomes.

4. Methods

To illustrate the framework, I applied it to a dataset of students' cognitive maps that documented their understanding of relationships among causal factors that relate to climate change. The following section describes the data collection process, the operationalization of the three systems thinking dimensions, and the data analysis method conducted to distinguish between simple and complex systems thinking.

4.1 Data Collection

Between March and April of 2021, interviews (n=35) were conducted with undergraduate and graduate students at a large public Midwestern university in the United States using a student subject pool, which was approved by the university's Institutional Review Board (ID: 2021E0150). The student subject pool provides students an opportunity to gain extra class credits by participating in scientific studies.

As part of the interview, participants took part in a cognitive mapping exercise using an online software (https://www.mentalmodeler.com/). During the exercise, students were asked to identify quantitative factors related to their perception of climate change as well as draw causal linkages indicating the type of relationship (positive or negative) between these factors. Participants were prompted (but not required) to identify variables relating to causes, impacts, and responses to climate change across different dimensions (e.g., ecological, biological, social, political, economic). The duration of the cognitive mapping exercise ranged from 6 minutes to 41 minutes, with an average of 22 minutes (SD=8.024) for the entire study population.

4.2 Measurement of Systems Thinking Dimensions

<u>Dimension One: System Components</u>

To capture the components of the system across different dimensions, the factors featured in each cognitive map were coded according to three sets of classes developed specifically for this study. First, I classified the factors according to their parent classes. The parent classes draw upon the DPSIR framework, which is widely used to assess and manage environmental problems and involves the identification of cause-effect relationships between natural and human processes (Bradley and Yee, 2015). The framework was slightly modified to render it more suitable for my study system. To further narrow down the set of ecological and social variables, I assigned all factors in each parent class to a child class. Table 2.1 lists examples of factors classified based on their parent and child classes (refer to Appendix A for complete list of parent and child classes). Finally, factors were classified according to their domain class: Individual human level (e.g., adopting a plant-based diet), Social (e.g., social justice), Economic (e.g., industrialization), Political (e.g., political conflict), and Biophysical (e.g., water quality). Moreover, factors that were unclear and open to multiple interpretations were coded as ambiguous for the child and domain classes, and were excluded from the analysis. By accounting for all the distinct sets of classes, I have focused on capturing the comprehensiveness of the cognitive map and the student's ability to include all or nearly all components of the system.

Table 2.1: Examples of factors classified as parent and child classes

Parent Class	Child Class	Example
Driving Forces	Natural driver	Volcanic eruptions
	Individual behavior driver	Meat consumption
	Industrial driver	Manufacturing and production
State	Physical state	Melting of glaciers
	Biological state	Biodiversity
Impact	Human impact	Quality of life
	Economic impact	Water affordability

Dimension one was operationalized using two measures: (1) number of classes identified per each set of classes, and (2) diversity index per each set of classes to account for the number of classes identified relative to all classes within that set. Drawing upon the work of Morales et al. (2021) which describes the use of different diversity indices for network data, the Shannon Evenness Index (SEI) was calculated for each set of classes to capture both the 'richness' and 'evenness' of factors across the different classes. SEI ranges from 0 to 1 where 1 is reached when factors are spread equally across all classes. Figure 2.3 shows two examples of cognitive maps that differ in the number and diversity of domain classes incorporated.

$$SEI = \frac{-\sum(Pi \times \ln(Pi))}{\ln(m)}$$

where P_i = relative proportion of a particular class, m = number of all classes in a set.

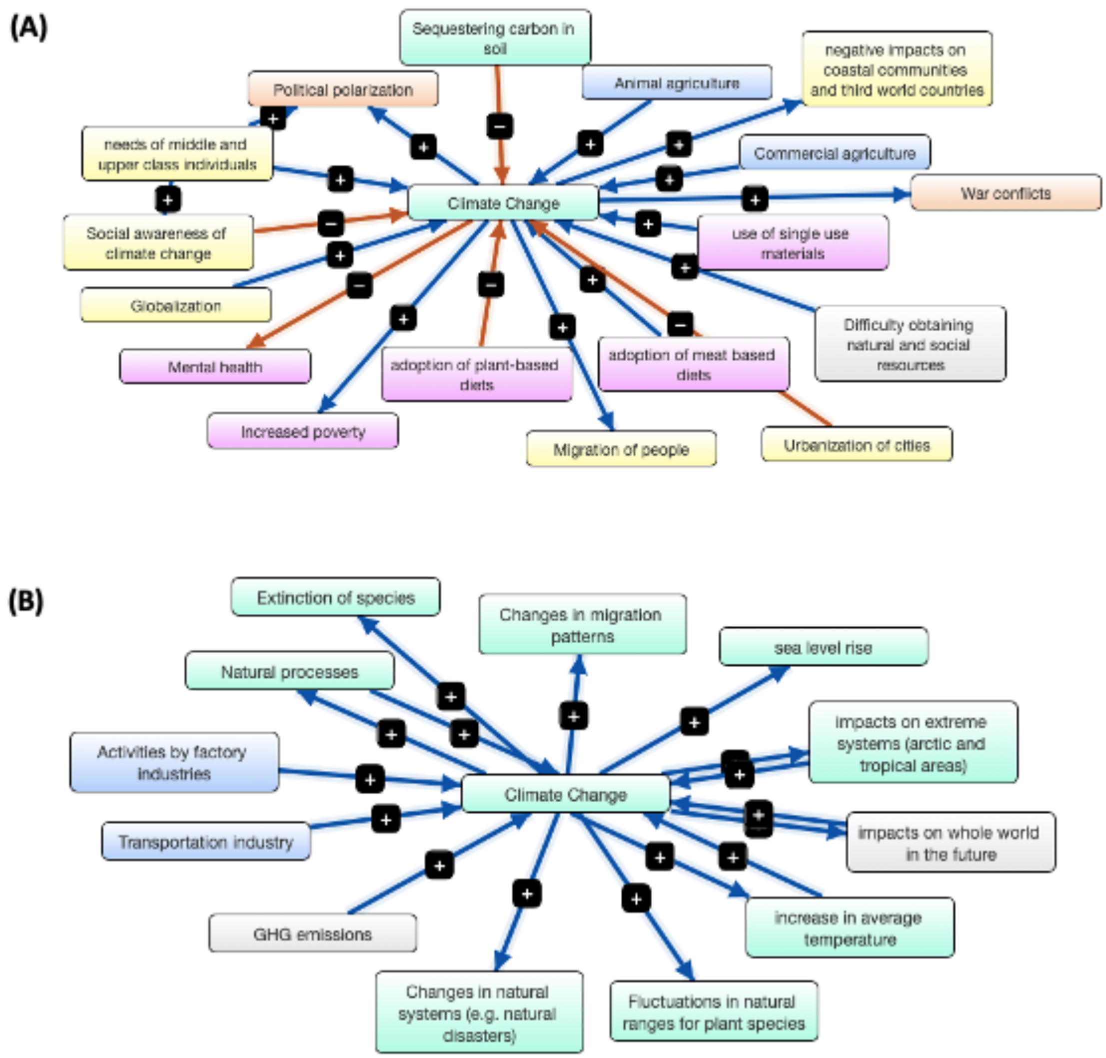

Figure 2.3: Examples of cognitive maps that vary in the number and diversity of domain classes. Map (A) includes 5 domain classes: individual human (pink), social (yellow), biophysical (green), economic (blue), political (orange). While map (B) only includes 2 domain classes: biophysical and economic. Some concepts (grey) were not coded due to their ambiguity, and thus excluded from the analysis.

<u>Dimension Two: System Structure</u>

The second dimension focuses on the structural characteristics of the cognitive map in terms of the prevalence of causal substructures indicative of cognition of complex causality. The prevalence of these substructures in a cognitive map is highly correlated with other structural characteristics (e.g., number of nodes and linkages). Thus, to compare between cognitive maps, I measure the prevalence of each of the four motifs described earlier using baseline modeling, an approach that was similarly adopted by Levy et al. (2018) and Hamilton et al. (2019). Specifically, I estimate separate Exponential Random Graph Models (ERGMs) for each cognitive map network and then use these models to simulate large numbers of networks (n=5000) with similar structural characteristics of each empirical network (i.e., of the same size and density while also controlling for isolates). This approach allows us to compare the count of observed motifs in an empirical network with the distribution of counts in simulated networks and then calculate corresponding z-scores which are used to compare cognitive maps. For example, a z-score greater than zero indicates that a cognitive map has a larger number of reciprocal pairs (representing bidirectionality) compared to the average of the distribution of counts in random networks of the same size and density.

Dimension Three: System Function

System function was operationalized as connecting factors in a logical manner according to their parent class. Figure 2.4, which draws on the DPSIR framework (Bradley and Yee, 2015), was developed to visualize, and organize cause-effect connections between parent classes in a meaningful way.

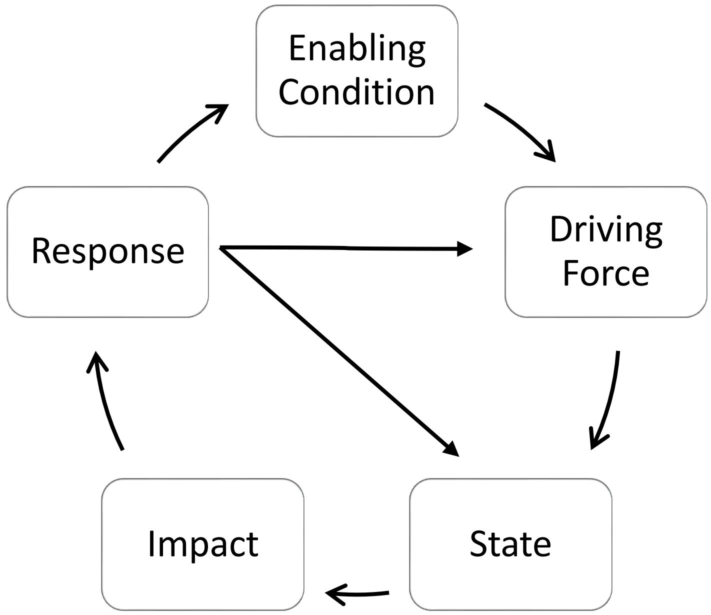

Figure 2.4: Proposed structure depicting relationships between parent classes.

To measure system function, first I scored dyads (a link between two nodes) based on whether they are consistent with the proposed figure to capture simple cause-effect relationships. Secondly, I examined path lengths of 3 (which would include 4 nodes and up to 4 parent classes) to capture higher-order relationships and assigned each path length a score out of 1 depending on how many of the 3 connections in the path length follow the logical arrangement of connections in the proposed figure.

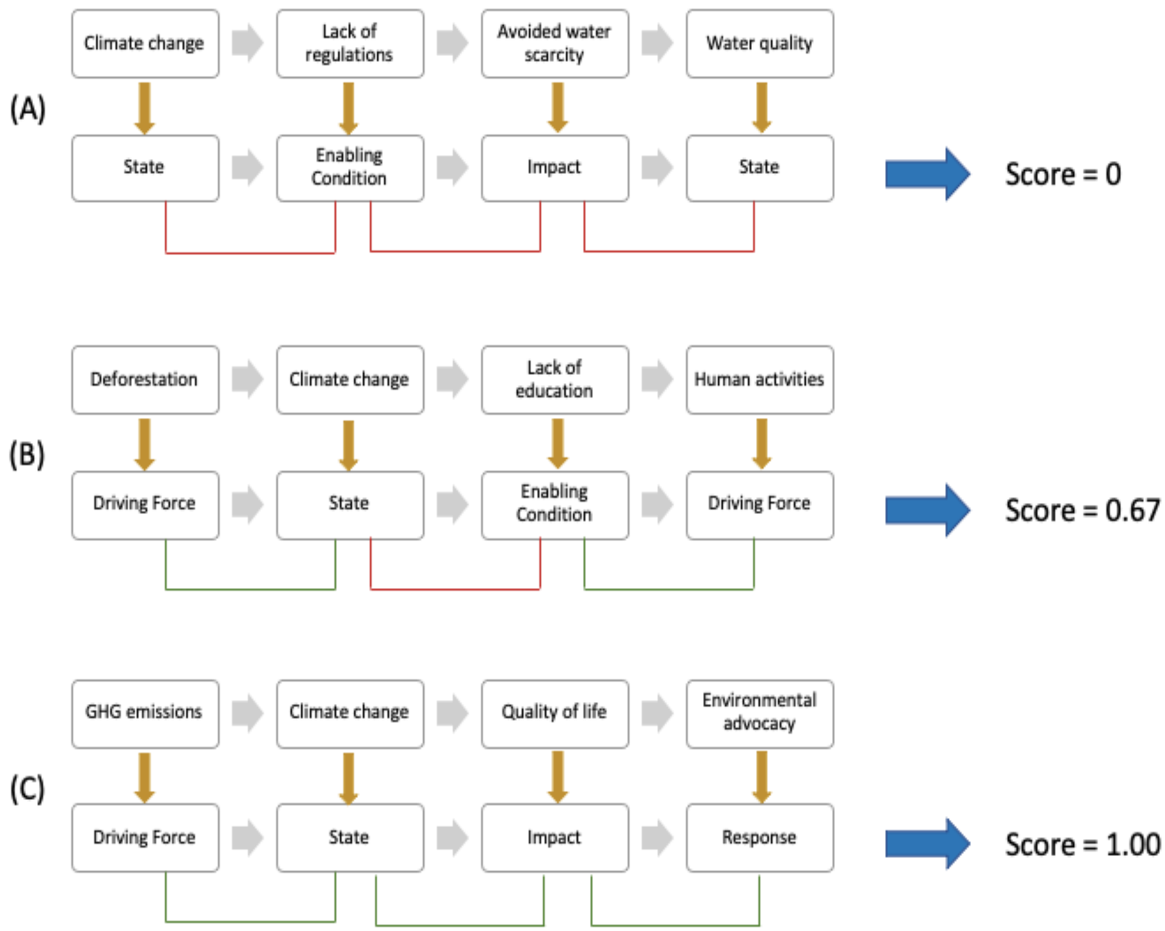

Figure 2.5: Examples showing how different path lengths were scored.
In (A), the student connects an enabling condition (lack of regulations) directly to an impact (avoided water scarcity) neglecting to identify a driving force and the resulting change in state, therefore the connection is scored as incorrect. In (B), the student correctly connects a driving force to a change in state, and an enabling condition to a driving force. However, they incorrectly connect a change in state to an enabling condition. While in (C), the student correctly identifies a driving force that leads to a change in state leading to an impact.

4.3 Clustering Analysis

To distinguish between cognitive maps with simple and more complex systems thinking, hierarchical clustering was performed for each dimension to group together maps that have similar results. In this context, complex systems thinking is defined as the extent to which a cognitive map: (1) includes a larger number of classes (dimension one), (2) has a higher prevalence of motifs indicative of cognition of complex causality (dimension two), and (3) scores higher in terms of logically connecting factors together (dimension three). Hierarchical clustering is a form of exploratory data analysis where observations are divided into clusters that share common characteristics. Clusters are formed based on dissimilarity (Euclidean distance = $\sqrt{(\Sigma(x_i-y_i)^2)}$) between both rows and columns of a data matrix such that each additional observation minimizes the sum of squared Euclidean distances within clusters (Murtagh and Legendre, 2014; Levy et al., 2018). To compute the distance between indicators with different scales, values are standardized using the following equation $x_{standardized} = (x - mean)/standard\ deviation$.

Table 2.2: Summary of systems thinking indicators and their measurements

Dimension	**Systems Thinking Indicator**	**Measurement**
Dimension One: System Components	Number of parent classes	Count between 1 – 5
	Number of child classes	Count between 1 – 23
	Number of domain classes	Count between 1 – 5
	Diversity of parent classes	Value ranges from 0 to 1
	Diversity of child classes	Value ranges from 0 to 1
	Diversity of domain classes	Value ranges from 0 to 1
Dimension Two: System Structure	Prevalence of reciprocal pairs (Bidirectionality)	$Z - score = \frac{x - mean}{SD}$
	Prevalence of cyclic triples (Feedback loops)	x = count of motif in empirical network
	Prevalence of out stars (Multiple effects)	mean = average count of motif in random networks
	Prevalence of two paths (Indirect effects)	SD = standard deviation of count of motif in random networks
Dimension Three: System Function	Dyads average score	Score ranges from 0 to 1
	Path length of 3 average score	Score ranges from 0 to 1

5. Results

The heatmaps in Figure 2.6 illustrate the results of hierarchical clustering for each dimension. Each heatmap distinguishes between simple (i.e., maps with lower values across systems thinking indicators) vs. complex systems thinking (i.e., maps with higher values across systems thinking indicators). The dashed lines depict how the dendrogram was cut to differentiate between the two clusters.

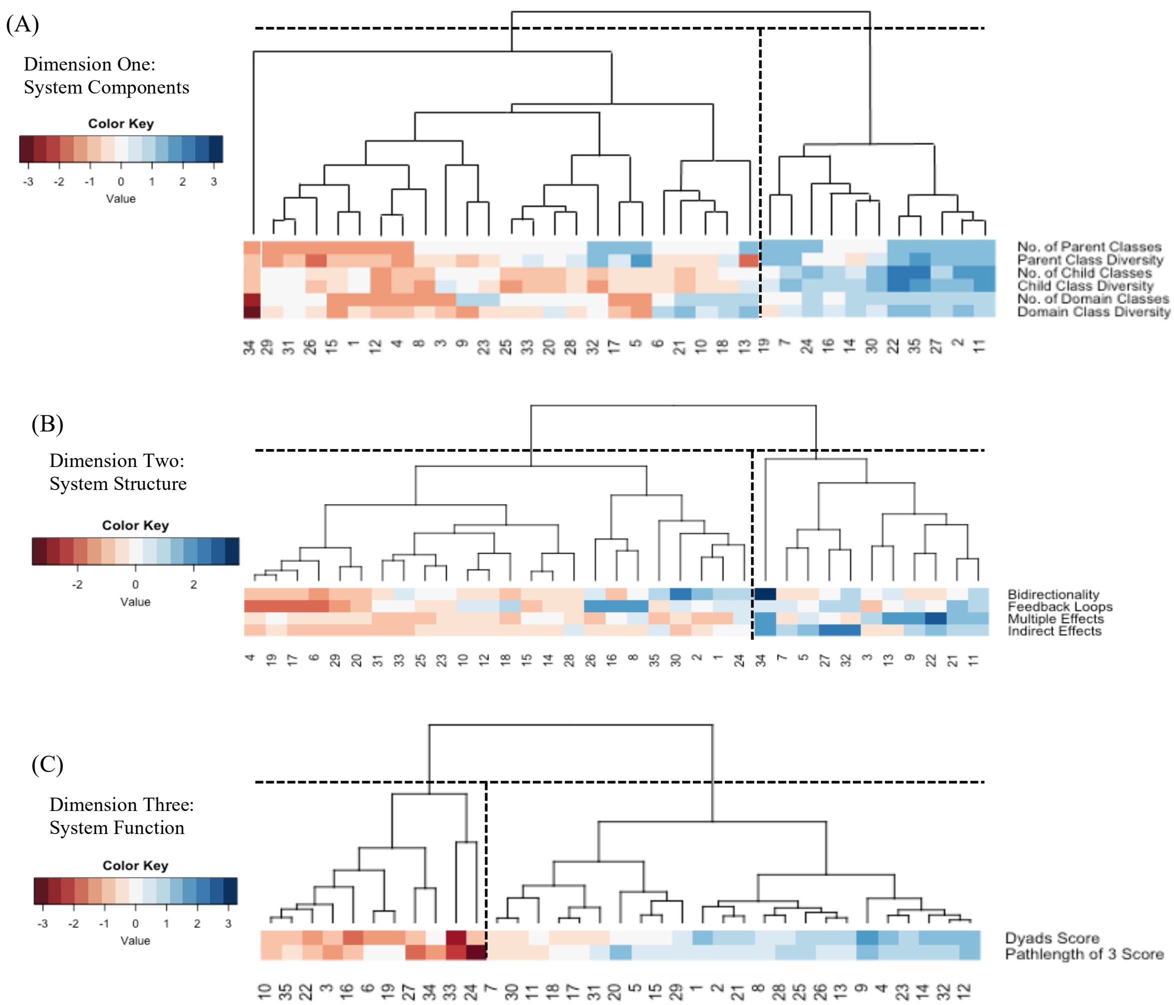

Figure 2.6: The three heatmaps depict cognitive maps for each subject (numbered), clustered on the systems thinking indicators across the three dimensions. Cells with darker blue colors indicate higher values on the different measures (after standardization), while cells with darker red color indicate lower values.

For dimension one (figure 2.6.A), students in the first cluster (right; complex systems thinking) identify a larger number of classes and have greater diversity indices for all three sets of classes, whereas students in the second cluster (left; simple systems thinking) either have greater number of classes and diversity indices for only one of the sets or lesser values across all three sets. Table 3 summarizes the results of systems thinking indicators for dimension one.

Table 2.3: Summary of dimension one results for high and low systems thinking clusters

	n	No. of Parent Classes	Parent Classes Diversity	No. of Child Classes	Child Classes Diversity	No. of Domain Classes	Domain Classes Diversity
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Complex Cluster	11 (31%)	4.73 (0.47)	0.88 (0.09)	10.82 (1.60)	0.72 (0.05)	4.73 (0.47)	0.83 (0.07)
Simple Cluster	24 (69%)	3.83 (0.70)	0.73 (0.10)	6.00 (1.12)	0.52 (0.05)	3.83 (0.87)	0.66 (0.15)

For dimension two (figure 2.6.B), the first cluster (right; complex systems thinking) differs from the second cluster (left; simple systems thinking) in that it includes cognitive maps that have higher prevalence of at least two of the four complex motifs compared to random networks of the same size and density. Although some cognitive maps in the simple systems thinking cluster incorporate bidirectional effects and feedback loops, multiple effects and indirect effects were largely absent in these cognitive maps.

For dimension three (figure 2.6.C), the heatmap distinguishes between students who connect parent classes in a logical manner and those who do not follow the proposed arrangement of parent classes as depicted in figure 2.4. On average, students in the complex systems thinking cluster (right) score 0.87 (SD=0.07) for dyads and 0.92

(SD=0.07) for path lengths of 3. While students in the simple systems thinking cluster (left) have an average score of 0.70 (SD=0.07) for dyads and an average score of 0.70 (SD=0.13) for path lengths of 3.

The findings suggest that engagement in systems thinking falls on a continuum ranging from simple to progressively more complex systems thinking as more dimensions are recognized. As depicted in figure 2.7, students were classified into four categories depending on whether they fall under simple versus complex systems thinking cluster for each dimension: category one – simple systems thinking across all dimensions, category two – complex systems thinking in one dimension, category three – complex systems thinking in two dimensions, category four – complex systems thinking across all dimensions.

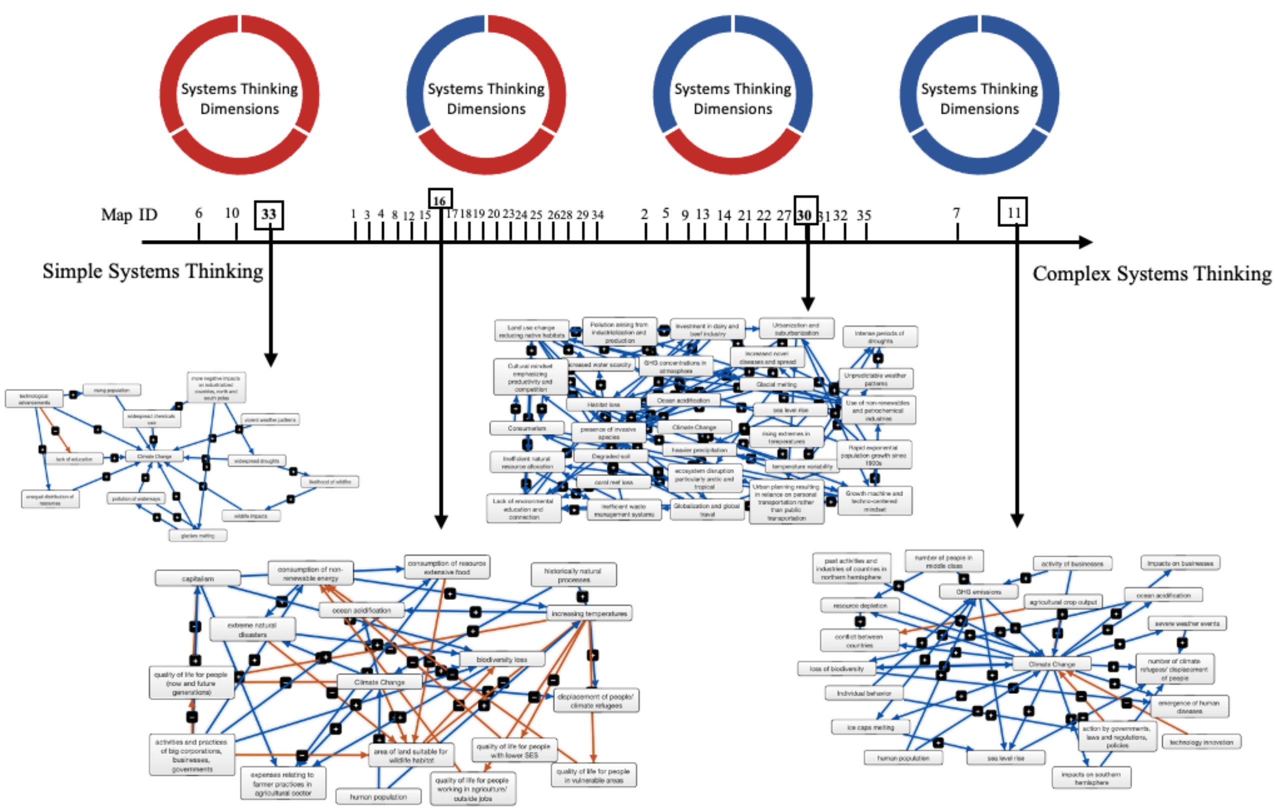

Figure 2.7: Examples of cognitive maps for each category on the continuum ranging from simple to complex systems thinking.

6. Discussion

6.1 Theoretical Implications

Motivated by the methodological gap in literature, the study's main objective was to expand emerging literature that utilizes a network approach to operationalize systems thinking by developing a conceptual framework that assesses systems thinking through multiple lenses. The multidimensional approach integrates fundamental systems thinking skills – the ability to identify system components, structure, and function – to provide a more holistic and rigorous assessment that departs from prior literature's use of single or composite measures. It's important to mention that the accuracy of the cognitive maps (i.e., the correctness of the concepts included and their interconnections) was not considered as systems thinking does not involve reaching a 'correct' answer but rather focuses on grasping the complex nature of the issue at hand. The findings provide valuable insights on how individuals grapple with different dimensions of system complexity. To demonstrate the use of the systems thinking assessment tool, I used climate change as an example of a complex system and analyzed the cognitive maps of university students to assess their engagement in systems thinking to understand climate change.

I found that most students are unable to produce a comprehensive cognitive map that includes all or nearly all aspects of climate change but rather tend to focus on one subsystem (i.e., natural or social) while ignoring others. One potential explanation for this finding is that individuals focus on concepts and processes that they are familiar with and fall within their domain expertise (e.g., social sciences students concentrate on the social dimension of climate change). This is in line with findings from a study with local fisheries stakeholders which found that groups' specialized interests and skills shape the qualitative composition of their cognitive maps (Aminpour et al., 2021).

The result show that complex motifs are often underrepresented in cognitive maps and only a small portion of students incorporate more of the complex substructures. This finding is consistent with other studies that have measured the prevalence of complex motifs in cognitive maps as an indicator of higher cognition of complex causality (Levy et al., 2018; Aminpour et al., 2021). However, the results differ from those in the study by Levy et al. (2018) in that bidirectional effects and feedback loops are still represented in some of cognitive maps in the simple systems thinking cluster while their results revealed that cognitive maps often lacked both of these complex motifs and were incorporated primarily in the complex systems thinking cluster.

As for dimension three, the results indicate that a large proportion of students connect concepts in a logical order, which indicates an understanding of system function based on the sequence of perceived causal connections among climate change drivers, environmental stressors, and climate change impacts on natural and human systems. Organizing key components of complex social-ecological systems in a logical sequence contributes to effective evaluation of consequences of alternative environmental management decisions by linking human and ecological processes to ecosystem condition (Bradley and Yee, 2015).

One of the most important findings from my study is that individuals who fall in the complex (or simple) systems thinking cluster in one dimension do not necessarily fall in the same cluster for the other two dimensions. In fact, across all dimensions, only two fall in the clusters defined by most complex while just three students demonstrated the most simple systems thinking. The highest proportion of the students had mixed results with over half falling under the complex systems thinking cluster for one dimension and under the simple systems thinking clusters for the other two dimensions, while the remaining belong to the complex systems cluster in two dimensions and the simple systems thinking cluster in one dimension. These results suggest the possibility of trade-offs between the different systems thinking dimensions, which can be explained by the fact that we as humans are boundedly rational and have limited capacities, thus the more parts of the system we recognize the harder it becomes to logically connect all the parts together. For example, if an individual identifies numerous drivers of climate change (both natural and anthropogenic) (i.e., greater number of components in their cognitive map), it becomes difficult to understand how these drivers interact to produce multiple or indirect effects on ecological and human systems. Whereas an individual who identifies few causes may be able to think more clearly about how these drivers combine to affect social-ecological systems.

6.2 Practical Implications

Many of the existing systems thinking assessment tools employ self-assessment questionnaires to measure systems thinking using single or composite measures (e.g., Davis and Stroink, 2012; Dolansky et al., 2020). This method fails to consider key characteristics of systems thinking such as the ability to recognize the diversity of system components, complex systems dynamics, and the overall system-level behavior. Moving away from these traditional assessments, the approach of using cognitive mapping provides an innovative method for assessing systems thinking with potential for applicability into many significant issues of today. More specifically, cognitive mapping is gaining popularity as a decision-making tool in environmental management as these maps can embody the characteristics of complex social-ecological systems (Gray et al., 2015). For example, social-ecological systems consist of many interacting natural and human components and are characterized by interdependence and nonlinear dynamics such as feedback loops (Liu et al. 2007; Levy et al., 2018), both of which can be directly measured in cognitive maps. Assessing people's understanding of the system structure and dynamics, which are key components of engaging in systems thinking, are fundamental steps for addressing social-ecological change and resilience (Folke, 2006). For example, agricultural professionals and farmers need to consider interdependencies among system components (e.g., effect of farming practices on wild fauna which in turn affects agricultural habitats) to adopt "biodiversity friendly" farming practices (Vuillot et al., 2016). By engaging in systems thinking, they can consider cascading effects that have an impact on components other than those immediately involved and enables them to focus on the most critical components of the system to make a particular decision (Levy et al., 2018).

Moreover, the findings of my study demonstrate the value of employing this framework as an assessment tool in educational contexts. Many interdisciplinary sustainability programs have identified developing students' systems thinking skills as a core requirement to equip students with the skills necessary to address the ill-structured problems they will encounter in their careers (Wiek et al., 2011). However, there remains a gap in how to assess systems thinking skills among students. The framework can be used as tool to measure students' ability to engage in systems thinking across multiple dimensions, revealing gaps in their thinking abilities that can be addressed through improvements of program curricula development and teaching methods. The application of the framework in an educational setting will be explored more in Chapter 3.

6.3 Recommendations for Future Research

The objective of this study was to fill a gap in the literature on methods to assess and measure systems thinking by developing a novel conceptual framework that incorporates three fundamental dimensions of systems thinking – system components, system structure, and system function. However, this work does not come without its limitations.

First, I used a convenience sample of university students who are either enrolled in or taking courses offered by an environment and natural resource program at a large public university, thus there is an assumption that they possess more knowledge on climate change than the general population, and that they are already being trained to think in systems since many environment and sustainability programs are incorporating systems thinking in their curriculum (Vincent and Focht, 2011). I recommend future studies to apply the assessment tool with different population groups (e.g., policymakers, practitioners, resource users) to measure their systems thinking. The framework can also be used in comparative studies to compare the ability to engage in systems thinking across different groups (e.g., experts and novices).

Second, measuring systems thinking is challenging and limited, and a wide range of methodologies have been employed in attempt to measure it ranging from self-assessment surveys to task performance as proxy measures. Although my approach of using cognitive maps is a valuable tool to gauge an individual's ability to grapple with the complexity in terms of system structure and dynamics, I did not measure cognition of key characteristics of complex systems such as time delays, thresholds, and trade-offs. This limitation can be overcome in future research by combining my approach with other methods such as written and verbal assessments that delve deeper into other indicators of complex systems thinking.

Moreover, it's important to note that there are external factors that might influence the formation of an individual's cognitive map. For example, the number of concepts and connections included in the cognitive map is significantly affected by the interviewer's skills and the interview structure itself (Eden, 2004). Considering that a student subject pool was used, study participants were required to complete the cognitive mapping exercise in a specific timeframe. While some students did not utilize the entire allotted time, there were still instances where the exercise had to be cut short due to time constraints. Furthermore, the cognitive mapping exercise followed a semi-structured format where students were asked prompting questions pertaining to different aspects of climate change (e.g., causes, effects). Due to this, some study participants needed more prompting than others. Collectively, these factors might have affected the complexity of the resulting cognitive map and are important to control for and/or be taken into consideration in future research.

Finally, there is an assumption that systems thinking leads to better outcomes (e.g., effective decision-making, better performance, improved behavior) (Maani and Maharaj, 2004; Bosch et al., 2007). Although testing this assumption is beyond the scope of my research, I recognize the need to explore the link between applying systems thinking in different contexts and the resulting outcomes. Moreover, more research is required to determine when, to whom, and under what circumstances systems thinking should be promoted. For example, do environmental managers who adopt systems approaches succeed in managing a natural resource effectively? Do students with more complex systems thinking perform better in problem-solving tasks? Does a lay person need to engage systems thinking to adopt pro-environmental behaviors?

7. Conclusion

Addressing today's most critical global issues in a complex world that is made up of distinct yet highly interconnected subsystems, both environmental and social, is becoming more difficult. Tackling these issues in isolation will almost certainly fail. Rather a systems approach is required to uncover the moving elements, interactions, and interdependencies at play. However, assessing systems thinking is a challenging endeavor. Building on emerging literature, I developed a multidimensional framework for measuring systems thinking using cognitive mapping. The framework assesses systems thinking along a continuum, from simple to more complex systems thinking, depending on an individual's ability to identify the numerous system components, the complex interactions between them, and their ability to organize them to predict system function. While the framework is not meant to be a comprehensive list of systems thinking indicators, I believe my approach is an effective method for assessing systems thinking from multiple lenses by integrating the three dimensions that are relevant to systems thinking.

Chapter 3: Predicting Systems Thinking about Climate Change in Higher Education

1. Introduction

Current global environmental challenges such as climate change and water scarcity continue to grow in complexity in a rapidly changing and highly interconnected world. Such challenges have proven difficult to manage as a result of the complex nature of the social-ecological systems in which they are embedded (Levin et al., 2013). Developing effective policy solutions and interventions requires a shift from the traditional and linear way of thinking to a more holistic approach that considers the broader social, economic, political, and ecological contexts (Wulun, 2007; Grohs et al., 2018). Systems thinking has been proposed as an alternative paradigm that equips individuals with the necessary skills to grapple with the complexity of social-ecological systems and improve decision-making ability (Maani and Maharaj, 2004; Bosch et al., 2007; Fazey, 2010; Lezak and Thibodeau, 2016). As a result, employers are increasingly seeking out qualified professionals who possess such systems thinking skills required to address today's complex issues (Jaradat et al., 2020). In fact, in the report "The Future of Jobs" published by the World Economic Forum (WEF) in 2016, critical thinking and systems skills were highlighted as essential in the future workplace (WEF, 2016).

In response to the call for a more qualified cadre of systems thinkers in today's workforce, many educational institutions are emphasizing the importance of equipping students with systems thinking skills through formal education and curriculum development, starting from K-12 education (e.g., Jurewics, 2013; Vachliotis et al., 2021) to higher education (e.g., D'Eon, 2017; Gilbert et al., 2018). Moreover, higher education institutions play an integral role in preparing the next generation of policymakers, practitioners, researchers, and educators capable of addressing the complex problems they will encounter throughout their careers (Grohs et al., 2018). More specifically, systems thinking has been identified as an important prerequisite of environmental education since it is a key element for analyzing complex environmental problems and developing effective solutions (Vincent and Focht, 2011). For example, specific emphasis is placed on introducing systems thinking in teaching climate change (Roychoudhury et al., 2017). The complexity of climate change necessitates advanced cognitive abilities in order to comprehend it (Grotzer and Lincoln, 2007). Therefore, systems thinking can facilitate understanding climate change as a complex system and the intricate interplay between biophysical and anthropogenic processes across many spatial and temporal scales (Roychoudhury et al., 2017; McNeal et al., 2014).

However, questions on how to develop and evaluate the effectiveness of courses, program curricula, and teaching methods in promoting a systems approach to understand complexity remain unanswered (Arnold and Wade, 2015). Moreover, there has been minimal research into how programs and courses are designed to help students develop systems thinking skills. Systems thinking assessment tools and frameworks are required to help universities better design courses and programs that foster systems thinking skills without overloading cognition which can act as a barrier to effective learning (Gray et al., 2019). Furthermore, evaluating the development of students' systems thinking skills ensures that learning outcomes are in line with the specific requirements of today's job market (Grohs et al., 2018), and enhances systems-oriented instruction (Plate, 2010).

The main objective of this study is to address the knowledge gap highlighted above through the application of the conceptual framework for measuring systems thinking (described in the previous chapter). The assessment evaluated systems thinking about climate change on a continuum ranging from simple to more complex systems thinking by measuring network-derived indicators of systems thinking across three dimensions – system components, structure, and function. This study builds on the previous chapter by examining what factors pertaining to academic training predict indicators of systems thinking. In doing so, the conceptual framework can serve as an evaluation tool for educational programs to inform curricula design and teaching strategies that foster systems thinking by identifying gaps in students' thinking abilities.

In the following sections, I describe the importance of developing students' systems thinking skills, the predictors of systems thinking, and review existing systems thinking assessment tools in educational contexts. I then present and discuss the results of this study, with particular focus on practical implications for educational programs and recommendations for future work.

2. The Importance of Training System Thinkers

In a fast-moving and highly interconnected world, we are surrounded by complex systems everywhere. Examples of complex systems include the Internet, economic and financial systems, transportation and telecommunication infrastructures, and entire cities and communities (Newman, 2011). Moreover, social-ecological systems are increasingly being understood as complex systems (Liu et al., 2007; Levin et al., 2013). A prime example of that is the application of complex systems principles to the study of earth's climate system and climate change (e.g., Donner et al., 2009; Jacobson et al., 2017). Given the complex nature of climate change that arises due to the interactions between natural and social systems, more emphasis is being placed on not only improving students' climate literacy but also on training students to understand complex systems concepts (e.g., feedback, nonlinearity, thresholds) (Plate, 2010; McNeal et al., 2014).

However, learning about complex systems is a difficult task. Research indicates that students often struggle to comprehend concepts and principles of complexity science (Hmelo-Silver and Azevedo, 2006; Jacobson and Wilensky, 2006; Scherer et al., 2017). For example, students tend to adopt a mono-causal linear thinking to explain causal relationships that exist in complex systems (Raia, 2005; Plate, 2010), and thus ignore the dynamic and unordered nature of complex systems (Orion and Libarkin, 2014). Moreover, students tend to learn in fragments, failing to connect isolated pieces of information together which inhibits a coherent and cohesive understanding of complex phenomena (Raia, 2005). As a result of the challenges of learning about complex systems, students develop inaccurate and incomplete mental models (e.g., Sterman, 2008; Attari et al., 2017; Dauer et al., 2019). These challenges are also applicable when learning about climate change. In their paper, Roychoudhury et al. (2017) reveal that students do not comprehend climate as a system, but rather have fragmented and inaccurate knowledge on climate change (e.g., lack of distinction between climate and weather, and failure to recognize spatial-temporal dynamics). Therefore, there is a need to train students to shift from a linear and compartmentalized way of thinking to a more holistic approach to understand the intricate characteristics of complex systems. Paul and Elder (2002, para. 10), support this notion, writing "Can we deal with incessant and accelerating change and complexity without revolutionizing our thinking? … the problems we now face, and will increasingly face, require a radically different form of thinking, thinking that is more complex, more adaptable, and more sensitive to divergent points of view."

For many, the answer lies in systems thinking (e.g., Pavlov et al., 2014; Gilbert et al., 2018; Elsawah et al., 2021). Systems thinking has been promoted as a model to understand complexity and facilitate problem-solving and decision-making (Jaradat et al., 2020). First, systems thinking requires students to consider the dynamic interactions between system components, rather than examine the components in isolation, in order to understand and predict the behavior of the system as a whole (Meadows, 2008). Because the scale and complexity of global challenges can cognitively overwhelm students, leading to confusion and indifference, the ability to methodically identify system components and dynamics improves student engagement and participation (Hicks and Bord, 2001; Gray et al., 2019). Secondly, systems thinking improves students' problem-solving skills and their capacity to develop effective solutions through the evaluation of trade-offs between alternative intervention measures implemented within the system (Gray et al., 2019). For complex problems, there is rarely one optimal solution, instead, several options with drawbacks must be explored (Jaradat, 2015). The goal of employing systems thinking is not to come up with the 'correct' answer but to examine expected system behavior and all possible outcomes in order to generate solutions that achieve the desired outcome while minimizing adverse negative impacts (Grohs et al., 2018). Finally, complex problems are interdisciplinary in nature and require integrating knowledge across natural and social scientific disciplines (Mathews and Jones, 2007). Systems thinking bridges disciplines by enabling students to connect concepts and theories learned in diverse courses to better comprehend how natural and social systems work and interact to produce the observed system outcomes (Gray et al., 2019). When learning about climate change, systems thinking could potentially enable students to consider the complex interactions (e.g., nonlinear feedback loops) between natural and anthropogenic drivers of climate change, understand the spatial and temporal dimensions of cause and effect, evaluate trade-offs among alternative mitigation and adaptation measures, and make informed decisions that positively impact the environment and society, both locally and globally (Roychoudhury et al., 2017).

2.1 Teaching Systems Thinking in Higher Education

Although the benefits of training students to be systems thinkers continues to be highlighted in recent literature, there are still significant gaps in identifying effective systems thinking teaching strategies (Arnold and Wade, 2015). However, universities are increasingly adopting different approaches of incorporating systems thinking in their curricula and coursework to equip students with the knowledge and skills required to address today's social, economic, and environmental needs. For example, Mathews and Ford (2008) adapted an undergraduate economics course to include a systems thinking unit which introduces systems thinking concepts, computer simulation of systems, and causal mapping. While the study did not assess students' systems thinking skills, the authors state that both students and faculty members benefited greatly from the revised course content in terms of learning effective methods to teach systems thinking and improving students' understanding of complex relationships between stakeholders. A similar approach was adopted by Gilbert et al. (2018) who developed a systems thinking module in three courses (environmental science, oceanography, and climate science) as part of InTeGrate – a collaborative project aimed at supporting undergraduate geoscience education. Their study revealed that students who completed the module performed significantly better on systems thinking assessments than those who did not. These examples provide guidance on how to actively integrate systems thinking in formal education.

However, little research has been conducted to examine how programs and courses are designed to promote students' systems thinking skills. In other words, what factors pertaining to a student's academic background predict their systems thinking skills? In my exploratory study, I examine how different factors influence a student's ability to engage in systems thinking in relation to climate change. I specifically focus on variables related to students' program of study, interdisciplinarity, years of study, exposure to coursework, and climate change knowledge. The student's area of study as well as the knowledge and skills they gain through the various courses they take might play an important role in developing their systems thinking abilities.

Program of Study

The Next Generation Science Standards identified systems and system modeling as a cross-cutting concept that is vital for science education (NGSS Lead States, 2013). Accordingly, and irrespective of academic discipline, undergraduate and graduate programs are urged to integrate systems thinking into their curricula. For example, systems thinking is considered a fundamental skill for Science, Technology, Engineering, and Mathematics (STEM) students which promotes active learning, increases student engagement with STEM content, and facilitates higher order thinking (York et al., 2019). Moreover, systems thinking concepts are increasingly being applied to the development of the natural and social sciences (Jackson, 2001; Papero et al., 2018). Furthermore, many environmental and sustainability science programs identify systems thinking as a core competency for students to be able to understand the complexity of coupled human-nature systems (i.e., social-ecological systems) (Vincent and Focht, 2011; Wiek et al., 2011). I investigate how academic programs promote the development of systems thinking skills in students.

Interdisciplinarity

Introducing interdisciplinary approaches in higher education curriculum design provides students with knowledge and skills that span multiple dimensions, allowing them to develop effective solutions for ill-structured problems (Ashby and Exter, 2019). In particular, it is frequently regarded as a desirable component of environmental education as it trains students to integrate information across spatial, temporal, and societal scales to address multidimensional environmental challenges (Vincent and Focht, 2011). This is emphasized in the report issued by the National Science Foundation Advisory Committee for Environmental Research and Education, which calls for the development of interdisciplinary educational approaches to better understand the complex interactions in social-ecological systems which are necessary to meet society's most pressing needs (AC-ERE, 2009). I assess whether enrolling in interdisciplinary programs fosters systems thinking and helps students connect concepts across multiple disciplines.

Years of Study

In their paper, Gray et al. (2019) suggest that systems thinking is not present or absent at any given moment in time, but rather develops gradually as students gain new knowledge and make connections throughout their learning process (Dauer and Long, 2015). For example, Felder and Solomon (1988) found that a single three-credit course aimed at introducing principles of general systems theory was inadequate for freshman students to develop thinking skills necessary to understand complex concepts. In the context of teaching climate change, Roychoudhury et al. (2017) recommend gradually introducing systems thinking at the appropriate level of the climate system framework developed by Shepardson et al. (2012) which depicts the external and internal drivers of climate change, and their connections to external responses and climate variability. In my study, I test the effect of the number of years spent in school on students' capacity to engage in systems thinking.

Exposure to Coursework

Climate change education is an important component of any environmental science program (Aksit et al., 2018). More importantly, it is critical to strengthen students' understanding of the Earth as a system as it is imperative for solving environmental problems (Scherer et al., 2017; Roychoudhury et al., 2017). In their systematic literature review, Scherer et al. (2017) identified four systems thinking frameworks that are utilized in geoscience education for undergraduates: Earth systems perspective, Earth systems thinking skills, complexity sciences, and authentic complex Earth and environmental systems. Knowledge of climate change and complex Earth processes can be acquired in coursework through classroom instruction and discussion (McNeal et al., 2014). In this project, I study how exposure to climate change science in coursework affects students' systems thinking skills.

Knowledge about Climate Change

In recent years, a plethora of research has focused on understanding how climate change knowledge affects perception and behavior (e.g., Hamilton, 2011; Shi et al., 2015; Stevenson et al., 2018). In their work, Stevenson et al. (2018) argue that increased climate change knowledge is positively correlated with increased climate change concern which in turn predicts positive changes in pro-environmental behavior. While it is important to understand how knowledge influences perception and individual behavior, it is also important to recognize that in order to make informed decisions one must engage in some level of systems thinking to identify components and interconnections of a complex and dynamic issue (Attari et al., 2017). My study aims at examining whether increased knowledge on climate change enables students to engage in systems thinking.

2.2 Assessing Students' Systems Thinking

Several assessment tools that utilize a variety of approaches and methods have been developed in response to the need to assess students' systems thinking skills. These assessments can be categorized as either self-assessment tools in which students reflect on and rate their perceived ability to engage in systems thinking, or instructor assessments which evaluate student performance on specific systems thinking tasks (Hu and Shealy, 2018). For example, Camelia and Ferris (2018) developed a self-report instrument to measure students' systems thinking in the context of systems engineering education. The 16-item questionnaire uses a seven-point Likert scale (ranging from "very untrue" to "very true") to assess students' engagement in systems thinking across three dimensions: theoretical (inclination towards having a whole system perspective), methodological (interest in the application of the whole system under consideration), and practical (inclination towards finding a system-level solution). Although self-assessment tools have been proposed as a way to get around some of the practical and financial drawbacks of other assessment methods (Moore et al., 2017), they nonetheless have several limitations of their own. For example, self-estimates of cognitive abilities are not reliable indicators of cognitive function as studies have shown that they are weakly to moderately correlated with performance-based cognitive abilities (e.g., Freund and Kasten, 2012; Visser et al., 2008).

As for instructor assessments, different approaches have been used to assess systems thinking including scenario-based assessments and cognitive mapping. In their study, Hiller Connell et al. (2012) developed two case studies that illustrate real-world sustainability issues. Using a structured rubric, the authors scored students' responses to a set of questions on a scale of zero (no skill) to 5 (exceptional skill) and assessed their systems thinking based on their holistic thinking and conflict resolution skills. In another study, students were required to read material about the connection between climate change impacts and terrorism and then reflect on the reading and develop a cognitive map that represents their understanding of the subject (Gray et al., 2019). The authors proposed pairing the cognitive maps with student writing to assess systems thinking across four dimensions: system structure, system function, leverage points, and trade-offs. The use of cognitive mapping to measure systems thinking has been highlighted in the literature (e.g., Attari et al., 2017; Levy et al., 2018), as it facilitates the assessment of one's understanding of system components and structure which are integral to systems thinking (Arnold and Wade, 2015).

3. Methods

3.1 Data Collection

As previously described in chapter two, 35 interviews were conducted with undergraduate and graduate students at a large public university in the United States using a student subject pool. Table 3.1 describes demographic characteristics of study population. During the interview (refer to Appendix B for protocol), students answered questions pertaining to their academic background (e.g., major, minor, exposure to climate change science in coursework), climate change knowledge, and demographics. Following that, students took part in a cognitive mapping exercise during which they mapped out their conceptualization of climate change.

Table 3.1: Characteristics of Study Population

	N (total = 35)	% of total sample
Age		
18 – 22 years	30 (mean = 20.1)	86%
>23 years	5 (mean = 26.2)	14%
Gender		
Female	26	74%
Male	8	23%
Non-binary	1	3%
Political Orientation		
Democrat	22	63%
Independent	10	28%
Other	1	3%
Not political	2	6%
Education Level		
First-year	4	11%
Second-year	12	34%
Third-year	11	32%
Fourth-year	4	11%
Masters	2	6%
PhD	2	6%
International	1	3%

3.2 Predictors of Systems Thinking: Independent Variables

Program of Study

During the interview, study participants indicated their major and minor (if applicable). Students were enrolled in a variety of programs in the sciences and humanities (refer to Figure 3.1 for distribution of majors and minors across academic disciplines). However, it was challenging to classify students by academic discipline because many are pursuing multiple majors and/or minors that cover different disciplines. Moreover, to the authors' knowledge there is no universal standard to classify academic programs as many academic institutions take different approaches when establishing their program classification scheme (e.g., based on research approaches, or how faculty work in their departmental groups) (Stark, 1998). To overcome some of these challenges, each student was given an aggregate score out of 1 for each academic discipline depending on their major(s) and/or minor(s) (all scores add up to 1). For graduate students, I considered both their undergraduate and graduate programs to account for all training they obtained throughout the years. Table 3.1 shows different examples of how students were scored. I specifically examined how enrollment in an applied sciences program influences systems thinking skills. I adopted a focus on applied sciences as these programs tend to be problem-oriented and act as a bridge between pure sciences and practice through the application of scientific knowledge and theories to develop solutions to real-world problems (e.g., engineering, environmental science).

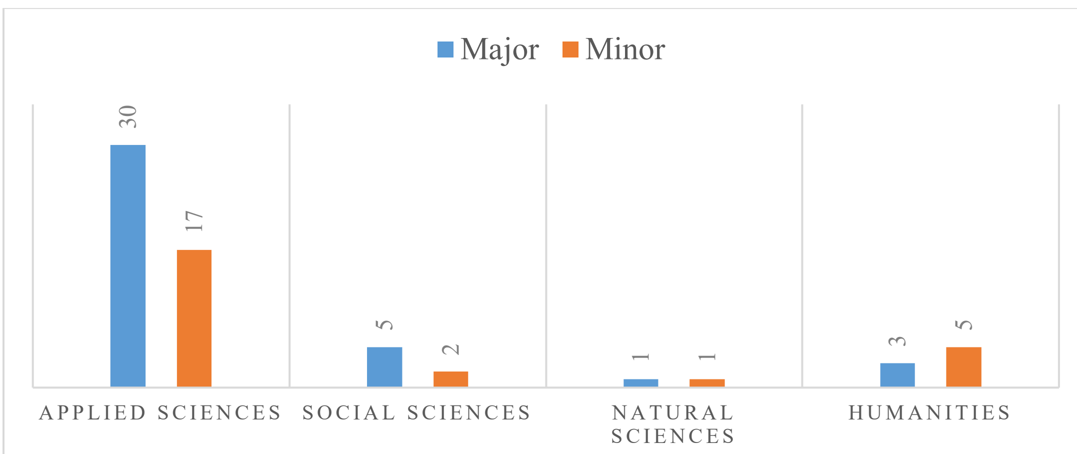

Figure 3.1: Distribution of majors and minors across academic disciplines.

Table 3.2: Examples of how students were scored based on their major and/or minor

Student #1 – Undergraduate	**Major:** Environmental Science	**Applied Sciences Score:** 1.00
Student #2 – Undergraduate	**Majors:** Environment, Economy, Development and Sustainability **Minor:** Spanish + Leadership Studies	**Applied Sciences Score:** 0.75 **Humanities Score:** 0.25
Student #3 – Graduate	**Major:** Evolution & Ecology **Minor:** Forestry, Fisheries & Wildlife + Studio Art **Graduate Program:** Evolution & Ecology	**Natural Sciences Score:** 0.66 **Humanities Score:** 0.17 **Applied Sciences Score:** 0.17

Interdisciplinarity

Interdisciplinary undergraduate degrees that aim to help students synthesize knowledge and skills from multiple disciplines around a specific subject are becoming more widespread (Onsman and Newton, 2015). The goal of these programs is to prepare students for their professional careers by training them to apply scientific knowledge to develop practical solutions to real-world problems which is achieved through interdisciplinary curricula and linkages with the professional world (Stark, 1998; Shaw, 2022).

Interdisciplinary programs were identified in two stages. First, I browsed each program's website and identified the ones that are explicitly described as being interdisciplinary in nature. Subsequently, I downloaded the curriculum of each program and examined whether it incorporates courses that span multiple disciplines. The General Education courses, which are required for all students, were not taken into consideration. All applied sciences programs were coded as interdisciplinary as they offer courses that integrate theories and methods across disciplines as well as focus on real-world applications. Programs that are specialized within a broader discipline (e.g., psychology, music, languages) were coded as not interdisciplinary with the exception of International Relations, Geography and Environmental Social Sciences as these programs are inherently interdisciplinary. Each student was scored depending on whether their major(s), minor(s) and/or graduate program is an interdisciplinary program (minors received half-points). Scores were normalized by dividing the total score by the number of degrees being pursued by the student. For example, a student majoring in environmental science and minoring in political sciences receives a score of 0.67 while a student majoring in environmental science and minoring in business administration receives a score of 1.00. Refer to Appendix C for a complete list of programs of students who participated in the study, and the classification of these programs according to discipline and interdisciplinarity.

Years of Study and Exposure to Coursework

During the interview, students were asked when they planned to graduate. Accordingly, the number of years they spent in university was calculated. For example, if an undergraduate student stated that they would be graduating in 2024, that means that they were a freshman and had only been enrolled in school for one year at the time of the interview. Whereas a master's student who is graduating in 2022 would have completed 5 years in university. An assumption was made that students were completing their undergraduate degrees in the standard four-year timeframe. Moreover, students identified the number of climate change science related courses they had taken throughout their studies.

Climate Change Knowledge

Students were asked to answer three questions about various aspects of climate change in order to assess their understanding of the subject. Two questions assessed student knowledge of the physical impacts of climate change, while one question focused on the socioeconomic dimension of climate change. For the first two questions, responses were scored 1 if they fall within the range of correct answers. Responses that are above or below the range of correct answers by the same range value (±0.4 for question one, ±50 for question 2) were given a score of 0.5. For the third question, responses were scored either 0 or 1. Table 3.2 shows the three questions, correct answers, examples of student responses, and the scores assigned to the responses.

Table 3.3: Climate change knowledge questions with examples of student responses and scores

Question	Correct Answer	Examples of Student Responses	Score
How much has the climate warmed in the last 100 years?	0.8 – 1.2 °C [1]	1 °C	1
		1.5 °C	0.5
		4 °C	0
How much did the global sea level rise in the last century?	160 – 210 mm [2]	180 mm	1
		130 mm	0.5
		760 mm	0
Which country as a whole emits the most volume of GHG in the world?	China/USA [3]*	China	1
		USA	1
		India	0

[1] (Intergovernmental Panel on Climate Change, 2018)
[2] (The National Aeronautics and Space Administration, n.d.)
[3] (International Energy Agency, 2021)
*Although China is currently the top CO_2 emitter, historically, the top emitter has been the United States. Identification of either country was scored as a correct response.

3.3 Systems Thinking: Dependent Variable

Systems thinking was measured using the students' cognitive maps of relationships among causal factors related to climate change and its impacts. These cognitive maps, as visual representations of students' mental models, serve as a valuable tool in understanding how students construct knowledge, gather information, and make inferences based on what they learn in their courses (Raia, 2005). Cognitive maps have been used to operationalize systems thinking in two ways: (1) their qualitative composition (e.g., Attari et al., 2017), and (2) structural characteristics (e.g., Levy et al., 2018; Gray et al., 2019). In an attempt to combine both approaches, a conceptual framework was developed to measure systems thinking across three dimensions: system components, system structure, and system function. As described in chapter 2, network-derived measures were used to operationalize systems thinking across the three dimensions. The first dimension (system components) captures the comprehensiveness of the cognitive map by accounting for the class and diversity of factors included based on three sets of classes: (1) parent classes, (2) child classes, and (3) domain classes. The second dimension focuses on the cognitive map's structural characteristics in terms of the prevalence of network motifs that reflect higher cognition of complex causality. For the third dimension (system function), cognitive maps were scored depending on whether students connected factors in a logical way according to their parent classes. Using hierarchical clustering, simple versus complex systems thinking was distinguished based on how cognitive maps with similar results cluster together.

3.4 Analytical Approach

I estimated a set of multiple logistic regression models to test how variables related to a student's academic training predict complex systems thinking for each dimension. In the model, the independent variables are the applied sciences score, interdisciplinarity score, number of climate change science courses, years of study, and climate change knowledge score. Multiple logistic regression was employed because it predicts the outcome of a binary variable (membership in a complex systems thinking cluster) based on a set of independent variables.

4. Results

4.1 Descriptive Analysis

<u>Predicators of Systems Thinking: Independent Variables</u>

Table 3.3 shows the descriptive statistics of the independent variables for all study participants. As shown in Figure 3.1, many students are enrolled in majors and/or minors in the applied sciences (number of applied sciences degrees represented among the 35 respondents = 47). Of the study population, 77% (n=27) were pursuing a major related to environmental studies (e.g., environmental science, environmental policy and decision-making, natural resource management). Moreover, since all study participants are pursing majors and/or minors related to environmental studies, all students were exposed to climate change science in at least one of their courses. For the climate change knowledge questions, 2 students failed to answer any question, while 17 students answered all three questions. For the first question, 29% provided a correct answer, and 17% provided an answer close to the range of correct answers. For the second question, almost all students

did not know how much the sea level has risen in the last century with only 2 students providing the correct answer. Many of the students did, however, correctly identify the U.S. or China as the country that emits largest volume of carbon dioxide (average score = 0.91).

Table 3.4: Descriptive summary of independent variables for entire sample

Variable	Mean	SD	Range
Applied Sciences Score	0.81	0.27	0.14 – 1.0
Interdisciplinarity Score	0.86	0.23	0.14 – 1
Number of climate change science courses	4.66	2.35	1 – 10
Years of Study	2.77	1.17	1 – 5
Climate change knowledge score	1.35	0.65	0 – 3

Systems Thinking: Dependent Variable

Students were asked to create a cognitive map that represents their perception of climate change by identifying factors (e.g., drivers, impacts, responses) and drawing causal connections among these factors. Students' cognitive maps were diverse in terms of their qualitative composition (i.e., types of factors included in the cognitive map) and structural characteristics (e.g., number of factors and connections). Figure 3.2 shows different examples of student cognitive maps that reflect varying levels of understanding of climate change.

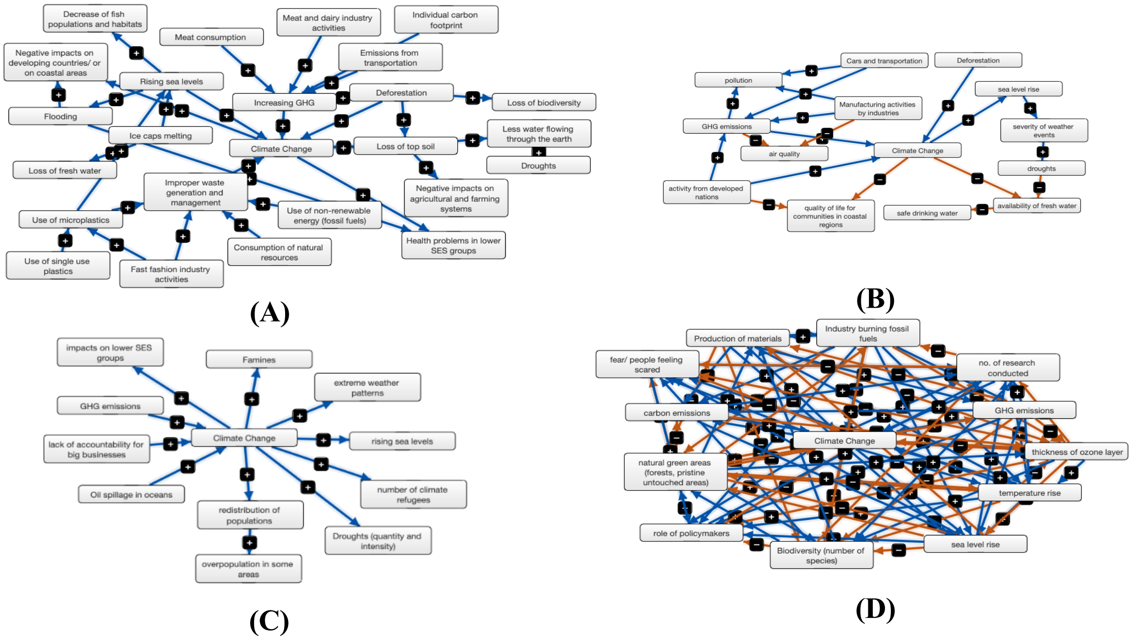

Figure 3.2: Examples of students' cognitive maps.
(A) shows a map with a large number of factors (n=25) but relatively low number of connections. Map (B) has low number of factors and connections but includes negative relationships unlike map (A). Similarly, map (C) has low number of factors and connections but is centralized around climate change (i.e., all connections going to and from climate change). Finally, map (D) includes only 13 factors but is highly interconnected.

As described in chapter 2, network-derived indicators of systems thinking were measured using the cognitive maps. Hierarchical clustering was then performed to distinguish between simple and complex systems thinking based on how cognitive maps with similar values across the different indicators grouped together. Table 3.4 summarizes the results of the clustering analysis.

Table 3.5: Summary of clustering analysis results and values of systems thinking indicators for the three dimensions

		Simple Systems Thinking Mean (SD)	**Complex Systems Thinking** Mean (SD)
Dimension One: System Components	N	24	11
	Parent Classes: Number	3.83 (0.70)	4.73 (0.47)
	Parent Classes: Diversity Index	0.73 (0.10)	0.88 (0.09)
	Child Classes: Number	6.00 (1.12)	10.82 (1.60)
	Child Classes: Diversity Index	0.52 (0.05)	0.72 (0.05)
	Domain Classes: Number	3.83 (0.87)	4.73 (0.47)
	Domain Classes: Diversity Index	0.66 (0.15)	0.83 (0.07)
Dimension Two: System Structure	N	24	11
	Bidirectionality	-0.72 (1.15)	0.008 (1.47)
	Feedback Loops	-0.92 (0.45)	-0.65 (0.23)
	Multiple Effects	1.06 (0.97)	4.43 (2.34)
	Indirect Effects	-0.04 (0.89)	3.57 (2.05)
Dimension Three: System Function	N	11	24
	Dyads Score	0.70 (0.07)	0.87 (0.07)
	Pathlength of 3 Score	0.70 (0.13)	0.92 (0.07)

4.2 Statistical Analysis

Results of the multiple logistic regression models are provided in Table 3.5. For the first dimension, climate change knowledge positively and significantly predicted complex systems thinking, estimate = 1.54 (0.76), $p < 0.05$, while it negatively predicted complex systems thinking for dimension three (estimate = -2.23 (1.00), $p < 0.05$). Moreover, years of study negatively predicted complex systems thinking for dimension three, estimate = -1.16 (0.58), p <0.05. For dimension two, the model failed to significantly predict complex systems thinking.

While a commonly accepted equivalent statistic to R-squared does not exist for logistic regression, several pseudo R-squared measures have been proposed in existing literature (DeMaris, 2002). For all three models, three pseudo R-squared measures were computed, which indicate that the Dimension 1 model explained 17-27% of the variation, and that the Dimension 2 and 3 models explained 6-12% and 28-42% of the variation. However, pseudo R-squared indices should be interpreted with caution as they are not equivalent to R-squared values in linear regression (Smith and McKenna, 2013).

Table 3.6: Multiple logistic regression results

Variables	**Dimension One**	**Dimension Two**	**Dimension Three**
	Estimate (SE)	Estimate (SE)	Estimate (SE)
(Intercept)	-7.26 (3.05) *	-0.94 (2.77)	6.13 (3.62) .
Applied Science Score	-1.55 (3.77)	-1.22 (3.19)	0.35 (4.19)
Interdisciplinarity Score	4.19 (4.27)	3.11 (4.17)	-0.07 (4.60)
Number of Climate Change Courses	0.13 (0.19)	-0.01 (0.18)	0.31 (0.23)
Years of Study	0.43 (0.47)	-0.42 (0.41)	-1.24 (0.61) *
Climate Change Knowledge Score	1.58 (0.74) *	-0.21 (0.60)	-2.33 (1.00) *
McFadden Pseudo R-squared	0.172	0.068	0.286
Cox and Snell Pseudo R-squared	0.193	0.084	0.299
Nagelkerke Pseudo R-squared	0.271	0.116	0.420
AIC	47.42	53.85	42.04
BIC	56.75	63.18	51.38
Log Likelihood	-17.71	-20.93	-15.02
Deviance	35.42	41.85	30.04

*** p < 0.001; ** p < 0.01; * p < 0.05; . p < 0.1

5. Discussion

5.1 Theoretical Implications

While promoting systems thinking among students has been identified as an important facet of higher education, there is currently a gap in our understanding regarding how curricula and course content must be designed in order to achieve that goal. Moreover, assessment tools aimed at evaluating students' systems thinking skills are limited and methodologically divergent in existing literature. The present study aimed to fill these gaps by examining how academic training facilitates systems thinking among students by measuring their systems thinking skills using a multidimensional approach and examining the relationships between their academic background and systems thinking abilities using climate change as an example.

The study's results reveal that knowledge about climate change positively predicts a student's ability to identify different types of system components (dimension one). This indicates that as students learn more about climate change, they are better able to integrate knowledge from multiple perspectives including the natural and social sciences, which is key to understanding climate change (Roychoudhury et al., 2017). Surprisingly, however, understanding of system function (dimension three) is negatively predicted by knowledge, which suggests that as knowledge of a topic increases, an individual is unable to connect the components logically to explain system function. This is consistent with results from chapter two that reveal that there is often a trade-off between the systems thinking dimensions. Thus, if knowledge improves a student's ability to recognize the various components of the system, they become less able to make logical connections between them. One explanation for this is that system function is generally the most difficult to define (Meadows, 2008). It is possible that other forms of knowledge (e.g., knowledge of complex systems instead of climate change), which can be acquired through non-traditional teaching strategies, are required to understand how complex system interactions and dynamics influence system outcomes. In their study, Soltis et al. (2019) argue that active learning strategies that deploy systems-modeling approaches (e.g., using computer software to predict system outcomes using 'what-if' scenarios) are critical to understanding complex systems, and more specifically earth complex systems. Another surprising result is the negative relationship between years of study and complex systems thinking across the function dimension. As students progress in their studies, one would anticipate that they become more able to detect system outcomes and function. The results, however, do not support this notion. Several scholars have applied learning progression frameworks to systems thinking which describe the changes in students' level of thinking sophistication as their scientific understanding develops over time (e.g., Rehmat et al., 2020; Hokayem and Gotwals, 2016). In their study, Mambrey et al. (2020) identify three core systems thinking components: system organization, system behavior, and system modeling. Their findings revealed that the learning progression stages do not appear to be in a linear ascending order which means that students can acquire the different dimensions of systems thinking in no particular order. This might explain why higher-level students do not necessarily connect components in a logical manner.

The study failed to identify a significant effect of the predictor variables on complex systems thinking across the structure dimension. Although insignificant, all variables with the exception of interdisciplinarity score negatively predicted systems thinking across the second dimension. This indicates that other variables, potentially unrelated to a student's academic training, predicts them incorporating complex substructures in their cognitive maps. Moreover, enrolling in an applied sciences program does not seem to predict complex systems thinking as one would expect due to their interdisciplinary and problem-oriented nature. However, considering that a large number of students in the study sample are enrolled in these programs, there is not a lot of variation in the sample which might explain the insignificant results. While certain variables might actually be significant, the results indicate that the data is not sufficient to make a conclusion due to statistical power issues. Finally, it is worthwhile to mention that various models with different combinations and/or versions of variables were tested that indicated significant results. However, I was not comfortable interpreting and reporting those findings due to substantial collinearity among the variables.

5.2 Implications for Higher Education and Future Research

Collectively, these results raise the question as to why some of these variables predicted complex systems thinking across only two dimensions. Engaging in a combination of these dimensions of systems thinking is needed to understand why a system behaves as it does, predict possible future behaviors, and restructure the system to achieve desired outcomes (Meadows, 2008). Moreover, the variables predicted complex systems thinking in opposite directions across the dimensions, as was the case with climate change knowledge. On that account, it is imperative to understand what factors predict a student's ability to comprehend the system's components, structure, and function in order to inform curriculum design, course content, and teaching strategies.

The results show that educating students increases their ability to identify the various components of a system, specifically in relation to climate change. However, increased knowledge does not necessarily predict students comprehending system structure and function. It is possible that the courses being taught focus on introducing multiple concepts regarding climate change but fail to actively engage students in adopting a system perspective to connect these concepts together. Different forms of knowledge and skills might be necessary to acquire certain elements of systems thinking skills. This generates several future research questions: How should courses be structured to achieve higher orders of systems thinking? How do different teaching strategies promote the different dimensions? Should curricula design aim at fostering the different dimensions of systems thinking skills at once or in stages? And finally, when should the different dimensions of systems thinking be introduced in a curriculum?

Another main objective of this study was to design a systems thinking assessment tool that can be used in a classroom. Some of the main advantages of the framework is the use of cognitive mapping, a method that is rooted in systems thinking approaches, as well as the multidimensional approach to assessing systems thinking. For example, instructors can administer an in-class assignment where students are asked to construct a cognitive map that reflects their understanding of a particular topic using guiding and prompting questions. Students can either sketch out their cognitive maps or create them using an online software. Moreover, if teaching systems thinking is a continuous process, it must be iteratively evaluated. It is recommended that educators employ the assessment tool before and after a course to test how student understanding of the different dimensions of a system improves over the course duration. This method can assist instructors in identifying gaps in students' understanding, refine course material, and adjust teaching strategies to achieve the desired learning outcome. There are several examples of using this strategy in existing literature (e.g., Dauer and Long, 2015; Kordova et al., 2018). Additionally, periodic assessment of students' systems thinking skills is advised to evaluate how they progress throughout the course of their education.

Finally, it is crucial to keep in mind that teaching systems thinking is a challenging task in and of itself. Despite having extensive subject-matter expertise, academics and educators are often primarily trained in one discipline and lack the formal training required to incorporate systems thinking in their teaching (Mathews and Ford, 2007; Arnold and Wade, 2017). While more research is required on systems thinking pedagogy and development of instructional resources, it is equally important to understand how teachers can be trained to employ effective systems thinking pedagogical strategies and create a learning environment that fosters systems thinking in their classrooms.

5.3 Limitations and Recommendations

One of the main limitations of the study is the use of a convenience sample of university students at a large public Midwestern university. Given that the student subject pool is offered by at the School of Environment and Natural Resources, all participants were either enrolled in programs or taking courses offered by the school. Furthermore, the study participants share similar demographics (e.g., 86% were in the same age group, 74% were females, and the majority shared similar political views) which indicate some selection bias. Combined with the relatively small sample size (n=35), these constraints limit the generalizability and representativeness of the study's findings since external validity in this case is affected by differing admission requirements at different institutions and the level of diversity among students in a university (Lupton, 2019). To increase the generalizability of my study, I recommend conducting a similarly designed study with a larger and more diverse sample such as with students enrolled in different programs at a university, or with students enrolled in different universities, both locally and internationally.

Moreover, the measurement of some of the independent variables can be further improved. Although there is no universal standard to classify academic programs, one established model is Biglan's taxonomy of academic disciplines which classifies academic programs along three dimensions: (1) pure/applied, (2) hard/soft, and (3) life/nonlife (Biglan, 1973). Since the study sample consisted of students that have similar academic training, it was not possible to use this model in my own study. This can be remediated if this study was to be conducted again using students from different programs and departments. Furthermore, interdisciplinarity was measured depending on whether the student was enrolled in an applied versus pure academic discipline (with the exception of geography, international relations, and environmental social sciences due their interdisciplinary nature). Another approach to measure interdisciplinarity is to assess student's interdisciplinary thinking using the Wolfe/Haynes Interdisciplinary Writing Assessment (2003). This approach focuses on evaluating student skills rather than program interdisciplinarity which can be more challenging. Finally, while I believe that the use of open-ended questions provides a more meaningful measure of knowledge than self-reported measures, I recommend researchers to include more questions in future studies to better understand student's knowledge of the topic of interest. For example, in the context of climate change, Roychoudhury et al. (2017) developed a 16-item test that assessed student knowledge of key information on climate change as well as their analytical skills.

Finally, the study focused specifically on examining the relationship between academic training and engagement in systems thinking. Yet, there may be other factors that influence individuals' varying levels of systems thinking. Similar to other existing studies, I conceptualize systems thinking as a skill that can be taught and learned (e.g., Gilbert et al., 2018; Grohs et al., 2018). However, there is emerging literature that evaluates systems thinking as an individual difference variable that can be influenced by other psychological, cognitive, and behavioral variables (Randle and Stroink, 2018; Thibodeau et al., 2016). For example, Davis and Stroink (2015) examined the relationship between systems thinking and the New Ecological Paradigm, and concluded that systems thinkers possess stronger ecological worldviews, hold biospheric values, and exhibit more pro-environmental behaviors. I believe further research is needed in this area, which may help to explain why some students perform better than others on systems thinking assessments, especially in environmental problem-solving contexts.

6. Conclusion

Higher education institutions increasingly emphasize systems thinking education as a crucial skill for grappling with complexity. Yet, there are still significant knowledge gaps on the of pedagogy and assessment of systems thinking, as well as on best practices to incorporate systems thinking in curriculum development. In this study, students' systems thinking skills was measured using a multidimensional assessment tool and examined in terms of how academic training fosters systems thinking among university students using climate change as an example.

The results reveal that increased climate change knowledge positively predicts a student's ability to identify the different components of climate change while it negatively predicted their ability to connect them in a logical manner. Moreover, the findings suggest that as students advance in their studies, they are less capable of identifying system function. Finally, the study failed to establish a significant relationship between academic training and students' ability to understand system structure. While I believe my research is a step in the right direction, more research is necessary to determine what factors influence students' systems thinking across multiple dimensions. This will guide the development of curricula, course materials, and teaching strategies that promote systems thinking in a classroom.

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Appendix A: Parent and Child Classes Classification Framework

Parent Class	Child Class	Example
Enabling Conditions	Human condition	Individualism
	Social/societal condition	Human population density
	Economic condition	Capitalism
	Political condition	Political polarization
	Governance condition	Policies that support petroleum industry
	Technological condition	Efficiency of technology
Driving Forces	Natural driver	Volcanic eruptions
	Individual behavior driver	Meat consumption
	Social/societal driver	Urbanization
	Industrial driver	Manufacturing and production
State	Physical state	Melting of glaciers
	Biological state	Biodiversity
	Bio-chemical-physical state	Ecosystem stability
Impacts	Human impact	Quality of life
	Social/societal impact	Social justice
	Economic impact	Water affordability
	Political impact	Lack of political conflict
	Ecological impact	Preservation of habitats
Responses	Behavioral response	Adoption of plant-based diet
	Social/societal response	Social awareness of climate change
	Civil society organization response	Environmental advocacy
	Industrial response	Green innovation
	Government response	Environmental legislation

Appendix B: Interview Protocol

Introduction:

Thank you for taking the time to participate today.

My name is Lisa Shahin, I'm an international student from Jordan. I'm a first-year MS student at SENR and I'm specializing in Environmental Social Sciences. My research mainly focuses on understanding how people conceptualize climate change and what factors influence perception.

Before we begin, I will share a document with you regarding your consent to participate in this study. Please take a few minutes to read through it and let me know if you have any questions.

With your permission I would like to record our meeting today to ensure that I capture everything you're sharing. Is that okay?

[Turn on recording AND live transcript]

Thank you for allowing me to record our conversation. I want to remind you that your participation today is voluntary and you can leave at any time if you choose to. This will not affect you receiving extra credit.

The goal of these interviews is to gain an understanding how each person conceptualizes climate change using a cognitive mapping approach. Throughout our conversation, we will cover a variety of different topics ranging from factors contributing to climate change to impacts of climate change. I'm trying to capture your perspective and thoughts on climate change so there are really no right or wrong answers.

I would also like to remind you that your responses will remain confidential and will not be used for purposes outside the scope of this research.

Did you have time to go through the informed consent form? Do I have your consent to move forward with the interview?

Do you have any questions or concerns before we begin?

Section 1: Background Information

Q1: I will start by asking some background questions so I can get to know you a little bit. I would also like to add that if you feel uncomfortable about answering any of these questions, please say so and we can skip that one.

- How old are you?
- Where are you from? Is that the same city that you grew up in?
- Which of the following best describes where you grew up?
- How would you describe your parents or guardians' occupations?
- How would you characterize your work experience? And by work experience, I mean have you ever been paid to do a job? How many years have you been in the labor force? Are you currently working? Where did/do you work? How many hours do work per week on average? What did/does your job entail?
- What is your major(s)? If relevant what is your minor(s)? When do you plan to graduate?
- Do you have an idea of what you would like to do after you graduate? Which elements of a job appeals to you? Is it working with the public sector, doing research, advocacy work, etc.?

- What scale are you interested in working? Are you interested in working at the local, state, national, international level?
- Which of the following best describes your political identity?
    - Democrat
    - Republican
    - Independent
    - Other party
    - Not political
    - Prefer not to answer
- What gender do you identify with?
    - Male
    - Female
    - Non-binary
    - Prefer not to answer
- What are your religious affiliations if any?

Q2: Have you taken any courses or attended any seminars that focused on climate change throughout your studies? [yes/no] If yes, how many courses did you take?

- Have you taken a capstone course or any other form of an experiential learning course like the ones shown below that focused in any way on climate change issues? [yes/no]
    - Capstone course
    - Field experiences including field trips, field observations and field activities
    - Industry/ community research project
    - Internship

- Lab
- Service learning
- Other. Please specify

Can you talk about your experience a little bit.

Q3: We will talk more about where you get your information or news on the environment or climate change from. So for each of the following categories, please indicate if it's a yes or a no and if it's a yes then specify exactly from where you get your news from:

- News outlets
- Social media platforms
- Documentaries/podcasts
- Other

Do you discuss or talk about climate change with any of the following?

- Friends and families
- Roommates
- Professors and other students
- Others

Q4: Finally, I would like to ask a couple of questions to understand your knowledge of climate change

- How much has the climate warmed in the last 100 years?
- How much did the global sea level rise in the last century?
- Which country as a whole emits the most volume of GHG in the world?

Section 2: Modeling Exercise

For the remainder of our conversation we will be focusing on climate change and what it means to you. We will use a software called MentalModeler to create a map of the concepts and ideas that we discuss.

To give you a brief overview of the software that we will be using today, we'll go over an example together. Can you see my screen?

Let's say I want to explore what impacts level of traffic. The first thing that comes to mind is number of cars. Another concept is using public transportation. So we now have three concepts, level of traffic, number of cars and using public transportation which you can see here in these boxes. Next, I want to see if there are any connections between the concepts by drawing arrows between them. The first step is deciding which direction the connection goes. For example, number of cars affects traffic therefore I will draw an arrow from cars to traffic. Then for each connection, I have to decide whether that relationship is positive or negative. A positive relationship means that an increase in one concept causes an increase in the other concept. While a negative relationship means that an increase in one concept causes a decrease in the other concept. So I think that when the number of cars increases, the level of traffic also increases so it is a positive relationship. There can also be negative connections, so for me when people use public transportation rather than driving their own cars, it reduces traffic so that is a negative connection.

I keep repeating these steps until I feel like I added all of the concepts and connections that I can think of.

So this is just a quick overview of how we create a mental map, Do you have any questions before we move on?

Just a reminder, this mental map represents your own ideas and there are no right or wrong answers so if you feel like we put things in the wrong place, we can rearrange things.

Your mental map can include different aspects relating to climate change. That can include causes or factors contributing to climate change, impacts of climate change or key stakeholders affecting or affected by climate change. You choose what you want to include or not include in your map according to how you see things. I should also mention that this exercise can last from 20 – 30 minutes.

So to get us started: How would you define/characterize climate change?

So we'll now start creating your mental map,

Prompts:

- What do you think are the impacts of climate change that the world is facing nowadays?
- What are the primary factors that contribute to these impacts that you described?
- Who is responsible for causing these impacts? What sectors of the economy/ organizations are the main contributors?
- Do you think there are certain groups of the population/ geographic areas/ species that are affected by these impacts?
- Describe any relationship you see between the concepts on the screen.
- Do you think that is a positive or a negative relationship?

Clarification questions:

- Can you elaborate on that?
- Is the concept/connection I just added correct?
- Would you describe that connection from X to Y or from Y to X? Is it a positive or negative connection?

Take a minute to look at the screen. Did I capture everything we discussed? Is there anything you would like to add? A new concept or relationship? [repeat as needed]

Thank you for your participation! Just as a final reminder, our conversation today is confidential and the points that we discussed will not be used for purposes outside the scope of this research. Please feel free to send me any follow-up questions or comments you might have later on, I will drop my email in the chat box, or you can contact me through the SONA portal.

Appendix C: List of Academic Programs

Program	Major	Minor	Graduate Program	Interdisciplinary
Applied Sciences				
Environmental Science	9 1*	2	2	1
Environment, Economy, Development, and Sustainability	10	5	0	1
Environmental Policy and Decision Making	2 1*	0	0	1
Natural Resource Management	2	0	0	1
Forestry, Fisheries & Wildlife	1	1*	0	1
Business Administration	3	2	0	1
Fashion and Retail Studies	1	1	0	1
Ecological Engineering	1*	0	0	1
Society and Environmental Issues	0	2	0	1
Design Thinking	0	1	0	1
GIS	0	1	0	1
City and Regional Planning	0	1	0	1
Education	0	1	0	1
Leadership Studies	0	1	0	1
Social Sciences				
International Relations	2	0	0	1
Geography	0	1*	0	1
Environmental Social Sciences	0	0	1	1
Political Science	0	1	0	0
Psychology	1	0	0	0
Anthropology	1	0	0	0
Sociology	0	1	0	0
Humanities				
Chinese	1*	0	1	0
Music	1	0	0	0
German	1	0	0	0
Spanish	0	2	0	0
Studio Art	0	1 1*	0	0
Professional Writing	0	1	0	0
Arabic	0	1	0	0
Natural Sciences				
Evolution and Ecology	1*	0	1	0
Astronomy and Astrophysics	0	1	0	0

*denotes undergraduate degrees earned previously by current graduate students