Future Weather Trends

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Infrastructure

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and
Minnesota Climate Adaptation Partnership

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Contributors

About the Institute on the Environment (IonE)
At the Institute on the Environment (IonE), we pursue interdisciplinary research, leadership development, and public-interest communications to help build a sustainable Minnesota and world – drawing upon *all* disciplines and expertise of the University of Minnesota. That future includes sustainable agriculture that feeds the world; renewable energy that powers healthy homes; efficient transportation and flourishing businesses; oceans, lakes and rivers that are clean and healthy; ; and thriving ecosystems support thriving economies and societies. There are significant knowledge and leadership gaps to achieving these things, and IonE has a strategic focus on filling these gaps.

About the Center for Sustainable Building Research (CSBR)
The Center for Sustainable Building Research is a research center in the College of Design at the University of Minnesota. Building on past success and looking into the future, the work of the Center is focused in six areas, each directly linked to each other and to the built environment: energy and climate change; the water cycle; sustainable materials for a healthy built environment; measuring regenerative design; equitable designs to provide sustainability for all; and creating regenerative and resilient communities. It is impossible to solve any of these problems in isolation from each other, thus transforming building industries and the built environment will strike at root causes.

About the University of Minnesota Climate Adaptation Partnership (MCAP)
The University of Minnesota Climate Adaptation Partnership (MCAP) offers critical resources and training to help communities respond to changing weather and climate conditions and prepare for the years to come. Affiliated with both University of Minnesota Extension and the College of Food, Agricultural and Natural Resource Sciences, MCAP performs foundational climate research while also offering hands-on support to individuals and organizations across a range of backgrounds and industries in Minnesota, the Midwest region and beyond.

Authors

Richard Graves, FAIA and Dr. Jessica Hellmann served as co-principal investigators of the research to support this report. Richard Graves was primary editor and author of the Executive Summary, Recommendations, and Chapter 1: Introduction (co-authored with Dr. Patrick Hancock), Amanda Farris was the primary author of Chapter 2: Future Minnesota Climate, Dr Patrick Hancock co-authored Chapter 1: Introduction (with Richard Graves) and primary author of the Chapters 3: Developing a Resilient Infrastructure Policy Framework and Chapter 4: Using the Framework to Analyze Infrastructure Systems and Elizabeth Kutschke was primary author of Chapter 5: An Analysis of Future Weather Trends and the Built Environment.

The Center for Sustainable Building Research (CSBR) at the University of Minnesota co-managed the research project, analyzed feasibility and provided recommendations on policy and next steps. Researchers from the CSBR that participated in the research and report:

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The Institute on the Environment (IonE) at the University of Minnesota co-managed the research project, provided the conceptualization of the SETs analysis and system research and provided recommendations on policy and next steps. Researchers from the IonE that participated in the research and report:

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The University of Minnesota Climate Adaptation Partnership (MCAP) provided climate data and information, including relevant impacts to the study sectors, and provided recommendations on policy and next steps. Researchers from MCAP who participated in the research and report:

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Executive Summary

Climate data and observations show that Minnesota is experiencing consistent changes in weather patterns. Between 1895 and 2023, the average annual temperature has increased by 3°F[1] and average precipitation has increased by 3.3 inches. These changes are challenging aging infrastructure and, in some cases, causing infrastructure failures. When climatic changes are modeled for the end of the century, a range of possible scenarios are considered and presented (Chapter 2). Future climate average temperatures will be hotter and be accompanied by higher humidity, and with greater variability from season to season. Shifts in the timing and intensity of rainfall are expected to disrupt transportation along major rivers and increase chronic flooding. Green infrastructure as well as public and private investments may mitigate losses, provide relief from heat, and offer other ways to adapt the built environment to a changing climate.[2]

Infrastructure is defined in this report as the technology that the state uses to support society with materials, resources and other aspects of ecological systems to facilitate the economy and other needs of society (Chapter 1). This report explores "how projections of future weather trends may exacerbate conditions, including but not limited to drought, elevated temperatures and flooding"[3] for the design and evaluation of infrastructure and buildings constructed by the state of Minnesota and local governments. In addition, the report assesses the potential of future weather events to weaken existing systems creating the need for intervention to:

- Maintain and increase the amount and quality of food and wood production
- Reduce fire risk on forested land
- Maintain and enhance water quality
- Maintain and enhance natural habitats

Building research based on modeling indicates that annual energy usage will decrease for buildings constructed by the state and local government units (Chapter 5). While reduced need for heating will decrease overall energy usage and natural gas use, demand for cooling will significantly increase for new and existing buildings which will significantly increase the usage of electricity. Increased temperatures combined with inadequate building insulation, windows and other items will create internal temperatures that are uncomfortable and for some buildings, unsafe.

Research supports recommendations for:

- Additional insulation in building envelopes
- Mechanical systems that can operate through wider variations of conditions
- Exterior finish materials and roofs that can resist stronger wind
- Building sites that can reduce the risk of increased flooding and drought

[1] Historical climate data from Minnesota Department of Natural Resources, https://arcgis.dnr.state.mn.us/ewr/climatetrends/
[2] Fifth National Climate Assessment. https://nca2023.globalchange.gov/chapter/24/
[3] https://www.revisor.mn.gov/bills/text.php?number=HF2310&type=bill&version=4&session=ls93&session_year=2023&session_number=0

Because the relationships between infrastructure, future weather trends and the human-natural systems of agriculture, water, forests, and built environments are complicated, the research team developed a framework to analyze the Social, Ecological and Technological (SETs) relationships within each system, creating a common "language" to analyze potential interactions between multiple complex systems (Chapters 3 and 4). This approach is crucial for decision makers to be effective at mitigating costs and avoiding maladaptation[4] or making things worse from some resilience strategies. Additional research is needed in this area, which would yield significant returns on investment as the state determines goals and collaborative approaches responding to the challenges of complex weather risks and opportunities in the future.

[4] Maladaptation: adaptation actions that inadvertently exacerbate, redistribute, or introduce new climate vulnerabilities. (IPCC)

Recommendations

An understanding of complex systems is core to the research and path forward to resilient infrastructure. All activity should be considered in this context…Human–natural systems are dynamic and complex. Interconnected networks of people, infrastructure, commodities, goods, and services influence changing climate risks and are increasingly vulnerable to their impacts. The vulnerabilities in these networks, and their effects on human–natural systems, strongly depend on human responses and other compounding stressors. Decision-makers seeking to reduce future weather and climate risks have to navigate diverse and sometimes competing objectives and perspectives across many actors, institutions, and geographic scales while reconciling deep uncertainties and limits to predictability.[5]

Future Weather Scenarios (Chapter 2)

Future Weather Projections using a range of assumptions and scenarios need to be researched and incorporated into more use cases to enhance understanding of potential future impacts on infrastructure systems. This includes development of future weather data and information in formats used by industry professionals to ensure future weather projections are directly applicable to policy- and decision-making. Tailoring future weather data to the specific needs of professionals will help to integrate weather considerations into design, construction, and resource management practices, ensuring that projects are built to withstand future conditions and minimizing long-term environmental, economic, and social risks.

> **Recommendations:** The ***Legislature*** should provide funding to support the additional research on the use of Future Weather Data for Infrastructure Planning by local governments and the state. ***Department of Administration*** to incorporate recommendations resulting from further research into infrastructure-related best practices for state agencies, local units of government and other stakeholders.

[5] Mach, K.J., R. Vallario, J.R. Arnold, C. Brelsford, K.V. Calvin, A.N. Flores, J. Gao, K. Jagannathan, D. Judi, C.E. Martín, F.C. Moore, R. Moss, E. Nance, B. Rashleigh, P.M. Reed, L. Shi, and L.L. Turek-Hankins, 2023: Ch. 18. Sector interactions, multiple stressors, and complex systems. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH18

Governance and Resilient Infrastructure Policy

Integrated Governance decisions between the state and local units of government are needed to analyze the risks/opportunities presented by future climate and other changing needs to the achievement of goals of the systems to provide for the needs of the people of Minnesota. This will require, in part, analyzing the current infrastructure policy landscape and the development of metrics to assess and evaluate policies for their integration to and potential for enhancing overall system resilience. **Infrastructure Policy** that is designed to have the capacity to remain resilient in the face of a wide range of future weather scenarios is needed. In order to provide policies that have both the flexibility to respond to diverse future weather and climate scenarios and the reliability needed for long-term project implementation, a balance must be created between their adaptability to evolving weather-related impacts with consistent funding and stable regulatory frameworks.

Recommendations:

- The ***Legislature*** should consider reviewing bond funded projects for their impacts and potential benefits on infrastructure with a consideration for future weather trends and integration across units of government.
- The ***Department of Administration*** to work with the ***Minnesota Pollution Control Agency*** to develop goals for resilient infrastructure with support from the ***University of Minnesota.***

Resilient Infrastructure Planning (Chapter 3)

Resilient infrastructure needs **Data + Process + Planning**. The diverse human-natural systems in Minnesota and beyond are dynamic and complex networks of people, economics, ecologies and infrastructure (technology) that influence climate risks and opportunities. These systems are vulnerable to the impacts of future weather trends, especially when the events are compounded. Decision makers at all levels seeking to adapt and mitigate the effects of these risks need not only data, but also a continuous process to be developed that incorporates competing goals, actors, institutions and scales to reconcile uncertainty and plan for the future. **SETs Framework** to support the ongoing development, testing, and integration of the SETS framework, which is an integrated infrastructure policy planning and decision-support framework used to systematically evaluate the benefits, risks, and opportunities of various climate resilience actions across multiple infrastructure domains. The SETS framework offers a robust decision-support methodology that assesses climate resilience actions in a place-based and temporally informed manner, in order to address the complexities of identifying effective climate resilience interventions among interconnected infrastructure systems. By analyzing the viability of resilience actions within the context of current system dynamics, the SETS framework enables the creation of a resilient action space which is aligned with existing infrastructure system conditions. Additionally, it facilitates the evaluation and revision of policy responses against potential climate futures, resulting in a list of recommended actions that are likely to enhance resilient policy capacity and enhance long-term infrastructure resilience. **Integrated Solutions** to Future Climate Impacts are essential to address impacts that are interconnected across sectors and affect multiple systems simultaneously. For example, increases in temperatures and extreme precipitation events are already challenging aging infrastructure and are expected to impair surface transportation, water navigation, and the electrical grid. Combinations of green and grey infrastructure that are integrated at scale and across systems (agriculture, forest, water, built environment, etc.) will be more cost effective, impactful, help to avoid maladaptation, and will leverage the strengths of both systems to address a wider range of challenges. Together, they offer a more balanced, resilient approach, where green infrastructure can enhance the sustainability and effectiveness of grey infrastructure, while grey infrastructure ensures that green solutions are supported and reinforced in the face of extreme climate events. An integrated approach will support responses that are more effective, equitable, and sustainable, addressing the complex, multi-dimensional challenges posed by future weather scenarios.

Recommendations:

- The ***Legislature*** to work with the ***Department of Administration*** on integrating resilience into the infrastructure bonding process.
- The ***Legislature*** should fund additional research on the Resilient Infrastructure Planning framework as a tool for local units of government to coordinate projects with state agencies and legislative goals.
- ***Department of Administration*** to work with the ***Minnesota Pollution Control Agency*** to develop a resilient infrastructure planning process with support from the ***University of Minnesota***.

Built Environment (Chapter 5)

Built Environment - More investments in better building envelopes, split mechanical systems, Fortified standards for roofs and siding, and energy/water storage systems are needed to respond to future weather scenarios while performing efficiently now and in the near future.

Built Environment Sites - understand the challenge of the site in the context of the watershed and stormwater system. Current site "supporting" systems (stormwater, roads, water supply and wastewater) may become liabilities and risks in extreme events. Some site strategies may increase individual site costs, but lower larger infrastructure investment needs in the overall system.

Recommendations:

- The ***Legislature*** should fund and respond to risk assessments including extreme heat resistance for existing buildings and infrastructure, and upgrade as needed.
- The ***Department of Administration*** to work with the University of Minnesota to continue to integrate resilience into the B3 standards and look for guidelines that should apply to all state owned facilities..

Natural Systems (Habitat, Water, Forests and Agriculture) (Chapter 4)

Planning for More Extremes is necessary to minimize impacts on natural infrastructure, which includes the interconnected ecological systems that support vital resources, services, and functions. Climate-related changes–such as more frequent and intense rainfall and flooding events, soil degradation and erosion, and prolonged heat waves–are increasingly challenging Minnesota's natural systems by threatening ecosystem health, the type and quantity of food and wood production, and surface and groundwater quantity and quality. Because natural habitat often serves as or supports infrastructure in numerous ways, risks to natural habitat can also undermine the resilience of various infrastructure systems, potentially causing cascading effects across interconnected systems. Addressing these challenges is likely to require proactive strategies that reinforce the natural system's ability to be resilient to a range of possible climate futures, safeguard essential ecosystem services, and ensure the long-term well-being of Minnesota's communities.

Recommendations:

- The ***Legislature*** should fund coordinated programs that strengthen the resilience of natural systems and infrastructure, ensuring they receive consistent, long-term, and place-based investments.
- The ***Legislature*** should fund the development of an approach to measure resilience to future weather scenarios that would develop standardized resilience indicators, quantifiable metrics for weather risk, and robust data-gathering tools.
- The ***Department of Administration*** and other agencies with relevant jurisdiction should work with the ***University of Minnesota*** to further develop resilience standards and guidelines that should apply to all the natural systems and infrastructure that reside on state owned land.

Additional Research Needed

The **potential funding** needed to update the state's infrastructure for resilience to future weather scenarios is significant and needs more research. In addition, the siloed and disparate funding mechanisms to support infrastructure + resilience across systems should be researched and revised over time to increase efficiency and impact. **Planning for climate resilience has benefits** for other types of disruptions to infrastructure and there are numerous co-benefits of resilience and sustainability in infrastructure investment.

Recommendations:

- The ***Legislature*** should fund additional research on future weather scenarios and the financial impacts and opportunities to not only infrastructure systems, but also public health, economic impacts/benefits and other societal needs that rely on the materials and process from environmental systems that will change.

Table of Contents

Introduction

In the 2023 Legislative session, a bill was passed to conduct research examining how projections of future weather trends may exacerbate climate conditions, including but not limited to drought, elevated temperatures, and flooding that:

> (1) can be integrated into the design and evaluation of buildings constructed by the state of Minnesota and local units of government, in order to:
>
> > (i) reduce energy costs by deploying cost-effective energy efficiency measures, innovative construction materials and techniques, and renewable energy sources; and
> >
> > (ii) prevent and minimize damage to buildings caused by extreme weather conditions, including but not limited to increased frequency of intense precipitation events and tornadoes, flooding, and elevated temperatures; and
>
> (2) may weaken the ability of natural systems to mitigate the conditions to the point where human intervention in the form of building or redesigning the scale and operation of infrastructure is required to address those conditions in order to:
>
> > (i) maintain and increase the amount and quality of food and wood production;
> >
> > (ii) reduce fire risk on forested land;
> >
> > (iii) maintain and enhance water quality; and
> >
> > (iv) maintain and enhance natural habitats.

This report has been created by an interdisciplinary team from the Institute on the Environment (IonE), University of Minnesota Climate Adaptation Partnership (MCAP), and the Center for Sustainable Building Research (CSBR) at the University of Minnesota. In addition, the team worked with stakeholders from the public and private sectors to gather broad perspectives on the impact of future climate trends and infrastructure policy. The authors encourage additional long-term stakeholder engagement strategies to understand the impact of climate on diverse communities and to solicit ongoing community recommendations for infrastructure improvement.

Infrastructure is the foundational structure on which society is built.[6] In practice, this simple definition often holds, as our infrastructure consists of complex networks of long-lasting and interconnected systems that serve specific place-based societal needs.[7] Examples of different types of infrastructure include: communication networks, transportation systems, and the energy grid. These infrastructures provide services that, if accessible, can enhance human well being, facilitate economic growth, and benefit the environment.[8] However, the escalating impacts of

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[6] Walter Buhr, "What Is Infrastructure?," *Volkswirtschaftliche Diskussionsbeiträge* 107 (2003).

[7] L. A. Bollinger et al., "Climate Adaptation of Interconnected Infrastructures: A Framework for Supporting Governance," *Regional Environmental Change* 14, no. 3 (June 1, 2014): 919–31, https://doi.org/10.1007/s10113-013-0428-4.

[8] Janice Morphet, "The Role of Infrastructure in Society," in *Infrastructure Delivery Planning* (Policy Press, 2016), 1–18, https://bristoluniversitypressdigital.com/display/book/9781447316800/ch001.xml.

climate change,[9] and other future risks,[10] not only endanger current infrastructure[11] but also risk furthering existing social inequalities[12] as well as environmental degradation[13]. The severity of impacts arising from these issues hinges on the *risk* of disruption they pose to infrastructure systems. However, any assessment of this risk will inherently come with *uncertainty* regarding the presence or scale of disruption. Ultimately, decision-making now and in the future will greatly impact the *resilience of infrastructure systems* to disruption.

This report, funded by the State of Minnesota (see Appendix A for the complete funding langage), employs a mixed-methods research approach incorporating interviews, qualitative and quantitative modeling, and analysis to develop the conceptual **Framework for Resilient Infrastructure Policymaking**. The study applies a complex-systems approach to place-based policy formation for enhancing infrastructure resilience. It culminates in proposing a conceptual dynamic policy tool that helps policymakers make scientifically informed decisions for long-term infrastructure resilience. This research contributes to ongoing discussions on practical applications of advances in downscaled future weather modeling and decision-making in the face of future uncertainty.

This study seeks to address several critical research questions. First, it proposes a process for incorporating a social, ecological, and technological systems perspective of infrastructure. By modeling current climatological states, future scenarios, and policy responses, this approach can illuminate new, effective pathways for enhancing resilience and sustainability in response to future risks, including changing weather. Additionally, the research examines whether a Framework for Resilient Infrastructure Policymaking can identify additional risks to infrastructure as compared to current methods. Lastly, it assesses whether the framework can identify opportunities, barriers, and best practices for achieving the State of Minnesota's future goals for infrastructure function and resilience compared to current methods.

The legislative charge for this report required the adoption of a complex systems perspective. Infrastructure is typically viewed as a technology that uses ecological resources to provide for society's needs.[14] Instead, this work considers social, ecological, and technological systems (SETS) and their interaction with infrastructure. From this perspective, infrastructure is seen as a complex, interconnected, and irreducible system of social, ecological, and technological components.[15] The SETS approach is a method of analysis which accounts for dynamic interactions that are at play and includes variables from multiple interconnected systems. This framework allows for a holistic understanding of the climatological system and potential trends

[9] Julie Shortridge and Janey Smith Camp, "Addressing Climate Change as an Emerging Risk to Infrastructure Systems," *Risk Analysis* 39, no. 5 (2019): 959–67, https://doi.org/10.1111/risa.13234.
[10] Krishna Khatri and Kalanithy Vairavamoorthy, "A New Approach of Risk Analysis for Complex Infrastructure Systems under Future Uncertainties: A Case of Urban Water Systems," April 26, 2012, 846–56, https://doi.org/10.1061/41170(400)103.
[11] Edward G. Means III et al., "Impacts of Climate Change on Infrastructure Planning and Design:Past Practices and Future Needs," *Journal AWWA* 102, no. 6 (2010): 56–65, https://doi.org/10.1002/j.1551-8833.2010.tb10130.x.
[12] Santanu Chatterjee and Stephen J. Turnovsky, "Infrastructure and Inequality," *European Economic Review* 56, no. 8 (November 1, 2012): 1730–45, https://doi.org/10.1016/j.euroecorev.2012.08.003.
[13] William F. Laurance et al., "Reducing the Global Environmental Impacts of Rapid Infrastructure Expansion," *Current Biology* 25, no. 7 (March 2015): R259–62, https://doi.org/10.1016/j.cub.2015.02.050.
[14] Helene Ahlborg et al., "Bringing Technology into Social-Ecological Systems Research—Motivations for a Socio-Technical-Ecological Systems Approach," *Sustainability* 11, no. 7 (January 2019): 2009, https://doi.org/10.3390/su11072009.
[15] Samuel A. Markolf et al., "Interdependent Infrastructure as Linked Social, Ecological, and Technological Systems (SETSs) to Address Lock-in and Enhance Resilience," *Earth's Future* 6, no. 12 (2018): 1638–59, https://doi.org/10.1029/2018EF000926.

therein, rather than focusing on isolated elements. By considering the whole system in motion, modeling of future weather trends is able to more clearly identify leverage points and potential unintended consequences.

This research was directed to examine how projections of future weather trends, which may exacerbate damaging conditions, can be integrated into the design and evaluation of infrastructure and buildings funded by the state of Minnesota, in order to reduce energy costs and preserve the investment by preventing and minimizing damage to infrastructure and buildings caused by extreme weather conditions.

For this work, focus areas were operationalized into five infrastructure systems: Water, Agriculture, Forestry, Built Environment, and Natural Habitat. For each system, a high-level social, ecological, and technological systems (SETS) map was created, and potential critical linkages across multiple infrastructure systems emerged as intervention points for the State’s overall capacity for infrastructure resilience.

Chapter 1: Background

Resilient infrastructure is a critical aspect of sustainable development, embodying the ability of a system to absorb shocks and disturbances while maintaining its essential functions. The challenge of the 21st century globally and in Minnesota is to use infrastructure (technology) to support development that provides for society's needs within the capacity of ecological systems[16] Resilient infrastructure systems should be intentionally designed with a recognition of the place-based interconnectedness and interdependence among the technical, ecological, and social systems that form the foundation of all infrastructure. This perspective emphasizes the importance of understanding the unique dynamics and relationships within specific geographic contexts across Minnesota. Accordingly, this report offers preliminary guidance on how to develop policy in the State of Minnesota in order to generate infrastructure that is designed from a place-based understanding of the technical, ecological, and social systems components that uniquely underpin each project. Progressing towards state policies that motivate the building of holistically resilient infrastructure systems is crucial to ensure stability for all Minnesotans to thrive in the future.

Infrastructure Overview

Broadly speaking, infrastructure is a set of basic services that comprise the foundational structure of human society, "matter that moves matter".[17] Yet, the specifics of what infrastructure is, the goals that define how it is designed, and the values that underpin effective infrastructure are variably defined across disciplines and practices. The multidisciplinary decision-making framework presented in this report integrates research across the social sciences, pure sciences, and applied sciences, and employs a multifaceted definition of infrastructure.

Different disciplines explore infrastructure questions in distinct ways and for varied purposes, ranging from understanding its social and cultural implications to optimizing its economic value, environmental sustainability, and technical functionality. For example, in the social sciences, researchers might explore how societal values impact preference for certain types of infrastructure. Factors influencing infrastructure use and preferences may include personal independence or social cohesion, and ultimately shape social and cultural norms around walkability, car dependency, accessibility, and green spaces.[18] Over time, these constructs are reinforced, determining which types of infrastructure systems decision-makers choose to implement and maintain in present society.

[16] https://www.kateraworth.com/doughnut/
[17] Brian Larkin, "The Politics and Poetics of Infrastructure," *Annual Reviews*, accessed September 4, 2024, https://www.annualreviews.org/content/journals/10.1146/annurev-anthro-092412-155522.
[18] Philipp Rollin and Sebastian Bamberg, "It's All Up to My Fellow Citizens. Descriptive Norms as a Decisive Mediator in the Relationship Between Infrastructure and Mobility Behavior," *Frontiers in Psychology* 11 (February 10, 2021), https://doi.org/10.3389/fpsyg.2020.610343.

> **Infrastructure**
>
> Infrastructure includes all built systems and intentionally used ecological systems, that support the use, movement, and transformation of matter (whether physical or digital) for the foundational purposes of society.

Meanwhile, engineers typically focus on the technology of infrastructure.[19] As such, in engineering, the study of infrastructure primarily focuses on the design and construction of objects in the built environment that provide foundational functions and services that enable society. This includes physical infrastructure objects, such as roads and bridges, but also digital ones such as the internet. Infrastructure engineers focus on designing, building, and maintaining these physical and digital infrastructure systems to meet society's needs.

In economics, infrastructure is studied in terms of resource allocation required for its creation and maintenance, as well as the trade-offs between value, benefits, and costs it provides to society. Economic infrastructure, which typically refers to "hard" infrastructure, includes systems that promote economic activity, such as energy, communications, water, and transportation systems.[20]

In public policy, infrastructure is often thought of as the types of projects that require large scale capital investments, typically by the public sector, such as roads, water systems, electricity, and telecommunications. These projects in turn stimulate economic development in the private sector and serve to benefit society as a whole.[21]

In the applied sciences, infrastructure is often thought of as human-made systems that support the foundational purposes of society. Growing research in ecology recognizes that ecosystems can be as infrastructure.[22] Through the concept of natural capital[23] (e.g. the accounting of stocks of natural resources) ecological infrastructure forms a part of the supporting and regulating ecosystem services,[24] i.e.. the direct and indirect benefits that ecosystems provide to society. In practice, when natural processes or ecosystems are intentionally used for infrastructural

[19] Lucy Firth, Karin Boersma, and Bill Melody, “Infrastructure Concepts and Classifications: A Framework for Scenario Analysis of Infrastructures in an Economic Perspective,” in *The Infrastructure Playing Field in 2030: Proceedings of the First Annual Symposium ; Noordwijk, November 19, 1998*, 1999.
[20] Johan Fourie, “Economic Infrastructure: A Review of Definitions, Theory and Empirics,” *South African Journal of Economics* 74, no. 3 (September 1, 2006): 530–56, https://doi.org/10.1111/j.1813-6982.2006.00086.x.
[21] William F. Fox, “Public Infrastructure and Economic Development,” in *Rural Economic Development in the 1980’s: Preparing for the Future* (Agriculture and Rural Economy Division, Economic Research Service, U.S. Department of Agriculture, 1987), 13-1-13–23.
[22] José Maria Cardoso da Silva and Emily Wheeler, “Ecosystems as Infrastructure,” *Perspectives in Ecology and Conservation* 15, no. 1 (January 1, 2017): 32–35, https://doi.org/10.1016/j.pecon.2016.11.005.
[23] Robert Costanza et al., “The Value of the World’s Ecosystem Services and Natural Capital,” *Nature* 387, no. 6630 (May 1997): 253–60, https://doi.org/10.1038/387253a0.
[24] Gretchen C. Daily, “Introduction: What Are Ecosystem Services.,” in *Nature’s Services: Societal Dependence on Natural Ecosystems*, 1 1, 1997.

purposes it is referred to as “green infrastructure.[25] While many of the various definitions of infrastructure that exist in the literature meet the demands of this work, one single definition was not found that did it all. Exhibit 1.1 presents the key definitions of infrastructure that will be used throughout this document. Exhibit 1.1, includes broad definitions for infrastructure and infrastructure policy, along with sector-specific definitions for water, agricultural, forestry, built environment, and natural habitat infrastructure.

Table 1.1:
Definitions of Infrastructure Policy and Infrastructure Sub-types.

Infrastructure Policy	The rules governing all built systems and intentionally used ecological infrastructure systems including definitions, funding, use, design, operation, maintenance, and access.
Water Infrastructure	Water infrastructure includes all built systems and intentionally used ecological systems that support the use, movement, and transformation of water.
Agricultural Infrastructure	Agricultural infrastructure includes all built systems and intentionally used ecological systems that support the production, processing, distribution, consumption, or transformation of grown or raised food and non-food products.
Forestry Infrastructure	Forestry infrastructure includes all built systems and intentionally used ecological systems that support the production, processing, distribution, and consumption of grown wood products.
Built Environment Infrastructure	Built environment infrastructure includes all built systems and intentionally used ecological systems that support the design, construction, operations, and maintenance of foundational built infrastructural systems.
Natural Habitat Infrastructure	Natural habitat infrastructure includes all the built systems and intentionally used ecological systems that support the protection, conservation, adaptation, and enjoyment of natural habitat infrastructure systems.

Infrastructure Policymaking

“Infrastructure policy” is defined as the rules governing all built systems as well as ecological systems intentionally used for infrastructural purposes. Lawmakers and other state government entities design these policies to guide real-world actions toward goals they have established, which can range from specific objectives, such as road treatment procedures for safe winter driving to broader aims like setting standards for road construction. These policies provide a strategic framework to address both existing and emerging infrastructure needs. Currently, the Midwest is facing significant challenges to upgrade and modernize infrastructure systems for a range of societal needs, with varying funding levels, while also addressing the impacts for a range of possible climate futures. Developing and implementing climate resilient infrastructure policies is essential to guide these efforts.

[25] Mark A. Benedict and Edward T. McMahon, *Green Infrastructure: Linking Landscapes and Communities* (Island Press, 2012).

The process of upgrading and modernizing infrastructure in the Midwest will require significant investments into a variety of infrastructure systems, such as the water, agriculture, forestry, built environment, and natural habitat systems that are the focus of this report. According to estimates by the American Society of Civil Engineers (ASCE), the average per capita cost for modernizing these systems in the Midwest is $7,547 (in 2022 dollars).[26] While making these repairs and upgrades are critical, ensuring they are as resilient as possible to the range of likely future weather scenarios is a significant challenge, due to heightened risk for infrastructure failures from increased impacts from changing conditions. Data suggests that many of the existing infrastructure systems in the Midwest lack the design attributes necessary to remain resilient to the types of weather risks that are expected to grow in severity. For example, more frequent severe precipitation and flooding events increase the risk for infrastructure loss over time.[27] Without redesigning infrastructure, repairs to enhance resilience or, in some cases, removal of failed infrastructure are likely to become more frequent and severe due to a range of future weather impacts.

Comprehensive investments will be required to enhance infrastructure resilience to a wide range of weather scenarios across the domains of water, agriculture, forestry, built environment, and natural habitat infrastructure. Adequate funding will be essential to support long-term projects with extended lifespans, ensuring sustained infrastructure improvements . As such, there will be a need to balance policy flexibly (i.e., the ability, necessity, or likelyhood for policies to change over time) with the need for policy constancy (i.e., for a stable governance or funding environment) in order to support the types of long-term infrastructure projects that will be necessary to enhance resilience.[28] Additionally, legislators must foster public support to identify and implement infrastructure projects that align with community interests and needs. Surveys and other tools to understand public perception can provide insight and objectives in the development of local resilience strategies. In some instances there might be limited viable actions for infrastructure resiliency and in those cases care should be given to explain these projects in terms of building community resilience in an attempt to garner public approval. Research supports the notion that cultivating a sense of place is one of the strongest indicators for the presence of disaster resilience in communities.[29] Additionally, significant investment in research and development is crucial to advancing resilient design and construction methodologies, including the adoption of new materials, updating design guidelines, and requiring new training and education for practitioners. For example, increased temperatures place thermal stresses on railways and bridges that could result in buckled rail lines, bridge joint failure, or increased maintenance needs for these infrastructure systems.[30] Lastly, new and revised decision-support tools are necessary to aid local, state and federal policymakers in

[26] ASCE, 2021: A Comprehensive Assessment of America's Infrastructure: 2021 Report Card for America's Infrastructure. American Society of Civil Engineers. https://infrastructurereportcard.org/
[27] Fifth National Climate Assessment. https://nca2023.globalchange.gov/chapter/24/
[28] Jonathan Boston and Judy Lawrence, "The Case for New Climate Change Adaptation Funding Instruments" (Institute for Governance and Policy Studies, 2017), https://ir.wgtn.ac.nz/server/api/core/bitstreams/de17424d-d7cb-43ac-b583-295e4cc46831/content.
[29] Helen Boon et al., *Recovery from Disaster: Resilience, Adaptability and Perceptions of Climate Change* (Gold Coast: National Climate Change Adaptation Research Facility, 2012).
[30] John Posey, "Climate Change Impacts on Transportation in the Midwest," U.S. National Climate Assessment Midwest Technical Input Report, 2012.

crafting informed, complex policies that enhance system resilience, decrease costs, and minimize tradeoffs, through an integrated approach to infrastructure planning.

Infrastructure Policy Capacity

Current policies designed to meet Minnesota's infrastructure goals may not be effective across a range of plausible climate futures, especially if those policies are faced with unexpected shocks or changes to the context for which the policies were designed. The ability of existing infrastructure policy to remain effective in achieving their goals across various plausible futures is known as policy capacity.[31] There are several ways to test a policy's capacity to handle future disturbances. This section will provide an overview of some of those approaches.

To develop infrastructure policies that have the capacity to remain effective in the face of future climate uncertainty, decision-makers should base their policy design strategies on the latest scientific projections of future climate conditions. The future climate data for Minnesota, in this report, was modeled by the University of Minnesota Climate Adaptation Partnership (MCAP). The data was used to analyze the potential impacts of future weather scenarios on the capacity of existing infrastructure policies to meet their intended goals. In doing so, this report assessed whether current goals for infrastructure in Minnesota which inform the design of infrastructure policies, and the tactics used to achieve them, remain viable in light of future climate projections.

Risks to Infrastructure Systems

Risk is a term for measuring the probability for and severity of an undesirable event, temporally and spatially.[32] In decision-making, understanding the different types of risks facing infrastructure systems is helpful for developing scientifically informed strategies, goals, and action priorities for a particular context. As this research is focused on the impact of future weather and climate trends to infrastructure systems, the risk studied in this report is primarily climate risk. Yet, climate risks are complex and it is important to be able to explain their impact both temporally and spatially. infrastructure systems were assessed temporally through the near-term (2024-2040), mid-term (2041-2060), and long-term (2081-2100) projections used in IPCC Sixth Assessment Report.[33] This differentiates risk across time and intensity by identifying immediate and long-term threats to infrastructure and the natural environment. Spatially, climate risk falls into two categories: *physical risk*, which describes the risk of infrastructure systems succumbing to physical effects of nature due to climate change, and *transition risk*, which describes the risk of infrastructure systems to responses to combat climate change impacts.[34] The degree of risk to an infrastructure system is dependent on the hazards, vulnerabilities, and

[31] Jonathan Craft and Michael Howlett, "Policy Capacity and the Ability to Adapt to Climate Change: Canadian and U.S. Case Studies," *Review of Policy Research* 30, no. 1 (2013): 1–18, https://doi.org/10.1111/ropr.12000.
[32] Yacov Y. Haimes, "On the Complex Definition of Risk: A Systems-Based Approach," *Risk Analysis* 29, no. 12 (2009): 1647–54, https://doi.org/10.1111/j.1539-6924.2009.01310.x.
[33] "Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" (Geneva, Switzerland: IPCC, 2023), 10.59327/IPCC/AR6-9789291691647.
[34] Ajay Gambhir et al., "Near-Term Transition and Longer-Term Physical Climate Risks of Greenhouse Gas Emissions Pathways," *Nature Climate Change* 12, no. 1 (January 2022): 88–96, https://doi.org/10.1038/s41558-021-01236-x.

exposures that the system is faced with due to climate change, as well as current and future climate responses.[35] Lastly, infrastructure risk can be simple, such as increased flood risk to transportation from higher spring rainfall, or complex, involving systemic, cascading, or compounding factors[36]—like agricultural drain tile installation, which reduces soil moisture retention and compounds spring flood risk through higher runoff rates alongside increased rainfall. The definitions used in this report for infrastructure risk and its determinants for infrastructure systems and policy can be found in Table 1.2 below.

Table 1.2:
Definition of Risk and its Determinants for Infrastructure Systems and Policy.

Risk(s) to Infrastructure[37]	The potential for adverse consequences for human or ecological infrastructure systems, and other interconnected systems, recognising the diversity of values and objectives associated with the functioning of such infrastructure systems.
Infrastructure Risk Management[38]	Plans, actions, strategies or policies to reduce the likelihood and/or magnitude of adverse potential consequences, based on assessed or perceived risks to infrastructure systems.[39]
Infrastructure Hazard[40]	The possible future occurrence of natural or human-induced physical events that may have adverse effects on vulnerable and exposed infrastructure systems and other interconnected elements.[41]
Infrastructure Exposure[42]	The inventory of infrastructure systems and other interconnected elements in an area in which hazard events may occur.
Infrastructure Vulnerability[43]	The propensity of exposed infrastructure systems and other interconnected elements such as human beings, their livelihoods, and assets to suffer adverse effects when impacted by hazard events.

[35] Nicholas P. Simpson et al., "A Framework for Complex Climate Change Risk Assessment," *One Earth* 4, no. 4 (April 23, 2021): 489–501, https://doi.org/10.1016/j.oneear.2021.03.005.
[36] Simpson et al.
[37] Adapted from "Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change."
[38] Adapted from Andy Reisinger, Mark Howden, and Carolina Vera, "The Concept of Risk in the IPCC Sixth Assessment Report: A Summary of Cross-Working Group Discussions" (Geneva, Switzerland: IPCC, 2020).
[39] Adapted from Cardona O.D. et al., "Determinants of Risk: Exposure and Vulnerability.," in *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, ed. Field C.B. et al., A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC) (Cambridge, UK, and New York, NY, USA: Cambridge University Press, 2012), 65–108.
[40] Adapted from Reisinger, Howden, and Vera, "The Concept of Risk in the IPCC Sixth Assessment Report: A Summary of Cross-Working Group Discussions."
[41] Adapted from O.D. et al., "Determinants of Risk: Exposure and Vulnerability."
[42] Adapted from Reisinger, Howden, and Vera, "The Concept of Risk in the IPCC Sixth Assessment Report: A Summary of Cross-Working Group Discussions."
[43] Adapted from Reisinger, Howden, and Vera.

Infrastructure Response[44]	The possibility of responses to the risks to infrastructure systems and policy not achieving their intended objectives or having trade-offs or adverse side effects for other societal objectives.

Risk management approaches—such as sustainability, resilience, and robustness—offer strategies to mitigate potential climate catastrophes. For instance, a floodplain may be an infrastructure hazard to inhabitants of an area. However, behavior changes of residents and structural adaptation are likely to reduce vulnerabilities and minimize potential losses. To evaluate efficacy of infrastructure and policy capacity across the range of plausible climate futures, it is important to consider how existing policies incorporate (or lack) sustainability, resilience, and robustness measures. Here, sustainable infrastructure is defined using a modified version of the definition of sustainability set by the State of Minnesota's Office of Enterprise Sustainability.[45] *Sustainable Infrastructure* is the development of infrastructure policies and systems that meet the economic, social, and environmental needs of the present without compromising the ability of future generations to meet their needs. Additionally, this report defines *infrastructure resilience*, adapted from the definition of resilience from the Brundtland report,[46] as "the ability of infrastructure policies and systems to withstand and recover from disruptions or unexpected changes, ensuring they can adapt to various plausible disruptions." This is equivalent to the definition of infrastructure resilience by Poulin and Kane,[47] except for the explicit inclusion of infrastructure policies into the definition due to the focus of this report. Lastly, *infrastructure robustness*, adapted from a more general definition of robustness from Munoz and Billsberry,[48] here means the capability of infrastructure policies and systems to maintain, cope, and withstand extreme events or stresses. These definitions can be found in Table 1.3. By examining these factors, amongst others, policymakers can better assess the capacity of existing infrastructure policies and systems to remain effective in achieving their designed goals amidst a range of plausible futures.

Table 1.3:
Definitions of Key Terms that Describe the Ability for Infrastructure and Infrastructure Policy to Meet Challenges.

Infrastructure Policy Capacity[49]	The ability of existing infrastructure policy approaches to remain effective in achieving their goals across various plausible futures.
Sustainable Infrastructure	The development of infrastructure policies and systems that meet the needs of the present without compromising the ability of future generations to meet their own needs.

[44] Adapted from A.R. Begum et al., "Point of Departure and Key Concepts," in *Climate Change 2022: Impacts, Adaptation and Vulnerability.*, ed. H.-O. Pörtner et al., Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge, UK and New York, NY, USA: Cambridge University Press, n.d.), 121–96, 10.1017/9781009325844.003.
[45] "Office of Enterprise Sustainability," Minnesota.gov, accessed November 1, 2024, https://mn.gov/admin/government/sustainability/.
[46] G.H. Brundtland, "Our Common Future: Report of the World Commission on Environment and Development" (Geneva, 1987), http://www.un-documents.net/ocf-ov.htm.
[47] Craig Poulin and Michael B. Kane, "Infrastructure Resilience Curves: Performance Measures and Summary Metrics," *Reliability Engineering & System Safety* 216 (December 1, 2021): 107926, https://doi.org/10.1016/j.ress.2021.107926.
[48] Albert Munoz, Jon Billsberry, and Véronique Ambrosini, "Resilience, Robustness, and Antifragility: Towards an Appreciation of Distinct Organizational Responses to Adversity," *International Journal of Management Reviews* 24, no. 2 (2022): 181–87, https://doi.org/10.1111/ijmr.12289.
[49] Craft and Howlett, "Policy Capacity and the Ability to Adapt to Climate Change."

Infrastructure Resilience	The ability of infrastructure policies and systems to withstand and recover from disruptions or unexpected changes, ensuring they can adapt to various plausible disruptions
Infrastructure Robustness	The capability of infrastructure policies and systems to maintain, cope, and withstand extreme events or long-term stresses.

Interplay of Resiliency and Sustainability in Infrastructure

Infrastructure systems vary widely in their ability to balance resilience and sustainability. Systems that are neither resilient nor sustainable include single-purpose dams, coastal highways, monoculture agricultural systems, and fossil fuel energy systems. These are vulnerable to environmental stressors, therefore lack resilience, and are also unsustainable due to their degradation of ecosystems and high resource demands.

On the other hand, some systems are resilient but not sustainable, such as stormwater pipes capable of handling extreme weather, which is system resilience, yet transport untreated runoff—due to a stormwater system design that allows for an overflow of untreated sewage—into river ecosystems, causing unsustainable ecosystem damage through the pollution. Other examples include coastal hardening, offshore oil rigs, desalination plants, and nuclear power plants, which, despite their durability, face long-term sustainability challenges like environmental degradation and finite resource depletion.

In contrast, sustainable but not resilient systems, such as organic farms relying on natural water sources or passive heating and cooling in buildings, operate with minimal environmental impact, meaning the system is sustainable, but can fail under extreme weather events, meaning the system lacks resiliency.

Finally, some systems aim to be both resilient and sustainable, like adaptive coastlines designed to flood during storms, providing flood protection, while offering recreational opportunities at other times, green roofs, floodplain restoration projects, and distributed renewable energy grids, offering a more balanced approach compared to the status quo.

Chapter 2: Future Minnesota Climate

Changes We've Already Observed

Climate data and observations demonstrate that Minnesota's weather patterns are already changing. We can expect these trends to continue in the coming years.

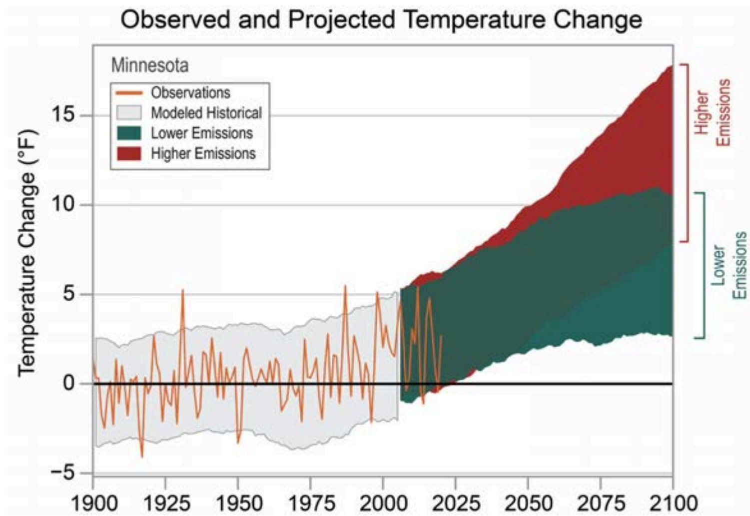

Figure 2.1: Observed and projected temperature changes in Minnesota under "lower" (teal) and "higher" (red) emissions scenarios out to 2100 compared to historical temperature observations (orange). Source: Minnesota State Climate Summary[50]

Between 1895 and 2023, the **average annual temperature in Minnesota has increased by 3.0°F.**[51] Warming trends have accelerated in recent years; the rate of warming between 1980 and 2010 was greater than between 1950 and 2010.[52] Eight of the ten warmest years on record have also occurred since 1998.[53] The most marked warming occurs in the coldest months of the year. Of note, northern Minnesota has suffered the most significant warming, considering regional distinctions. Daily average minimum temperatures during winter (Dec-Feb) have increased 7.3 degrees from 1895-2021 in northern Minnesota, 6 degrees in central Minnesota and 4.9 degrees in southern Minnesota.

The state has also experienced, on average, an increase of 3.3 inches of precipitation per year between 1895 and 2023. Significantly, the number of weather events bringing more than 2 inches of precipitation has increased dramatically in recent years; the years 2015-2020 had the highest multi-year precipitation average on record.[46].

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[50] Kunkel, K.E., R. Frankson, J. Runkle, S.M. Champion, L.E. Stevens, D.R. Easterling, B.C. Stewart, A. McCarrick, and C.R. Lemery (Eds.), 2022: State Climate Summaries for the United States 2022. NOAA Technical Report NESDIS 150. NOAA/NESDIS, Silver Spring, MD.
[51] Historical climate data from Minnesota Department of Natural Resources, https://arcgis.dnr.state.mn.us/ewr/climatetrends/
[52] Pryor, S. C., D. Scavia, C. Downer, M. Gaden, L. Iverson, R. Nordstrom, J. Patz, and G. P. Robertson, 2014: Ch. 18: Midwest. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 418-440. doi:10.7930/J0J1012N.
[53] Runkle, J., K.E. Kunkel, R. Frankson, D.R. Easterling, S.M. Champion, 2022: Minnesota State Climate Summary 2022. NOAA Technical Report NESDIS 150-MN. NOAA/NESDIS, Silver Spring, MD, 4 pp.

Lake Superior is a critical asset to Minnesota from a social, ecological, and technological perspective. It is also one of the world's fastest warming lakes[54] with water temperatures increasing about 1°F per decade since 1980.[55]. Lake Superior's annual maximum ice cover has decreased over recent decades[56]. Increased water temperatures and ice cover declines have the potential to further alter the regional climate in northeast Minnesota through increased evaporation and potential for increased lake effect snowfall.[57] Ice is also melting faster in the inland lakes in Minnesota's northeastern region; the 1854-Ceded Territory have also seen earlier ice out dates in the spring[58] with ice out dates occurring, on average 2-5 days earlier.

Future Climate Projections[59]

Future climate projections are presented using the nine regional climate divisions dictated by the National Oceanic and Atmospheric Administration (NOAA). These divisions are structured to coincide with county boundaries and cover the total area of the state. A list of counties included in each region can be found at: https://climate.umn.edu/regional-climate-summaries.

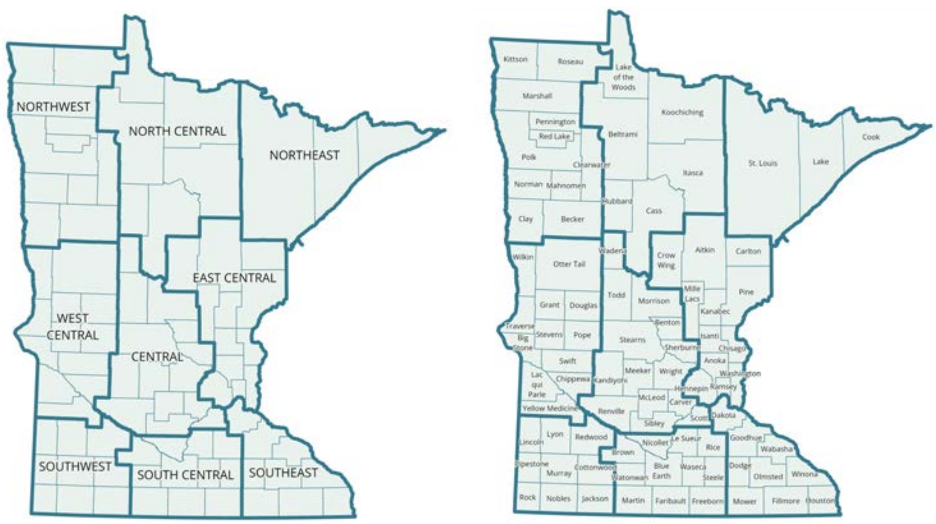

Figure 2.2: The nine NOAA regional climate divisions in Minnesota (left) and the counties in each region (right).

[54] O'Reilly et al., 2015 "Rapid and Highly Variable Warming of Lake Surface Waters around the Globe." *Geophysical Research Letters*. https://doi.org/10.1002/2015GL066235
[55] Austin and Colman, 2008. "A Century of Temperature Variability in Lake Superior." *Limnology and Oceanography*. https://doi.org/10.4319/lo.2008.53.6.2724
[56] Ozersky et al., 2021. "The Changing Face of Winter." *Journal of Geophysical Research*. https://doi.org/10.1029/2021JG006247
[57] Vavrus, Notaro, and Zarrin, 2013. "The Role of Ice Cover in Heavy Lake-Effect Snowstorms over the Great Lakes Basin as Simulated by RegCM4." *American Meteorological Society Monthly Weather Review*. https://doi.org/10.1175/MWR-D-12-00107.1
[58] Stults. M., Petersen, S., Bell, J., Baule, W.,Nasser, E., Gibbons, E., Fougerat., M., 2016.Climate Change Vulnerability Assessment and Adaptation Plan: 1854 Ceded Territory Including the Bois Forte, Fond du Lac, and Grand Portage Reservations. Duluth, MN: 1854 Ceded Territory.
[59] Liess, S. Roop, H.A., Twine, T.E., Noe, R., Meyer, N., Fernandez, A., Dolma, D., Gorman, J., Clark, S., Mosel, J., Farris, A., Hoppe, B., Neff, P. 2023. Fine-scale Climate Projections over Minnesota for the 21st Century. Prepared for the University of Minnesota Climate Adaptation Partnership. V1 released October 2023.

Temperature

Future projections forecast that by mid-century (2040 -2059) the daily maximum temperature in Minnesota (averaged annually) will increase between 3.6°F (intermediate emissions scenario[60]) and 4.2°F (very high emissions scenario[61]).

Conforming with previously observed trends, future temperature increases are likely to raise wintertime low temps.

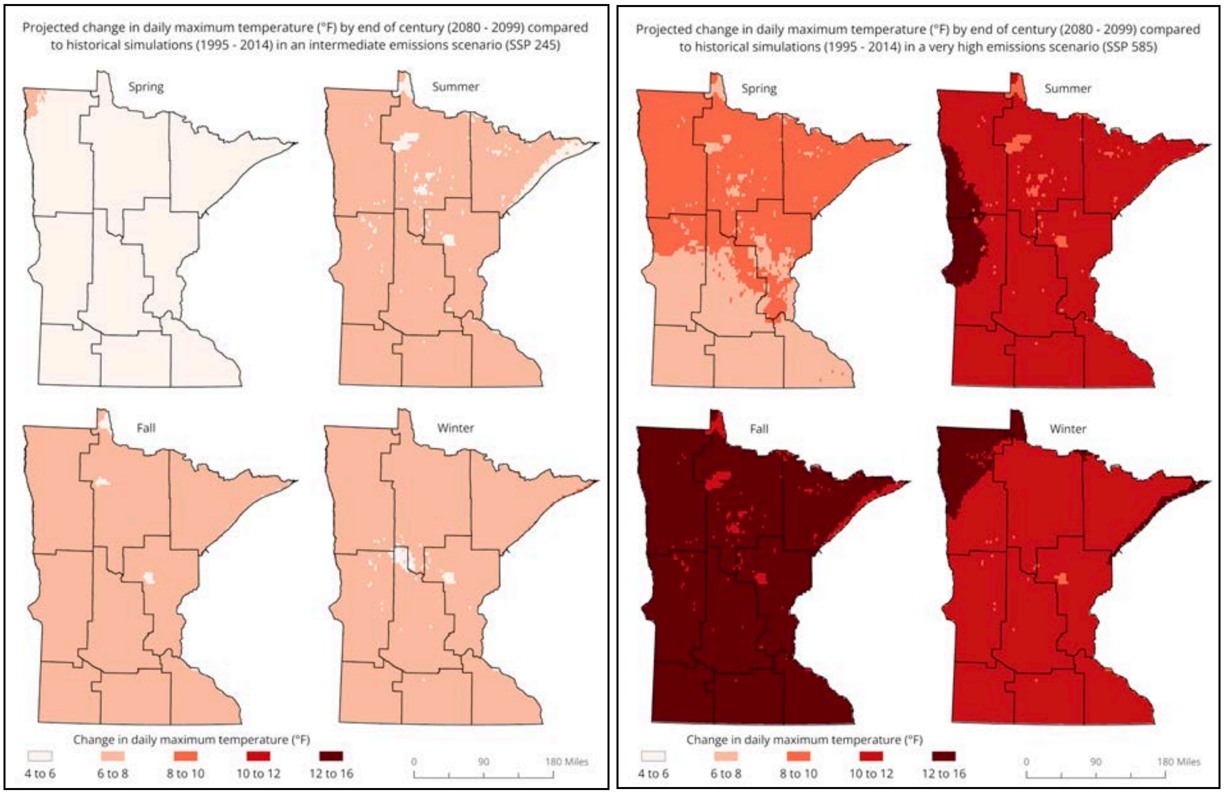

Figure 2.3: Projected change in seasonal daily maximum temperature (°F) by end-of-century (2080-2099) under intermediate (left) and very high (right) emissions scenarios, compared to historical simulations (1995-2014). These maps demonstrate the unequal distribution of higher temperatures throughout the year, which is not well-represented by annual averages.

Summers will warm too, though the changes to winter conditions will be more dire in the next century. Daily maximum temperatures in the summer are projected to increase by 5.5°F (very high emissions scenario). The average annual number of days exceeding 90 degrees F is projected to increase to 29 days per year by mid-century and 58 days per year by end-of-century(very high emissions scenario), compared to 14 days per year as represented by historical simulations (1995-2014). The table below shows the regional differences in these projected extreme heat days.

[60] Intermediate emissions scenario: “business as usual” economic, social and technological trends (SSP245)
[61] Very high emissions scenario: driven by increased fossil fuel consumption (SSP585)

Projected change in number of days that exceed 90°F										
		North West	**North Central**	**North East**	**West Central**	**Central**	**East Central**	**South West**	**South Central**	**South East**
Intermediate Emissions Scenario	**2040-2059**	+12	+6	+3	+17	+16	+11	+19	+19	+16
	2080-2099	+26	+16	+8	+34	+33	+25	+36	+36	+33
Very High Emissions Scenario	**2040-2059**	+17	+10	+5	+24	+23	+17	+26	+25	+22
	2080-2099	+51	+34	+22	+56	+56	+46	+60	+59	+55

Table 2.1: Projected changes in hot temperature extremes by mid-century (2040–2059) and end-of-century under intermediate (SSP245) and very high (SSP585) emissions scenarios relative to historical simulations (1995–2014).

Historical simulations (1995–2014) average the current annual number of days with a minimum temperature below 32 degrees F at 158 days. This number is projected to decrease to 133 days per year by mid-century and 96 days per year by end-of-century (very high emissions scenario). Nearly a month less of freezing temps by mid-century and two months less by end-of-century spells [what is the direct impact to humans and ecosystems]. The table below shows the regional differences in these projected changes in cold weather days.

Projected change in number of days with a minimum temperature below 32°F										
		North West	**North Central**	**North East**	**West Central**	**Central**	**East Central**	**South West**	**South Central**	**South East**
Intermediate Emissions Scenario	**2040-2059**	-21	-20	-20	-21	-22	-22	-21	-21	-21
	2080-2099	-37	-35	-35	-36	-37	-37	-35	-37	-37
Very High Emissions Scenario	**2040-2059**	-25	-23	-23	-25	-25	-25	-24	-25	-25
	2080-2099	-63	-60	-60	-62	-63	-63	-61	-62	-62

Table 2.2: Projected changes in cold temperature extremes by mid-century (2040–2059) and end-of-century under intermediate (SSP245) and very high (SSP585) emissions scenarios relative to historical simulations (1995-2014).

Precipitation

Precipitation patterns (rain and snowfall) across the state are projected to intensify, bringing wetter springs, drier summers, shorter snow seasons, heavier rain events, and longer dry spells without measurable rainfall. On average, rain events are projected to intensify, meaning more rain will likely fall in a single storm, with longer dry periods in between[62]. By end-of-century, the amount of rain that falls in a 2-day rain event in Minnesota is expected to increase, on average, by 0.4 to 1.2 inches for both intermediate and very high emissions scenarios. By end-of-century, statewide average annual precipitation is projected to decrease 0.1 inches under an intermediate emissions scenario, but is projected to increase 3.2 inches under a very high emissions scenario. However, projected changes vary widely by region. The southeast region of the state is projected to see the highest precipitation increases with annual precipitation increases of 4.4 inches relative to historical simulations (1995–-2014).

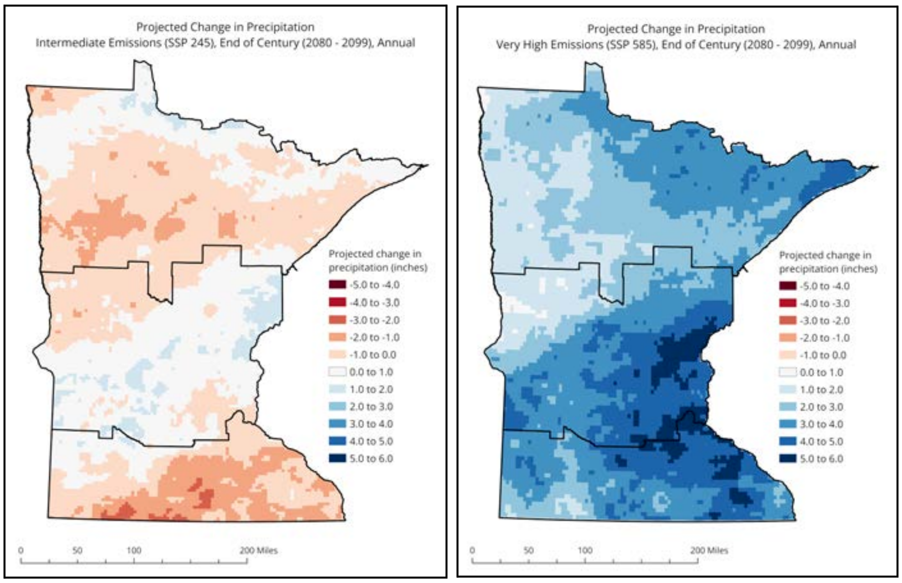

Figure 2.4: Projected change in average annual precipitation (inches) by end-of-century (2080-2099) under intermediate (left) and very high (right) emissions scenarios, compared to historical simulations (1995-2014).

Precipitation is also not projected to change uniformly throughout the year, often with wintertime and springtime averages projected to increase, and summertime averages projected to decrease (see maps below). In the higher emissions scenarios, summertime droughts are expected to reach such extremes so as to lower annual average values overall.

[62] Akinsanola, A A., G. J. Kooperman, A.G. Pendergrass, W.M. Hannah, and K.A. Reed, 2020. “Seasonal Representation of Extreme Precipitation Indices over the United States in CMIP6 Present-Day Simulations.” *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/ab92c1

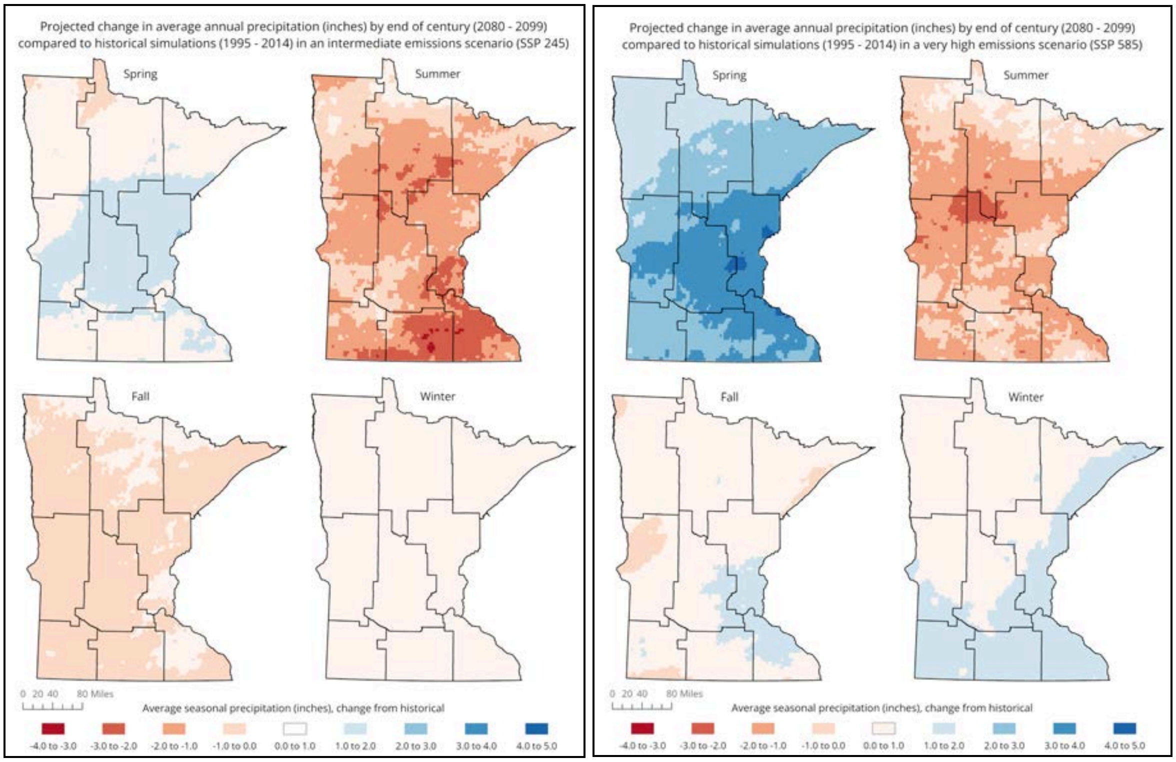

Figure 2.5: Projected change in average seasonal precipitation (inches) by end-of-century (2080-2099) under intermediate (left) and very high (right) emissions scenarios, compared to historical simulations (1995-2014). These maps demonstrate the unequal distribution of precipitation changes in each season, which is not well-represented by annual averages.

Projected annual maximum 2-day total precipitation (inches)										
		North West	**North Central**	**North East**	**West Central**	**Central**	**East Central**	**South West**	**South Central**	**South East**
Intermediate Emissions Scenario	**2040-2059**	4.1	3.9	3.6	4.8	5.0	4.6	5.5	5.9	5.6
	2080-2099	4.0	3.8	3.7	4.5	4.9	4.6	5.2	5.3	5.5
Very High Emissions Scenario	**2040-2059**	3.9	3.8	3.6	4.3	4.6	4.4	5.1	5.4	5.4
	2080-2099	4.5	4.3	4.3	5.2	5.7	5.4	6.1	6.7	6.8

Table 2.3: Projected changes in precipitation extremes by mid-century (2040-2059) under intermediate (SSP245) and very high (SSP585) emissions scenarios relative to historic simulations (1995-2014).

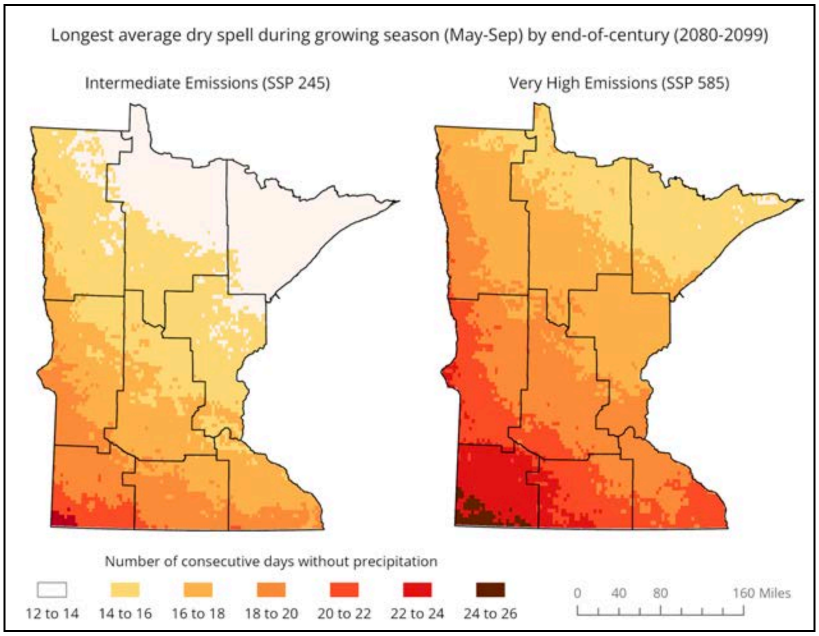

Figure 2.6: Projected number of consecutive days without precipitation during the growing season (May - September) by end-of-century (2080 - 2099) under intermediate (SSP245; left) and very high (SSP585; right) emissions scenarios.

Additionally, due to warming temperatures, by mid-century, the number of days per year with at least 1 inch of snow cover is expected to decline by 12 (intermediate emissions) to 15 (very high emissions) days. By end-of-century, the number of days per year is projected to decrease even further, from 23 days under an intermediate emissions to 39 days under very high emissions (see Figure 7 below).

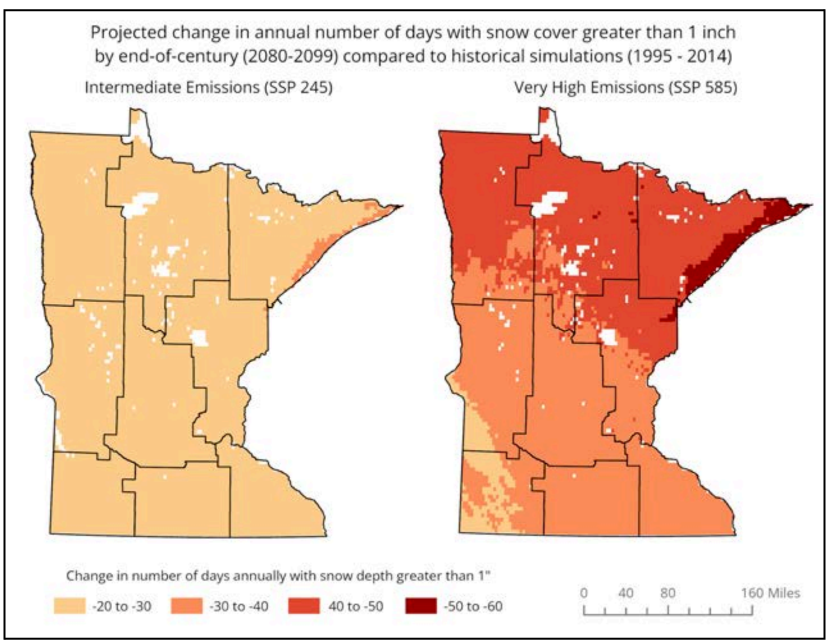

Figure 2.7: Projected change in annual number of days with snow cover greater than 1 inch by end-of-century (2080 - 2099).under intermediate (left) and very high (right) emissions scenarios compared to historical simulations (1995 - 2014).

Implications of Future Weather Scenarios for Minnesota Infrastructure

Changing climate trends present a variety of current and potential future challenges to infrastructure systems in Minnesota.

> **Shocks and Stresses on the Water System**
>
> During an Expert Input session, one Met Council employee shared that when they were starting the position, they were told to expect a flood response once every ten years. In reality, in the last 12 years, there were 5 instances of shifting to a flood response. These flood events are very disruptive and costly, and are the types of shocks to our system that can be expected with increasing frequency.
>
> There are persistent issues too, known as stressors. For example, drought conditions in the summer lead to lower oxygen levels in waterways which affects the health of everything in the water, and the water itself. The Met Council deals with this by aerating water ways, which can disrupt the functioning of essential microbes and uses energy, further contributing to greenhouse gas emissions.

Possible Future Climate Impacts to Water Infrastructure

Although overall springtime precipitation is expected to increase in Minnesota, the number of days with measurable rainfall is projected to decline, meaning more concentrated and intense rain events that will increase flood risk. These intense rainfall events often overwhelm stormwater infrastructure, resulting in injuries, fatalities, and the spread of waterborne diseases[63]. As spring precipitation increases, runoff into waterways is also expected to rise, leading to soil erosion[64], nutrient runoff[65], and poor water quality[66]. In urban areas, the higher proportion of paved surfaces exacerbates flood risks, causing transportation disruptions and strain to aging stormwater systems. Moreover, heightened summertime temperatures and the associated drought risks[67] will likely lead to increased water demand, pressuring our supply. Southeast Minnesota, with its karst landscape, faces unique challenges with water quality and flooding, which will likely worsen due to heavy precipitation events that increase runoff and nutrient leaching. The region is projected to experience some of the most significant decreases in summertime precipitation and increases in wintertime precipitation in the state, resulting in

[63] Payton, et. al. 2023. Ch. 4. Water. In: 5th National Climate Assessment Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds., Fifth National Climate Assessment. U.S. Global Change Research Program, Washington, DC.

[64] Srivastava, A., Grotjahn, R., Ullrich, P.A., 2020. Evaluation of historical CMIP6 model simulations of extreme precipitation over contiguous US regions. Weather and Climate Extremes 29, 100268. https://doi.org/10.1016/J.WACE.2020.100268

[65] Baule, W.J., Andresen, J.A., Winkler, J.A., 2022. Trends in Quality Controlled Precipitation Indicators in the United States Midwest and Great Lakes Region. Front. Water 4. https://doi.org/10.3389/frwa.2022.817342

[66] Johnson, T., Butcher, J., Santell, S., Schwartz, S., Julius, S., LeDuc, S., 2022. A review of climate change effects on practices for mitigating water quality impacts. J Water Clim Chang 13, 1684–1705. https://doi.org/10.2166/wcc.2022.363

[67] Otkin, J.A., Woloszyn, M., Wang, H., Svoboda, M., Skumanich, M., Pulwarty, R., Lisonbee, J., Hoell, A., Hobbins, M., Haigh, T., Cravens, A.E., 2022. Getting ahead of Flash Drought: From Early Warning to Early Action. https://doi.org/10.1175/BAMS-D-21-0288.1

fluctuating surface water levels and necessitating adaptable water storage solutions to meet demand[68].

Possible Future Climate Impacts to Agriculture Infrastructure

Increasing air temperatures in Minnesota's warmer months are elevating rates of evapotranspiration - the process of water movement from land to the atmosphere by evaporation from the soil and bodies of water, and by transpiration from plants. Minnesota's warm months are becoming hotter, increasing intensity and duration of evapotranspiration. Higher rates of evapotranspiration could in turn increase the risk of rapid-onset droughts. Both of these factors could severely impact crop yields and plant health. While higher early spring temperatures may initially benefit small grains like barley and oats, prolonged heat into the summer may be detrimental to yields[69]. Intense winter and spring precipitation can lead to ponding and soil saturation, damaging young crops, particularly root crops like sugar beets, which are at greater risk for root rot under warm soil conditions. Increased spring and heavy winter precipitation may saturate soils and flood fields, resulting in more frequent workday losses and impaired root growth[70]. Wetter pastures can heighten the risk of livestock diseases in the feet and complicate nutrition management[64]. Additionally, milder winter temperatures pose risks to perennial forage crops such as alfalfa, increasing their vulnerability to winter injury. Crop models indicate that sustained temperatures above 86°F can lead to declines in corn and soybean yields[64]. Furthermore, increased spring precipitation is likely to facilitate greater pest and disease transmission, while decreased summer rainfall may adversely affect a range of crops, from fresh market vegetables to grains. Although rising temperatures may allow for earlier planting and the expanded use of cover crops[64], they also heighten the risk of new or worsening pest infestations[62]. While future projected climate conditions present substantial risks to Minnesota's agricultural sector, there are also ample opportunities to divert repercussions through solutions such as crop diversification and water storage management.

Possible Future Climate Impacts to Forestry Infrastructure

Climate-driven changes in forest composition and health are likely to impact local economies and cultural practices in Minnesota communities that depend on forests for recreation, tourism, and timber. With fewer days below freezing, winter timber harvests may be reduced or shifted, affecting forestry operations[71]. Longer summer dry spells, particularly when combined with heat, can stress local tree species such as paper birch, balsam fir, and cedar[72]. Increasing temperatures and altered precipitation patterns are likely to result in more frequent and severe droughts, further compromising tree health and growth, especially for non-drought-resistant

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[68] Wilson et al. 2023. Ch. 24. Midwest. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds., Fifth National Climate Assessment. U.S. Global Change Research Program, Washington, DC.

[69] Klink, K., Wiersma, J.J., Crawford, C.J., Stuthman, D.D., 2014. Impacts of temperature and precipitation variability in the Northern Plains of the United States and Canada on the productivity of spring barley and oat. Int. J. Climatol. 34, 2805–2818. https://doi.org/10.1002/joc.3877

[70] Roop et al. 2024. Climate Change Impacts on Minnesota Agriculture. United States Department of Agriculture Climate Hubs, University of Minnesota Climate Adaptation Partnership and Great Lakes Research Integrated Science Assessment, Ames, IA.

[71] Contosta, Alexandra R., Nora J. Casson, Sarah Garlick, Sarah J. Nelson, Matthew P. Ayres, Elizabeth A. Burakowski, John Campbell, et al. 2019. Northern Forest Winters Have Lost Cold, Snowy Conditions That Are Important for Ecosystems and Human Communities. *Ecological Applications* 29, no. 7: e01974. https://doi.org/10.1002/eap.1974.

[72] Reich, P.B., Sendall, K.M., Stefanski, A., Rich, R.L., Hobbie, S.E., Montgomery, R.A., 2018. Effects of climate warming on photosynthesis in boreal tree species depend on soil moisture. *Nature* 562, 263–267. https://doi.org/10.1038/s41586-018-0582-4

species. Warmer conditions may also shift suitable habitats, leading to species decline in cold-climate trees, giving way to heat-tolerant species. Growth rates may vary among species, with some thriving in warmer conditions while others suffer, influencing timber production and forest management strategies. Additionally, milder winters can enhance the survival rates of pests like the emerald ash borer, threatening native trees, while changing conditions may affect the spread and severity of tree diseases[73]. Higher temperatures and drier conditions elevate wildfire risks, endangering forest ecosystems, air quality, and human safety. As forests play a crucial role in sequestering carbon, changes in tree health, species composition, and overall forest cover could undermine their ability to absorb CO2, potentially worsening future climate scenarios[74]. Despite ongoing losses, forests still cover one-third of Minnesota's land, home to 53 native tree species.[75] Of all potential nature-based solutions available to our State, forest stewardship (reforestation, management) offers the highest opportunity for carbon storage.[76]

Possible Future Climate Impacts to Built Environment Infrastructure

Future weather scenarios have the potential to significantly impact the built environment in Minnesota. Increased flooding from more frequent and intense rainfall events overwhelm stormwater systems and damage infrastructure. Rising temperatures heighten energy demand for cooling, straining power grids and increasing utility costs. Cooling systems in existing buildings are also likely to be strained,causing unsafe indoor temperatures for some[77]. Milder winters affect the longevity and performance of building materials designed for colder conditions, resulting in premature deterioration[78]. High density of impervious surfaces (e.g., paved roads, parking lots, roofs, sports fields with highly compacted soil) in urban areas may cause more intense heat island effects, exacerbating heat-related health issues. Furthermore, more severe weather events and temperature fluctuations lead to higher maintenance and repair costs for buildings and infrastructure. Changing precipitation patterns also impact water supply and quality, necessitating upgrades to water management infrastructure, such as stormwater drainage and storage, sewer systems, and treatment plants. Existing buildings may require retrofitting for protection against extreme weather, including stronger roofs and enhanced drainage. Transportation networks face disruption from flooding and winter storms, impacting accessibility and safety. Additionally, shifts in local ecosystems can affect green infrastructure, such as urban trees and parks, which play a crucial role in providing shade and managing stormwater. Warmer temperatures contribute to increased invasive pest activity (e.g.,

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[73] Ryan D. DeSantis, W. Keith Moser, Dale D. Gormanson, Marshall G. Bartlett, Bradley Vermunt. 2013. Effects of climate on emerald ash borer mortality and the potential for ash survival in North America. *Agricultural and Forest Meteorology*, 178–179, 120-128. https://doi.org/10.1016/j.agrformet.2013.04.015

[74] Anderegg, William R. L., Anna T. Trugman, Grayson Badgley, Christa M. Anderson, Ann Bartuska, Philippe Ciais, Danny Cullenward, et al.2020. Climate-Driven Risks to the Climate Mitigation Potential of Forests. *Science* 368,. 6497. https://doi.org/10.1126/science.aaz7005.

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[78] Al-Shatnawi, Zahra, Caroline Hachem-Vermette, Michael Lacasse, and Bahador Ziaeemehr. 2024. Advances in Cold-Climate-Responsive Building Envelope Design: A Comprehensive Review." *Buildings* 14, 11: 3486. https://doi.org/10.3390/buildings14113486.

termites[79]), weakening building integrity and demanding maintenance. Lastly, climate-related factors pose public health risks, prompting the need for changes in building designs to improve air quality and ensure access to healthcare facilities[80].

Possible Future Climate Impacts to Natural Infrastructure

Future climate impacts to natural ecosystems in Minnesota presents a variety of ecological and economic challenges. These natural systems are vital *infrastructure* insofar as they are public systems and resources providing a variety of services. Ecosystems and natural habitats are often termed "green" (land) and "blue" (water) infrastructure. Green (or blue-green) infrastructure provides the building blocks for solving urban and climatic challenges by building *with* nature.[81] Green infrastructure are "strategically planned network[s] of natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services, while also enhancing biodiversity." Such services include, for example, water purification, air quality improvements, space for recreation, as well as climate mitigation and adaptation solutions. This network of natural infrastructure improves citizens' health and quality of life as well as the quality of the environment and the condition of natural areas. Expanding our use of green infrastructure can also support a green economy and create job opportunities.[82]

Declining health of Minnesota's natural habitat poses economic risks for the State's lumber, fishing, tourism, and recreation industries, while also presenting considerable economic growth opportunities. Warmer winter temperatures prevent lake ice formation and reduce snowpack, creating poor conditions for popular winter activities like ice fishing, skiing, and snowmobiling, posing a potential threat to revenue from recreation and tourism. Economically, there are huge benefits to reap if State and local policies encourage climate solutions in ecosystem services. A study by The Nature Conservancy and Earth Economics, values the potential of MN ecosystem services at up to $37 Billion per year, if natural climate solutions are fully implemented.[83] This could potentially yield thousands of new jobs and generate significant economic benefits for the state.

Ecologically, natural habitats face a variety of risks due to future weather and climate scenairos. In Lake Superior, warming waters affect fish populations and overall water quality. More winter precipitation is likely to fall as rain, contributing to a shorter snow season. Changes in the type and amount of precipitation projected to fall in Minnesota threatens soil infrastructure, increasing

[79] Zanne, Amy E., Habacuc Flores-Moreno, Jeff R. Powell, William K. Cornwell, James W. Dalling, Amy T. Austin, Aimée T. Classen, et al. 2022. Termite Sensitivity to Temperature Affects Global Wood Decay Rates. *Science* 377, 6613: 1440–44. https://doi.org/10.1126/science.abo38

[80] Cissé et al. 2022. Health, Wellbeing, and the Changing Structure of Communities. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1041–1170. doi:10.1017/9781009325844.009.

[81] Hiltrud Pötz & Pierre Bleuze (2011). Urban green-blue grids for sustainable and dynamic cities. Delft: Coop for life. ISBN 978-90-818804-0-4.

[82] *Green infrastructure—European Commission*. (2024, December 20). https://environment.ec.europa.eu/topics/nature-and-biodiversity/green-infrastructure_en

[83] Mackey, E. (2023). *The Economic Benefits of Natural Climate Solutions in Minnesota*. Earth Economics. https://www.nature.org/content/dam/tnc/nature/en/documents/EarthEconomics_2023EconomicBenefitsofNaturalClimateSolutions.pdf

erosion and soil dehydration levels during drought. Further risks include potential for soil compaction and disruption to drainage systems. All of these outcomes pose consequences for other sectors and infrastructure including agriculture, water resources, and the built environment. Rising temperatures and changing precipitation patterns also endanger culturally significant species and native plant communities. Among native animals, walleye and other cold-water fish face habitat loss, bison body size is expected to shrink due to warmer temperatures and droughts, and moose also face increased stress as temperatures warm[84]. Wild rice harvests may decline because of increasing spring precipitation and less winter snowfall.[85] Warming temperatures are also expanding the habitat and life cycle of carriers of vector-borne diseases, such as the *Culex tarsalis* mosquito, which spreads West Nile Virus[86]. Additionally, changes in precipitation patterns are increasing the likelihood of wildfires, which not only threaten habitats but also degrade air quality and contribute to public health issues such as asthma and heart disease[87]. Warmer surface waters elevate the risk of harmful algal blooms, negatively affecting aquatic ecosystems, water quality, and human health by making lakes unsuitable for swimming and recreation[88]. Prolonged dry spells and fewer days with measurable precipitation during the summer can lead to stagnation and low flow in waterways, further degrading fish habitats. Additionally, these low flows render waterways inoperable for transportation, recreation, power generation and other social services. Natural infrastructure, like wetlands, forests, and rain gardens, can significantly aid in water purification by utilizing natural processes like filtration through vegetation, soil absorption, and microbial activity, thereby reducing the need for extensive built water treatment infrastructure systems to achieve clean water quality. Overall, these climate-related changes threaten biodiversity, disrupt ecological relationships, and compromise the resilience of Minnesota's natural habitats and ecosystems.

From Climate Modeling to Resilient Infrastructure Policy

Translating the climate projections for Minnesota, as presented in this chapter, into actionable policy insights is crucial for timely, climate informed and effective resilient infrastructure policy development. Downscaled climate models offer valuable projections of possible future climate conditions. However, the complexity of the infrastructure policy landscape poses challenges in translating these projections into concrete policy actions. Consequently, there is a need to establish a scientifically informed, rigorous, and robust policy framework that leverages climate data to guide investments, enhance resilience, and ensure that the state's infrastructure systems can effectively respond to a wide range of possible climate futures. A resilient infrastructure policy framework should support the development of policies that are flexible enough to adapt to evolving climate data, implement resilience strategies across interconnected infrastructure systems, and provide reliable funding mechanisms to sustain long-term resilience

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[84] Weiskopf, S.R., Ledee, O.E., Thompson, L.M., 2019. Climate change effects on deer and moose in the Midwest. The Journal of Wildlife Management 83, 769–781. https://doi.org/10.1002/jwmg.21649

[85] Tribal Adaptation Menu Team, 2019. Dibaginjigaadeg Anishinaabe Ezhitwaad: A Tribal Climate Adaptation Menu. Great Lakes Indian Fish and Wildlife Commission.

[86] Chala, Bayissa, and Feyissa Hamde. 2021. Emerging and Re-Emerging Vector-Borne Infectious Diseases and the Challenges for Control: A Review. *Frontiers in Public Health* 9): 715759. https://doi.org/10.3389/fpubh.2021.715759.

[87] Gao, Y., Huang, W., Yu, P., Xu, R., Yang, Z., Gasevic, D., Ye, T., Guo, Y., Li, S., 2023. Long-term impacts of non-occupational wildfire exposure on human health: A systematic review. Environ Pollut 320, 121041. https://doi.org/10.1016/j.envpol.2023.121041

[88] Paerl, H.W., Huisman, J., 2008. Blooms Like It Hot. Science 320, 57–58. https://doi.org/10.1126/science.1155398

initiatives. Additionally, establishing stable policy and regulatory environments is important to ensuring the consistent implementation of resilience projects and to increase confidence in projects amongst both stakeholders and investors. Such a proactive approach will increase the likelihood that Minnesota can protect its infrastructure against evolving climate uncertainties while maintaining the functionality and safety of foundational infrastructure services for its communities.

Promoting collaborative approaches to planning for infrastructure resiliency is also important; by engaging government agencies, private sectors, and local communities, policies can better address climate risks, while benefiting from diverse perspectives and expertise. To address the complexities of translating scientific data into practical actions, implementing a structured framework such as the SETS framework, which will be introduced in Chapter 3, is recommended. The SETS framework provides a systematic methodology for integrating climate data into the process of developing actionable policy measures, thereby enhancing the involvement of climate science into infrastructure policymaking, planning, and decision-making.

Chapter 3: Developing a Resilient Infrastructure Policy Framework

As outlined in the previous chapter, Minnesota infrastructure[89] (buildings, roads, bridges, dams, water/wastewater systems, energy generation systems, soil, forests, and other systems) will need to operate in a new set of environmental conditions and climate in the future. In addition, the State's infrastructure requires upgrades in order to address future goals for efficiency, weakening structures due to age, cost effectiveness, and societal needs (housing, health, etc.)[90]. Scientific review has revealed that many organizations in the public, private, and nonprofit sectors are working to mitigate (reduce the degree/rate of climate change) or adapt (adjust to the observed or expected future climate scenarios to moderate harm or take advantage of new opportunities) to changing weather. While there is shared desire to build resilience, prepare for threats, adapt to changing conditions, and enable the ability to recover rapidly from disruptions,[91] current activities are siloed within individual organizations, disciplines, and/or systems. This is not surprising because the interaction and connection between human- and natural systems are complex. The use and movement of resources from human - natural systems to support societal needs (e.g., food, water, income, housing) are dynamic due to their interdependence with economic, societal, environmental, and policy factors. When future weather and climate scenarios are factored into these dynamic systems the results are complex.

To respond to this challenge, the research team employed an oft-cited urban development policy framework, SETS, to bring together natural, technological, and socio-economic systems to enable optimal social-ecological outcomes when designing, planning, and managing urban nature-based solutions.[92] Using SETS to analyze infrastructure in the context of future climate allows researchers, policymakers and other stakeholders to organize the complex interactions among human- and natural systems and consider risks and opportunities associated with these systems.

[89] **Infrastructure** includes all built systems and intentionally used ecological systems, that support the use, movement, and transformation of matter (whether physical or digital) for the foundational purposes of society.

[90] ASCE (2021) Report Card on America's Infrastructure, ASCE. https://infrastructurereportcard.org/

[91] See Fifth National Climate Assessment definitions for Mitigation, Adaptation and Resilience.

[92] McPhearson, T., Cook, E. M., Berbés-Blázquez, M., Cheng, C., Grimm, N. B., Andersson, E., Barbosa, O., Chandler, D. G., Chang, H., Chester, M. V., Childers, D. L., Elser, S. R., Frantzeskaki, N., Grabowski, Z., Groffman, P., Hale, R. L., Iwaniec, D. M., Kabisch, N., Kennedy, C., … Troxler, T. G. (2022). A social-ecological-technological systems framework for urban ecosystem services. *One Earth*, *5*(5), 505–518. https://doi.org/10.1016/j.oneear.2022.04.007

Infrastructure as a social, ecological, and technological system

Infrastructure is an interconnected and inseparable system of sociological, ecological, and technological components[93]. We define infrastructure as *all built systems and intentionally utilized ecological systems that support the use, movement, or transformation of matter–whether physical or digital–for the foundational purposes of society*. This section of the report outlines a conceptual policy making analysis framework that is designed to integrate the social, ecological, and technological components of infrastructure systems. The analysis aims to inform infrastructure policy development as well as built and natural systems, so that Minnesota infrastructure remains resilient to the range of possible future weather risks facing our State.

Existing frameworks, such as Social-Ecological Systems (SES), Socio-Environmental (S-E) Systems, and the Institutional Analysis and Development (IAD) framework, each offer valuable insights but lack the capacity to capture the full complexity of infrastructure systems. For example, SES frameworks model how subsystems of resources, users, and governance interact to influence outcomes and feedback loops, but treats subsystems as separable entities[94]. Conversely, S-E frameworks focus on human-nature interactions at multiple governance scales[95], yet limit the range of interactions considered and do not often view technology as separate from social processes, potentially constraining the depth of analysis when applied to infrastructure systems. The IAD framework similarly views technology as distinct from social and institutional dynamics. In contrast, SETS, the framework applied in this report, regards social, ecological, and technological dimensions of infrastructure systems as fundamentally intertwined and irreducible[96]. By considering all three dimensions simultaneously, the SETS framework accounts for the interplay of natural and built systems that is integral to infrastructure analysis. SETS presents a unique lens from which to identify interactions, trade-offs, and intervention points that other frameworks cannot fully model.

Analyzing infrastructure as a complex interplay of social, ecological, and technological components can reveal effective climate actions that are often overlooked. This holistic perspective also reveals multifaceted and interconnected risks to infrastructure systems and the policies that guide their design and use. Our model measures potential policy against two main requirements: 1) whether the policy can meet current State infrastructure goals; and 2) whether the policy meets our standard for resiliency in the face of all possible future climate scenarios.

Understanding the complex dynamics of infrastructure systems is essential for making informed resilience action recommendations to decision-makers. The SETS framework emphasizes process-oriented questions over action-oriented ones, focusing on identifying effective place-based pathways to facilitate resilient infrastructure systems and policies rather than

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[93] Markolf et al., "Interdependent Infrastructure as Linked Social, Ecological, and Technological Systems (SETSs) to Address Lock-in and Enhance Resilience."
[94] Elinor Ostrom, "A General Framework for Analyzing Sustainability of Social-Ecological Systems," *Science* 325, no. 5939 (July 24, 2009): 419–22, https://doi.org/10.1126/science.1172133.
[95] Reinette Biggs et al., eds., *The Routledge Handbook of Research Methods for Social-Ecological Systems* (London: Routledge, 2021), https://doi.org/10.4324/9781003021339.
[96] Markolf et al., "Interdependent Infrastructure as Linked Social, Ecological, and Technological Systems (SETSs) to Address Lock-in and Enhance Resilience."

prescribing specific solutions broadly. Users of the SETS framework define the conditions for acceptable outcomes in the range of likely climate futures across the social, ecological, and technological components of the particular system being studied. The framework then guides the generation of scientifically supported resilience actions likely to achieve those outcomes.

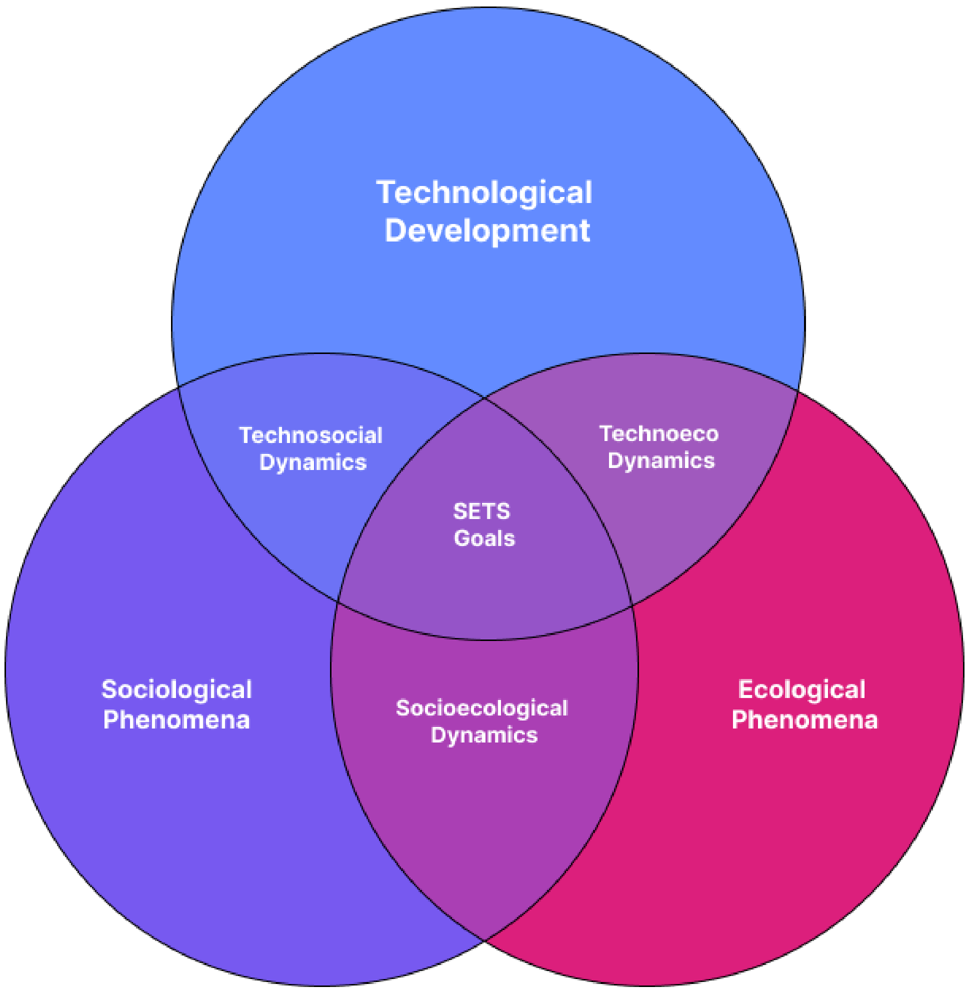

Figure 3.1: Infrastructure is defined as a social, ecological, and technological system.

Figure 3.1 illustrates the complex relationships among core SETS components—technological development, sociological phenomena, and ecological phenomena—using a Venn diagram. In the diagram above, each circle represents one of the three fundamental components of an infrastructure SETS. Their intersections highlight critical areas where these elements interact. In the center-most overlap, SETS goals represent the desired outcomes, present and future, as directed by policy intervention. The overlapping regions between each pair of circles represent specific system dynamics of the SETS: interplay between technological development and sociological phenomena produce technosocial dynamics, sociological and ecological phenomena produce socioecological dynamics, and technological development and ecological phenomena produce technoecological dynamics. Detailed definitions of each of these areas are provided in Table 3.1.

Technological Development	The process of creating, enhancing, or transforming systems, through the practical application of scientific knowledge, to meet social needs, desires, or goals and address social issues, problems, or dilemmas. These technological developments consist of built systems—such as transportation, energy, and communication— as well as the intentional use of natural systems—such as the atmosphere, water, and soils.
Sociological Phenomena	Any observable event, pattern, or behavior that emerges within a society, shaped by the interactions, norms, values, and institutions that define social life. These phenomena can include trends in social behavior, cultural practices, group dynamics, and societal structures.
Ecological Phenomena	Any event or pattern that occurs within ecological systems and relates to the interactions between organisms and their environment. This can include processes such as population dynamics, species interactions (like predation and competition), ecosystem changes, and responses to environmental factors, habitat destruction, and resource availability.
Technosocial Dynamics	The complex interactions and feedback loops between technological development and sociological phenomena. This concept covers how technology influences social processes—such as communication, organization, and culture—and, conversely, how social factors shape the development, adoption, and use of technology. It emphasizes the reciprocal relationship between society and technology, where changes in one domain can lead to significant transformations in the other.
Technoeco Dynamics	The complex interactions and feedback loops between technological development and ecological phenomena. This concept includes how technology impacts environmental processes, ecosystems, and biodiversity, and how ecological factors, in turn, influence the design, implementation, and evolution of technology. It highlights the interlinked relationship between technology development and ecological health, emphasizing the need for sustainable practices that link technological development with environmental preservation.
Socioecological Dynamics	The complex interactions and reciprocal influences between sociological phenomena and ecological phenomena. This concept examines how human behaviors, cultural practices, and social structures impact ecosystems, while also considering how ecological conditions and environmental changes shape sociological phenomena.

SETS Goals	Society places implicit or explicit outcomes that are desired for technology to provide for social outcomes within the ecological resources, constraints and climate.

Table 3.1: Definitions used for SETS infrastructure and the sub-types covered in this report.

The SETS framework is implemented through a three-phase process: 1) map existing SETS dynamics; 2) evaluate the policy capacity of infrastructure SETS; and 3) model effective policy responses for infrastructure SETS in the face of a range of possible climate futures. In the following Methods section, each of these phases are discussed in greater detail, including their relevance for enhancing infrastructure resilience.

Methods for Analyzing Infrastructure SETS

This section provides a workflow for how to perform an infrastructure SETS analysis to generate a range of policy recommendations to fortify Minnesota's infrastructure goals with resiliency planning in response to future weather trends. The analysis is completed at three distinct phases:

- **Phase One - High-level**: Offers broad strategic guidance by mapping existing Infrastructure SETS dynamics
- **Phase Two - Mid-level**: Targets policy adjustments by evaluating infrastructure policy capacity
- **Phase 3 - Fine-level**: Provides specific, actionable measures by modeling effective policy responses.

Exercised together, these phases can help policymakers develop effective strategies for creating resilient infrastructure goals and ensuring adequate policy capacity.

Infrastructure SETS Workflow

The workflow shown in Figure 3.3 demonstrates how to apply the infrastructure SETS framework to real-world policy contexts. The completed analysis will produce current-state, future-state, and dynamic models of the infrastructure SETS. These models can be used to generate policy recommendations to strengthen the resilience of infrastructure goals against the risks presented by possible future weather trends.

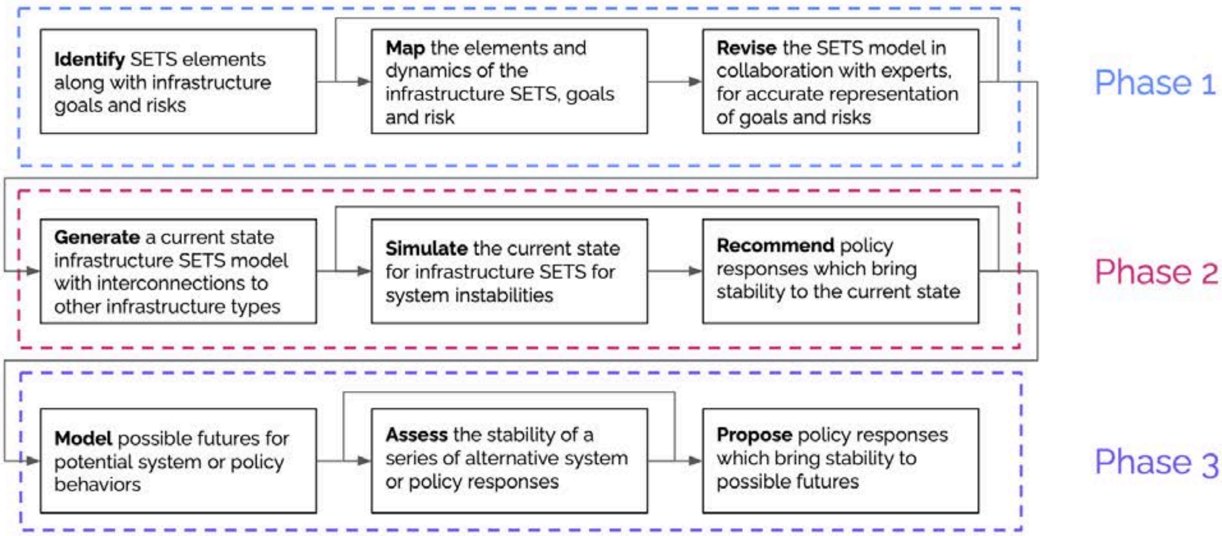

Figure 3.3: Workflow for applying the resilient infrastructure policy framework.

Phase 1: Map Existing Infrastructure SETS Dynamics

Phase 1 of infrastructure SETS analysis results in the generation of a current state map of the infrastructure SETS being studied and compares that map to the existing goals for and risks to that infrastructure system.

The Phase 1 analysis provides outcomes based on present climate and policies. This phase identifies ways in which current policies may be insufficient to meet existing infrastructure goals, or lack the resiliency to respond to present risks. This phase of analysis is not meant to explore future risk, only present risks based on current infrastructure SETS, and create the basis Phases 2 and 3 are compared against. Therefore, the policy recommendations generated from the Phase 1 analysis are focused on the immediate term, due to the temporally present focus of Phase 1. As such, when using the SETS framework, it is possible that preliminary recommendations for infrastructure policy produced in Phase 1 are deemed non viable as final recommendations; Phase 2 and 3 factor in long-term risks and future weather trends to produce recommendations based on likely future climate outcomes..

Agricultural infrastructure includes all built systems and intentionally used ecological systems that support the production, processing, distribution, consumption, or transformation of grown or raised food and non-food products.

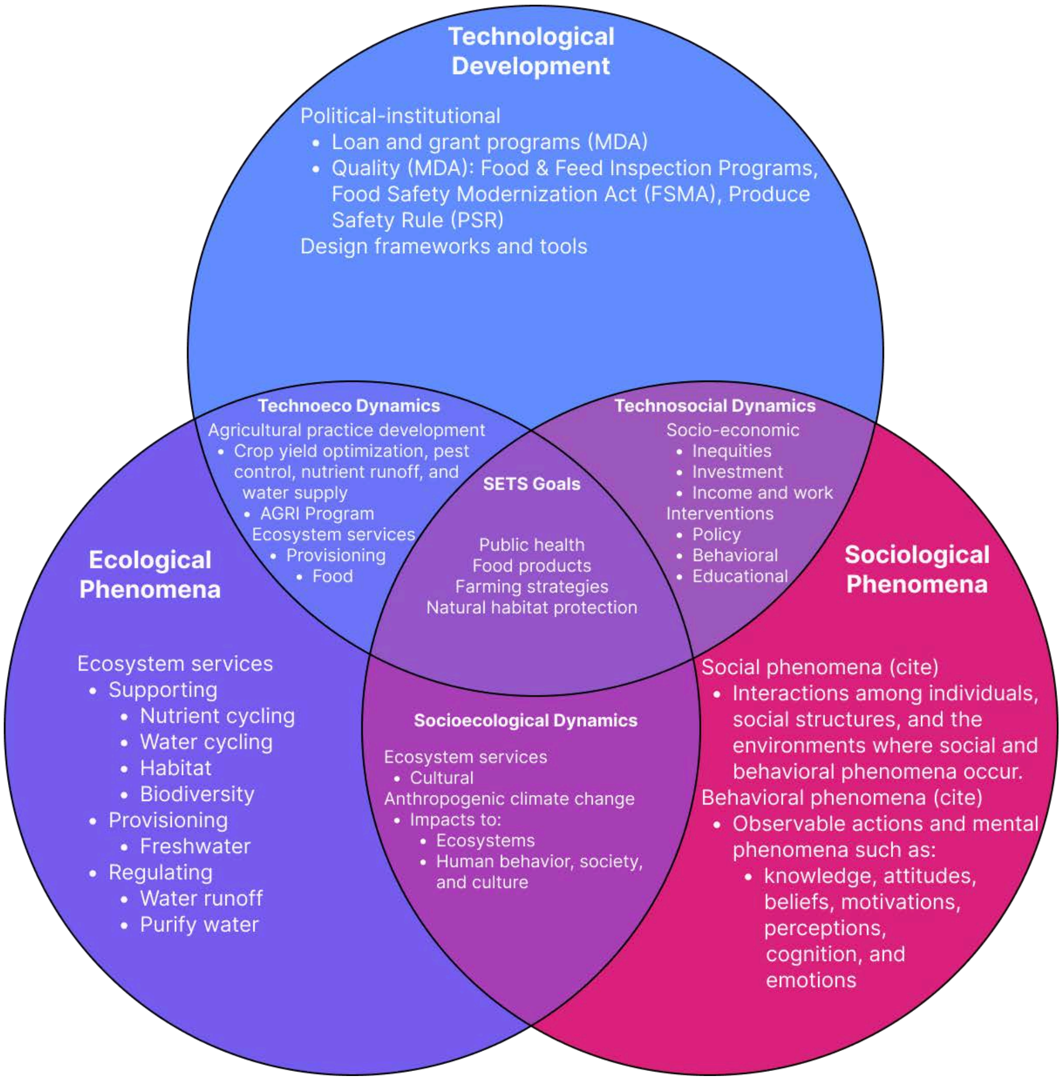

Figure 3.4: The current state SETS map for agricultural infrastructure.

Phase 1 of an infrastructure SETS analysis begins by **identifying** the sociological, ecological, and technological elements of the infrastructure system, along with the goals for and risks to the domain of interest. Next, these SETS elements are **mapped** onto the high-level SETS model (see Figure 3.4 above). The SETS model illustrates the ways in which a given infrastructure system is interconnected with the sociological, ecological, and technological dynamics comprising the system.

Mapping Infrastructure SETS in Relation to their Goals and Risks

Next, existing goals for, as defined explicitly by policymakers or implicitly through policy, and risks to infrastructure are **mapped** in relation to the SETS model in a separate figure (see Figure 3.5 below).

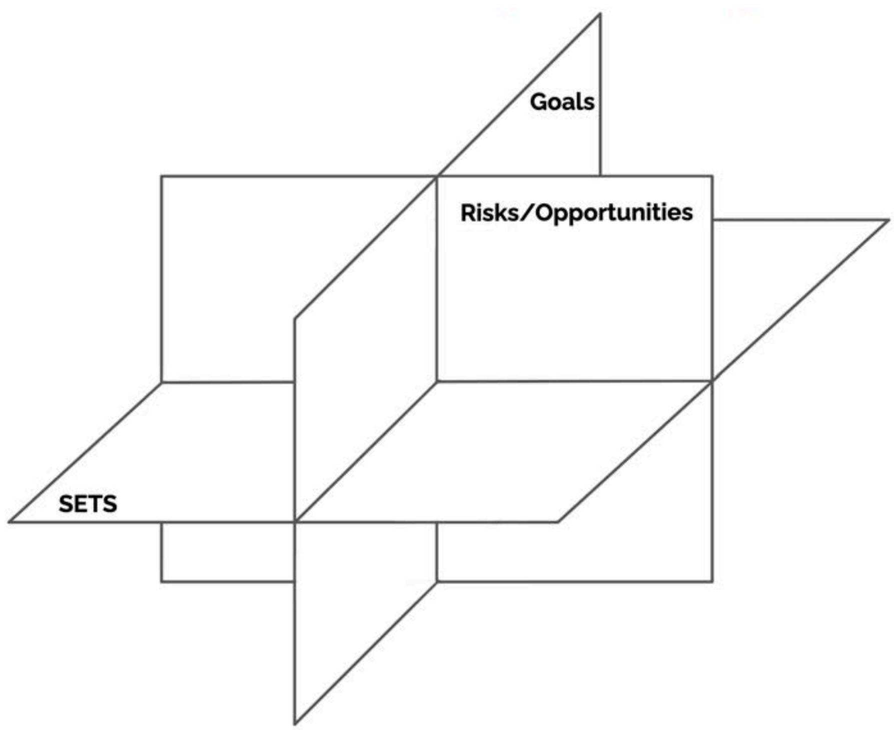

Figure 3.5: Mapping current goals for and risk to infrastructure in the current infrastructure SETS.

By mapping current infrastructure goals and risks/opportunities, the newly formed SETS model can identify potential points of intervention for policy improvements that address existing system risks or redefine current goals. In doing so, it may reveal previously unforeseen approaches and illustrate the complexity of intervening in such systems, where decision-makers must have the necessary information to weigh tradeoffs, benefits, costs, and other factors to determine possible action pathways.

Finally, the model is **revised** in collaboration with experts and stakeholders to ensure that both the SETS model and the identified goals and risks accurately represent the current state of the infrastructure system.

Evaluating and Creating Infrastructure Resilience Goals

Goals are the broad or specific targets or outcomes that are desired to be achieved in the future. In this work, goals refer to the targets or outcomes that directly or indirectly impact the resilience of infrastructure SETS. There are many different processes that can be used to create goals and measure the progress to their achievement. For example, the SMART goal framework encourages setting goals that are Specific, Measurable, Achievable, Relevant, and Time-bound[97]. Similarly, SWOT analysis, typically used by organizations, helps identify Strengths, Weaknesses, Opportunities, and Threats which can be used to inform the creation of goals around resilience[98]. However, goals for system resilience are context-specific[99], and identifying effective goals requires a detailed understanding of the system[100]. Therefore, a goal-setting process that analyzes the current state of infrastructure resilience goals and determines whether those goals are achievable in the face of the range of possible climate futures is important. For these reasons, the process that is used in the SETS approach is plan, do, check, act or PDCA[101]. The PDCA process that was developed for the SETS approach can be found in Figure 3.6 below. It should be noted that if the PDCA process was being used in goal setting each step of the process would be followed as goals are being created and enacted, but in the SETS process it is intended to **assess** the effectiveness and capacity of existing goals to enhance the resilience of infrastructure systems and the policies that inform their design and operation.

[97] K. Blaine Lawlor, "Smart Goals: How the Application of Smart Goals Can Contribute to Achievement of Student Learning Outcomes," *Developments in Business Simulation and Experiential Learning: Proceedings of the Annual ABSEL Conference* 39 (2012), https://absel-ojs-ttu.tdl.org/absel/article/view/90.
[98] Tanya Sammut-Bonnici and David Galea, "SWOT Analysis," in *Wiley Encyclopedia of Management* (John Wiley & Sons, Ltd, 2015), 1–8, https://doi.org/10.1002/9781118785317.weom120103.
[99] Intergovernmental Panel on Climate Change Working Group II, *Climate Change 2001: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2001).
[100] H. Fünfgeld and D. McEvoy, "Framing Climate Change Adaptation in Policy and Practice," 2011.
[101] Pratik Patel and Vivek Deshpande, "Application Of Plan-Do-Check-Act Cycle For Quality And Productivity Improvement-A Review," *International Journal for Research in Applied Science & Engineering Technology* 5 (January 1, 2017): 197–201.

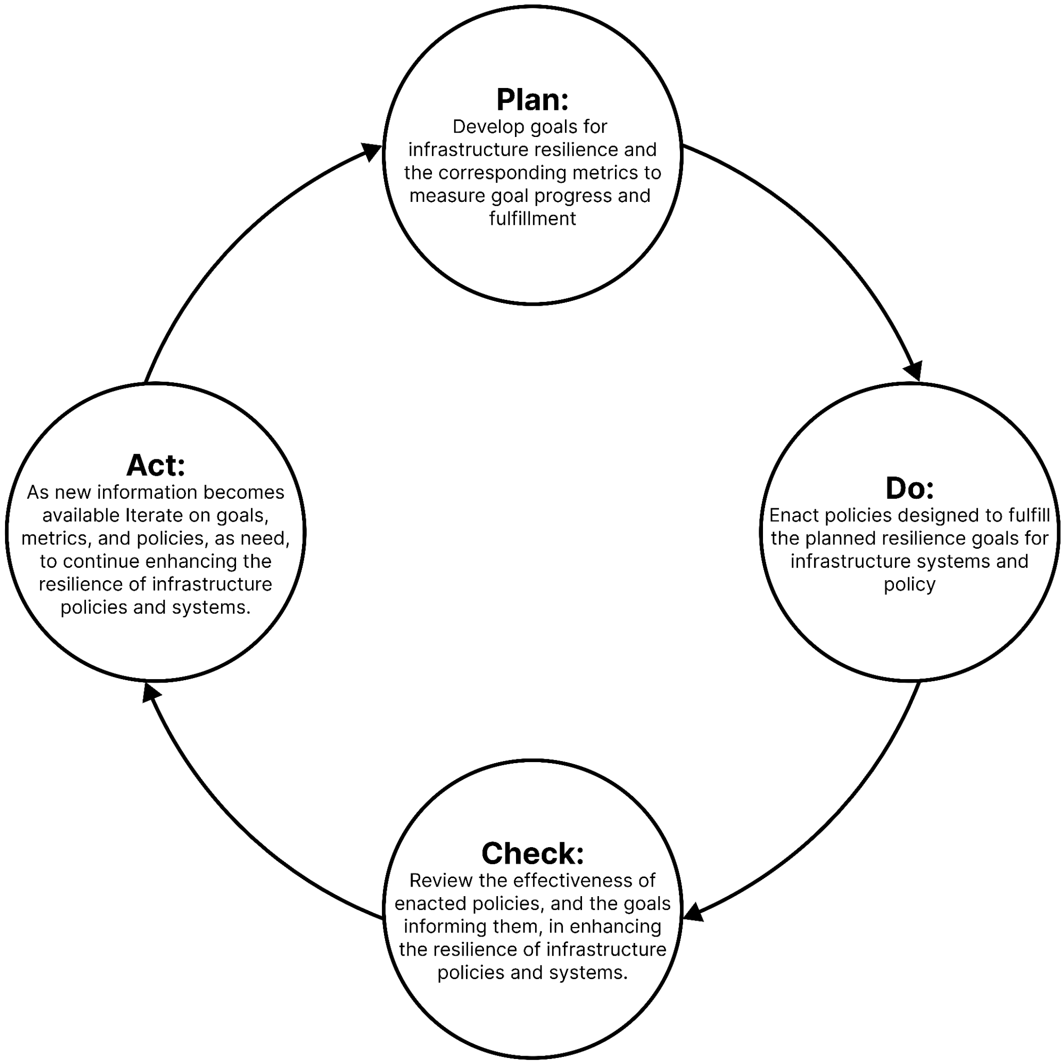

Figure 3.6: Implementation of the Plan-Do-Check-Act process to identify and evaluate existing goals and design and implement more effective goals around infrastructure resilience.

In the SETS analysis as the PDCA process is used to **check** if accomplishing existing infrastructure goals has been or would be effective at enhancing the resilience of infrastructure SETS. In addition, the PDCA process, as part of the SETS framework, is used to determine if the policies enacted (based on the planned goals) have sufficient capacity to **act** as a means to enhance the resilience of infrastructure systems across the range of possible future weather trends. If the existing goals are found not to be effective in enhancing the resilience of infrastructure SETS, then a **plan** which includes a series of recommended goals are created that would each be more likely to result in enhanced resilience of infrastructure SETS than the existing goals. The new recommended goals would then be provided to the legislature or other relevant body, where they would choose what to **do** with the recommendations.

Integrating Infrastructure SETS and Goals in a Complex Risk Analysis

Risk encompasses both the probability of an event occurring and the consequences if it does occur[102]. Infrastructure risks can range from simple, isolated issues to complex, interconnected challenges, and they may be independent or interdependent[103]. When analyzing the current state of an infrastructure SETS, understanding these risks is critical for determining viable action pathways that enhance the resilience of the infrastructure system and the policies that inform their design. Risks to the SETS can be considered in terms of its components, the existing goals guiding future decision-making, and the exogenous conditions that could impact the stability of the current state of the SETS. This includes the range of possible climate futures where existing policies may lack the capacity to remain resilient against future weather trends that have not been effectively mitigated within the SETS dynamics.

Building upon the initial steps of the SETS analysis, the SETS complex risk analysis starts by taking the identified SETS goals and reframing them as risks. The following steps–utilizing the framework for complex climate risk assessment outlined by Simpson et al.[104]– are used create a draft of the complex interacting risks specific to infrastructure SET of focus:

1. **Map Risks to SETS Goals:** Take the SETS goals identified in the high-level SETS analysis and reframe them as risks. For example, in the agricultural infrastructure high-level SETS map (see Figure 3.4) had a number of goals:
    - Public health
    - Food products
    - Framing strategies
    - Natural habitat protection

2. **Map Risks to SETS Components:** Identify risks connected to the various SETS components and assess how they might lead to impacts the SETS goals. For instance:
    - Risk to the agricultural industry could affect the variety of food product availability and support for experimental farming strategies (Socioecological and Technosocial dynamics)
    - Risk to the reputation of agricultural experts could lead to impacts in the adoption of farming strategies and natural habitat protection (Technosocial and Technoeco dynamics)

3. **Incorporate Existing Literature:** Use literature as another data source for the risk analysis in order to integrate insights from existing studies to identify known risk. For example, Komarek et al. (2020) identified five types of risks to agricultural systems due to climate change:

[102] Stanley Kaplan and B. John Garrick, "On The Quantitative Definition of Risk," *Risk Analysis* 1, no. 1 (1981): 11–27, https://doi.org/10.1111/j.1539-6924.1981.tb01350.x.
[103] Theresa Brown, Walt Beyeler, and Dianne Barton, "Assessing Infrastructure Interdependencies: The Challenge of Risk Analysis for Complex Adaptive Systems," *International Journal of Critical Infrastructures* 1, no. 1 (January 2004): 108–17, https://doi.org/10.1504/IJCIS.2004.003800.
[104] Simpson et al., "A Framework for Complex Climate Change Risk Assessment."

- Production risk
- Price or Market risk
- Financial risk
- Institutional risk
- Human or Personal risk

4. **Draft Interacting Complex Risk Map:** Develop a draft map (see Figure 3.7 for an example) of the interacting risks for the infrastructure SETS of focus for analysis using the complex climate change risk assessment. This will be the complex risks arising from the interplay of multiple factors within and outside of the infrastructure SETS. Understanding how these risks interact will help identify climate resilience action pathways that anticipate systemic vulnerabilities to the infrastructure SETS and potential cascading, or other, risk effects.

5. **Iterate with Experts:** Consult with experts with diverse backgrounds, perspectives, and roles related to the infrastructure SETS to review the draft of interacting risks. Their feedback will help to refine the risk map, ensuring that it is accurate, comprehensive, and context-specific.

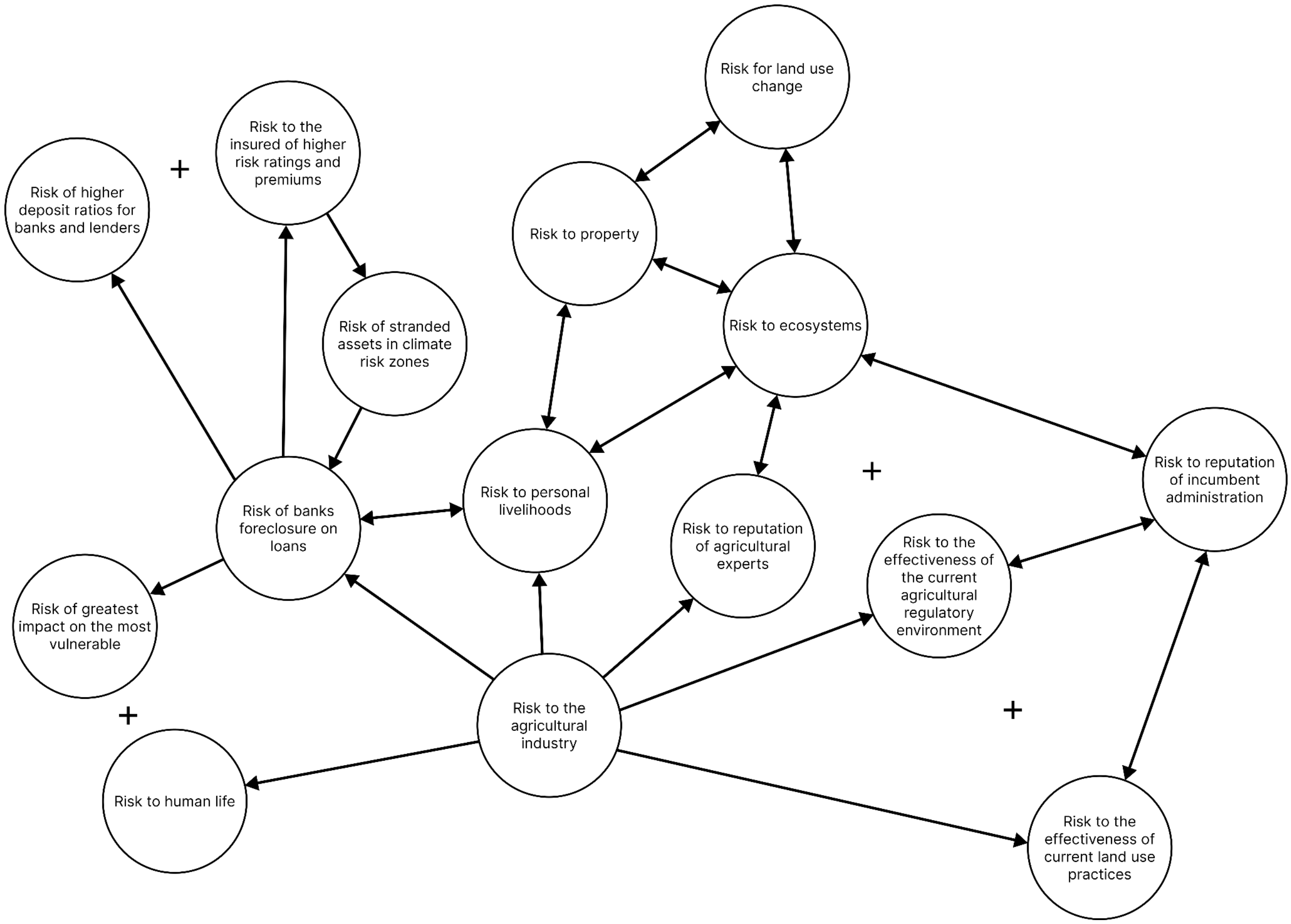

Figure 3.7: Mapping the complex interacting risks to agricultural infrastructure SETS due to climate impacts using the complex climate change risk assessment[105].

After systematically analyzing the risks to the infrastructure SETS of focus in order to create the complex interacting risk map, further risk analysis can be performed that focuses on the underlying interactions of drivers within and between the determinants of risk[106]. By dissecting these underlying drivers, various factors that contribute to the risks for the infrastructure SETS of focus can be identified. For example, Figure 3.8 shows a conceptual diagram of the risk interactions for agricultural infrastructure SETS due to future weather trends. In this exhibit, various climate change variables are mapped as drivers influencing the determinants of climate risk–hazard, vulnerability, exposure, and response. These variables include factors such as prolonged dry or heat conditions. By mapping these underlying drivers of climate risk during an infrastructure SETS analysis, resilience action pathways can be identified for further analysis which might break the relationships between these drivers and determinants of risk, thereby potentially reducing the overall risks to the infrastructure SETS. As a result, this detailed and multi-layered risk analysis enhances the ability to craft more resilient infrastructure policies and systems, which will be further developed in Phases 2 and 3 of the SETS framework.

[105] Simpson et al.
[106] Simpson et al.

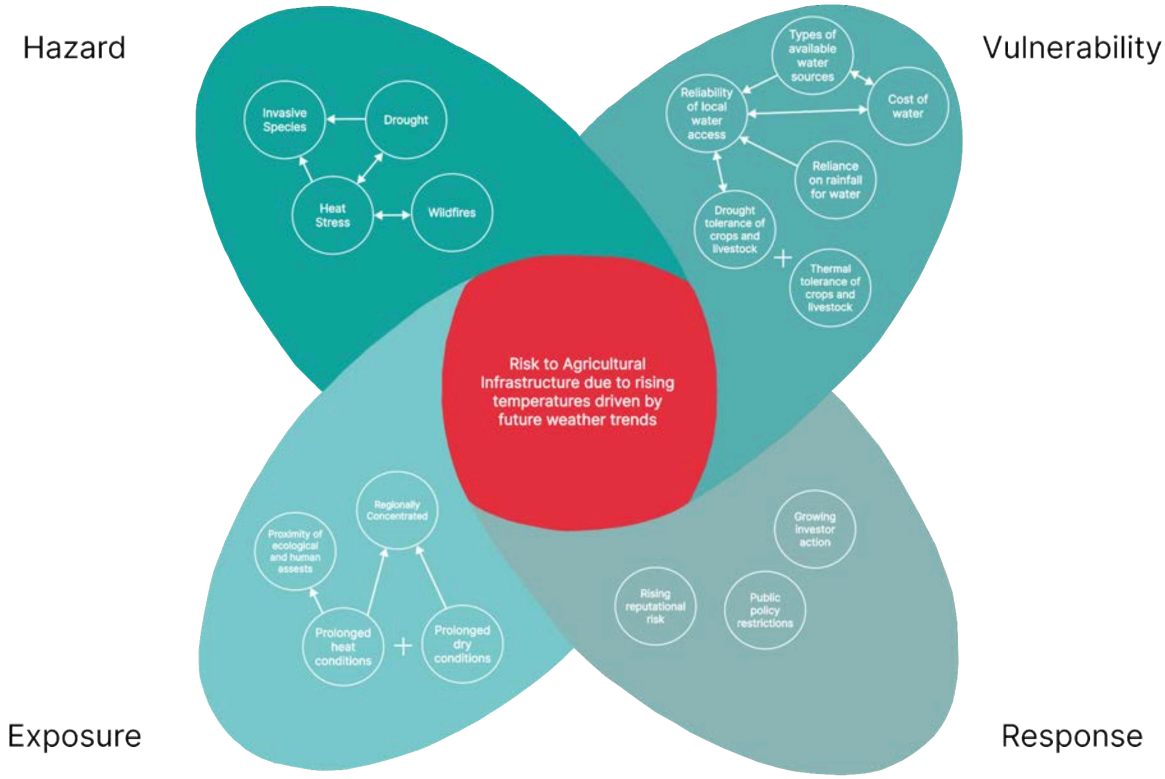

Figure 3.8: Mapping the interactions of drivers within and between the determinants of risk to agricultural infrastructure SETS using the complex climate change risk assessment[107].

The last step of Phase 1 follows the **Plan** step of PDCA process of goal setting, where it is assessed if it is necessary to improve the current state goals for the infrastructure SETS of focus. This involves conducting an integrated analysis of the Phase 1 outputs of existing infrastructure systems and policies. By examining the current state SETS components and their interactions, the existing goals can be evaluated for their adequacy in addressing the identified risks and resilience needs for the infrastructure SETS. If the evaluation reveals gaps, then the goals should be reexamined to be better aligned with the risks and opportunities that emerged in the Phase 1 of the infrastructure SETS analysis. This process seeks to create goals that are context-specific, actionable, and conducive to building resilience in the infrastructure SETS. With these refined goals, if refinement was necessary, the transition to Phase 2 of the SETS framework takes place, where the focus is on developing a resilience action space which will bring stability to the infrastructure SETS in the current state through implementing strategies, policies, and other interventions that are aligned to the goals from Phase 1.

[107] Simpson et al.

Phase 2: Evaluating the Policy Capacity of Infrastructure SETS

Phase 2 of the infrastructure SETS analysis evaluates whether existing infrastructure policies have the capacity to meet current infrastructure goals while being resilient to present-day risks. This phase will generate a series of policy recommendations to increase the resilience of infrastructure SETS, assess the viability of existing goals around infrastructure, and examine if current infrastructure policy has sufficient capacity to address the present-day risks to infrastructure systems. Phase 2 builds on the insights from Phase 1 and sets the stage for Phase 3, where further analysis will iterate on the policy recommendations from Phase 2 to ensure they have sufficient capacity to inform the creation of infrastructure systems that are resilient to the risks that could arise from the range of possible future weather trends.

The first step of phase 2 is to **generate** a current state infrastructure SETS model, see Figure 3.9 for a conceptual example, showing the interconnections between the infrastructure SETS that is the focus of the analysis, and other types of infrastructure SETS. This approach develops an understanding of how an infrastructure SETS, such as agricultural infrastructure, connects to other infrastructure SETS. This helps identify the complex interconnections between infrastructure SETS and highlights shared dependencies that need to be resilient to the risks from future weather impacts to prevent disruptions to the functions of the SETS that is the focus of the analysis. For example, if components of the water infrastructure SETS, such as reservoirs and other water storage systems, aren’t resilient to the range of drought conditions that are possible according to projected future weather trends, components of agriculture infrastructure SETS, such as irrigation systems, could face disruptions due to water shortages. This could trigger a cascade of failures, including reduced yields or costly water imports. In other words, due to their interconnectedness, a lack of resilience of water infrastructure SETS can weaken the resilience of agricultural infrastructure SETS to future weather trends. While this example is simple, most interdependencies are far more complex, making the mapping analysis approach conceptually shown in Figure 3.9 essential for highlighting these relationships across different types of infrastructure SETS.

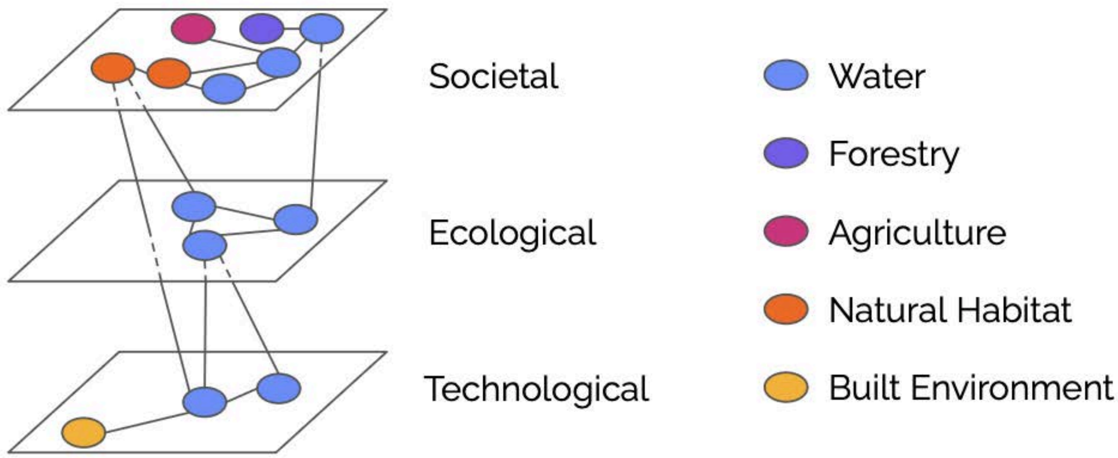

Figure 3.9: Conceptual diagram of the interconnections for agriculture infrastructure SETS map to other infrastructure systems.

The next step of Phase 2 uses various modeling approaches to **simulate** the current state of the infrastructure SETS model. This step aims to identify system or policy instabilities by analyzing how existing risks, goals, and other system behaviors interact to impact the resilience of the infrastructure SETS. The simulation process is iterative, as the choice of modeling techniques–ranging from quantitative simulations to qualitative assessments–will depend on the specific characteristics of the infrastructure SETS being examined and the recommendations of subject matter experts, those with embedded knowledge, and other diverse stakeholders. Additionally, the simulation will test a series of policy responses that might resolve instabilities identified in the current state of the infrastructure SETS model. By evaluating these potential policies within the simulated environment, an effective action space–defined as the set of context-specific actions likely to enhance the resilience of infrastructure across a range of possible climate futures–can be developed to support the decision-making of policymakers to increase the current state resilience of the infrastructure SETS.

At the conclusion of Phase 2 of the SETS framework, the **Do** step of PDCA goal analysis is revisited to develop policy recommendations. These recommendations establish resilient action pathways toward system stability by addressing the identified antecedents of risk in and increasing the resilience of the infrastructure SETS of focus. This process seeks to ensure that the policy recommendations generated from the model simulations are directly aligned with the goals, risks, and opportunities identified in Phase 1 of the SETS analysis while enhancing the policy capacity for resilience in the infrastructure SETS. Phase 3 of the SETS framework then takes the recommendations from Phase 2 and tests them against a range of possible climate futures. This process refines the policy recommendations to increase the likelihood there is sufficient resilient policy capacity for the infrastructure SETS of focus, enabling them to withstand evolving risks.

Phase 3: Modeling Effective Policy Responses for Infrastructure SETS

Phase 3 of the SETS framework, evaluates the capacity of the proposed policy recommendations from Phase 2 to remain effective in supporting infrastructure systems amid the uncertainties of future weather trends. This phase recognizes that exogenous factors that temporally impact the infrastructure SETS, such as changing weather, can vary in intensity based on the actions that are taken at various points now and into the future. Consequently, Phase 3 of the SETS analysis, tests the Phase 2 policy recommendations–that were made for the current state of the infrastructure SETS–against a range of possible climate futures to assess their capacity to remain resilient, in terms of still fulfilling the SETS goals, across those futures. By simulating different climate scenarios, it can be estimated whether the policies can sustain their effectiveness under varying conditions and, if necessary, identify possible adjustments to enhance their effectiveness across a wider range of possible future states. This evaluation can increase the likelihood that the recommended policies possess sufficient resilient capacity to address evolving risks and capture potential emerging opportunities, such as to better ensure the infrastructure SETS is prepared for future challenges. Phase 3 of the SETS framework comprises three steps: **Model**, **Assess**, and **Propose**. The remainder of this section will provide more details of the methodologies and considerations involved in each of these steps.

The **Model** step involves updating the Phase 2 infrastructure SETS model, or using a more appropriate alternative modeling approach, to simulate the interactions between the Phase 2 policy recommendations and various climate futures to understand their potential impacts on the stability of the infrastructure SETS. Acting as the **Check** phase of the PDCA goal process, this step–in conjunction with the Assess step below–is used to estimate the likelihood that the current SETS goals remain viable across a range of possible climate futures. By incorporating diverse climate scenarios, such as increased temperatures, altered precipitation patterns, and more frequent extreme weather events, the Model step creates a policy testbed to identify feasible resilient action pathways that are likely to effectively support the infrastructure SETS both now and into the future under a range of future conditions.

The **Assess** step is iterative, evaluating the likely effectiveness of the proposed policies in enhancing the resilience of the infrastructure SETS under a range of future climate scenarios. During this step, alternative policy responses are assessed for their ability to provide system stability and achieve the SETS goals identified in Phase 1. This involves both refining the proposed policies and evaluating existing policies that may require modifications to increase the likelihood they will enhance the resilience of the infrastructure SETS. Depending on the results from the Model step, multiple iterations of the Assess step may be necessary to ensure viable policy recommendations are identified. If the initial assessment indicates that certain policies are not viable, in the face of a range of climate futures, adjustments can be made to the proposed policies, and the modeling process can be repeated to test the revised policies. This iterative assessment helps to ensure that only the action pathways that are most likely to enhance the resilient capacity of infrastructure SETS to future weather trends are retained in the analysis.

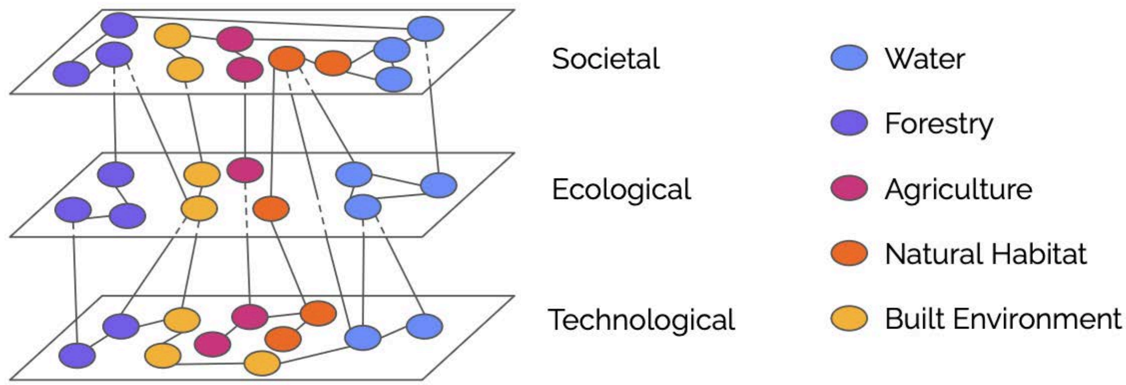

Figure 3.10: Conceptual diagram of a complete interconnected infrastructure SETS map.

Lastly, the **Propose** step involves forming and presenting the resilient action pathways that emerged from the assessment of policy recommendations in the last step. This includes outlining the trade-offs, opportunities, and barriers associated with each resilient action pathway, to increase the likelihood that decision-makers have a comprehensive understanding of the potential impacts and benefits of each policy strategy. By detailing these factors, the Propose step seeks to equip policymakers with the necessary background material to make informed decisions in the prioritization and selection of the most effective resilient action pathways. Over time, as more SETS analyses are undertaken, a more complete and interconnected infrastructure SETS map, like the one conceptually illustrated in Figure 3.10, could be developed to guide integrated and strategic policy development. As such, this step aligns with the Do phase of the PDCA process, because once a set of viable resilient action pathways are identified, one or more of these pathways can be formally proposed to bring stability to possible futures. Thus, the SETS framework concludes by presenting a set of viable policy recommendations, including potential benefits, costs, and implementation challenges to the relevant decision-makers.

Chapter 4: Using SETs to Analyze Infrastructure Systems

Minnesota's current policy approach to the design, construction, and maintenance of existing infrastructure systems faces challenges in navigating the complex, interconnected policy landscape. Our analysis aims to supply robust and resilient policy recommendations that withstand and adapt to a wide range of possible future risks facing the State of Minnesota. These policies would need to incorporate resilient capacities that address diverse climate scenarios, ensuring that the infrastructure systems remain functional and secure under different climate futures. The SETS framework can be engaged in conjunction with existing policy-making approaches. In this section, we examine each of the five infrastructure systems covered in this report: water, agricultural, forestry, built environment, and natural habitat infrastructure. We review existing policies and identify infrastructure SETS components. Our review also includes expert perspectives from the field, gleaned through focus groups with specialists. High-level SETS graphics illustrate the framework's application across the five infrastructure domains.

Minnesota's Current Infrastructure

Minnesota's existing infrastructure policy landscape is composed of five different policy types, which together form the governance structure for the State's infrastructure systems. The first of these types is substantive policies, which are policies that when implemented significantly impact the political system and key stakeholders such as individuals, organizations, or industries. Second, regulatory policies are designed to control or regulate the behavior and practices of individuals, organizations, or industries, in order to ensure compliance with established or newly formed standards. Constituent policies cover public-facing stances or functions, i.e. creating public agencies, for the purpose of performing specific and essential functions. Distribution policies allocate services, benefits, or resources to particular groups. Lastly, redistribution policies transfer resources or benefits from one group to another.

Despite the critical role that infrastructure plays in supporting society's foundational needs, state definitions of "infrastructure" are limited in scope and often fragmented across various infrastructure types. The clearest examples of what constitutes infrastructure are found in Minnesota state law, which provides guidance on its essential components through laws, regulations and other types of policies. Still, gaps remain. For example, the Greater Minnesota Business Development Public Infrastructure Grant Program, Section 116J.431 of the 2024 Minnesota State Statutes, definition of public infrastructure excludes natural systems.[108] We define infrastructure as: all built systems and intentionally used ecological systems that support the use, movement, and transformation of matter (whether physical or digital) for the

[108] **Public infrastructure** means publicly owned physical infrastructure necessary to support economic development projects, including, but not limited to, sewers, water supply systems, utility extensions, streets, wastewater treatment systems, stormwater management systems, and facilities for pretreatment of wastewater to remove phosphorus.

foundational purposes of society. This expanded definition of infrastructure conveys its integrated and complex, setting the stage for holistic and resilient policymaking.

Infrastructure Focus Groups

To broaden our research on climate resilience, we conducted focus groups, inviting organizations with expertise and/or direct involvement with Minnesota's infrastructure systems and policies. It is likely that some of these organizations measure climate risk, resiliency, and performance of infrastructure systems. Focus groups were organized by domain and convened a diverse range of experts. Specific dates of each meeting are listed in Table 4.1. All focus groups were held virtually over Zoom.

Infrastructure domain	First focus group series	Second focus group series
Water	Thurs. Oct. 17th, 2024	Wed. Dec. 4th, 2024
Agriculture	Wed. Oct. 9th, 2024	Wed. Nov. 13th, 2024
Forest	Wed. Oct. 30th, 2024	Wed. Dec. 11th, 2024
Built Environment	Wed. Nov. 6th, 2024	Thurs. Dec. 19th, 2024
Natural Habitat	Wed. Oct. 16th, 2024	Tues. Dec. 17th, 2024

Table 4.1: List of focus groups by date and series.

The first series of meetings surveyed individual and organizational definitions and attitudes toward climate resilience. A full list of questions can be found in Table 4.2. Meetings were 90 minutes and began with a brief overview of the report objectives, guiding legislative language, and a high-level overview on modeled future climate scenarios and the infrastructure SETS framework. These meetings sought to harvest organizational knowledge of infrastructure resilience against evolving climate impacts.

Section	Questions
Your definition: Weather resilience	● What does weather resilience mean in your organization?
Your organization: Measuring risks and setting goals	● How do you measure the impact of risks on system resilience? ● What goals does your organization have for resilience, adaptation, and sustainability?
Your work: Infrastructure systems and future weather trends	● How does your work intersect with climate goals in the State of Minnesota?

	● MN CliMAT data suggests an increase to the intensity of spring flooding, summer droughts and temperatures. How will this affect your work on water quality? ● Are there intersections between your work and other systems?
Your take: Infrastructure's role in adaptation to future weather	● How does your work interact with Minnesota's infrastructure systems? (Roads, Electricity, Water, Housing and other Buildings, etc.) ● How do you see the State' infrastructure systems and policy in facilitating adaptation to climate change? ● How would you define infrastructure resilience to climate risk?

Table 4.2: List of questions discussed in the first series of focus groups.

A second series of focus groups explored visions of a thriving infrastructure future. The session began with a recap of infrastructure definitions research to ensure all participants, new and returning, had a shared understanding of key concepts. Participants then engaged in a visioning exercise wherein they imagined and described their vision of a thriving infrastructure future. A discussion of implementation followed, outlining the actions required to achieve these idealized visions and how said actions would deepen system resilience. The meeting presented SETS as a climate action planning process used to identify effective policy solutions. Participants further identified potential risks to the resilience capacity of infrastructure systems, provided suggestions addressing challenges, and named key stakeholders for climate collaboration, including government entities, nonprofits, and citizens. A full list of questions from the second session can be found in Table 4.3. The meeting concluded with next steps in the report creation and dissemination.

Section	**Questions**
Our Future: Envisioning a thriving infrastructure future	● Take a few minutes to envision a thriving future where infrastructure systems and policies have effectively adapted to climate change. Imagine how elements such as community practices, environmental health, and technological innovations work together to enhance resilience. ○ What actions did you envision, and how did they increase the resilience of infrastructure?

Your Concerns: Risks to effectively increasing policy capacity	● What risks do you see hindering effective increases to the resilient capacity of infrastructure systems and policies?
Your Input: Recommendations to increase policy capacity	● What existing, improved, or new policies are needed to ensure infrastructure thrives in the future?
Your Perspective: Ensuring infrastructure thrives amid climate challenges	● What stakeholders (government, non-profit, citizens, etc.) would you need to work with to ensure infrastructure thrives amid climate change?

Table 4.3: List of questions discussed in the second series of focus groups.

Through structured dialogue, focus groups provided insights across a range of infrastructure domains that informed the development of the SETS framework. Results from the focus group conversations are shared in the subsequent sections of this chapter. Each section features high-level SETS diagrams in each infrastructure domain and supporting expert comments.

Minnesota’s Water Infrastructure

To guide the analysis in this section, a working definition of water infrastructure was established. *Water infrastructure includes all built systems or intentionally used ecological systems that support the use, movement, and transformation of water. (i.e., deliver, transport, divert, pump, store, and treat water).* This definition informed each of the subsequent steps in the analysis: reviewing existing policies, identifying SETS components, examining expert insights from the focus group meetings, and developing a high-level SETS map.

Existing Policies & SETS Components for Water Infrastructure

The SETS framework analysis of the current state of Minnesota’s water infrastructure starts by examining the existing policies and related components across sociological, ecological, and technological dimensions–as well as SETS goals. This section will first consider the agencies and organizations involved, then prioritization and financing mechanisms, and finally the frameworks and decision-support tools used for water infrastructure. Doing so can reveal potential gaps and analyze how various regulations, governance structures, and other systems interconnect. By identifying these SETS components the groundwork is laid for developing an integrated view of water infrastructure SETS that could be used for the development of recommendations to inform more resilient infrastructure policy.

Minnesota’s water infrastructure policies and systems involve multiple state agencies and organizations, including public water systems (PWSs). The Minnesota Pollution Control Agency (MPCA) and the Minnesota Department of Health (MDH) both play key roles in regulating water quality and ensuring safe drinking water. Another influential body, the Environmental Quality Board (EQB), produces the State’s assessment of water quality and quantity every five years, for both surface and groundwater, as mandated by Minnesota Statute 103A.43. The EQB also prepares reports on coordinating state groundwater programs and the ten-year state water plan. While these agencies and organizations perform activities that could be examined under other SETS domains, their coordinated governance and regulatory efforts are considered part of Technological development, reflecting organized social processes that guide and manage water infrastructure systems. Other aspects of their work, more closely aligned with different SETS domains, may require further study within those respective areas.

Water infrastructure prioritization and financing mechanisms seek to support the identification and delivery of the most pressing water infrastructure projects. In order to qualify for the various funding streams available through the Minnesota Public Facilities Authority (PFA) a proposed water infrastructure project must be listed on the Project Priority Lists (PPL), which are managed by the MPCA and the MDH. Several funds and financing programs are available for water infrastructure initiatives, including the Clean Water Revolving Fund, the Drinking Water Revolving Fund, and the Water Infrastructure Fund. Although these prioritizations and financing efforts have technological development components, they also represent the contextually specific technosocial dynamics emerging at the interface of individual, social, and cultural preferences, beliefs, and the governance limitations. For instance, the 2023 adjustments to cost-share requirements and expanded eligibility for the Lead Service Line (LSL) Replacement Funding Program[109] address a long-standing issue of lead remaining in pipes for decades–highlighting how policy changes respond not only to technical needs but also to broader social and cultural factors. Additional financing programs include the Point Source Implementation Grant, Small Community Wastewater Treatment, Transportation Revolving Loans, and the Credit Enhancing Program.

Currently, there are various tools, plans, and frameworks to guide water infrastructure decision-making in the State. For example, the MDH manages Source Water Protection Plans and Drinking Water Supply Management Areas in partnership with PWSs and other stakeholders, such as land owners or local decision-makers, to help safeguard drinking water at its source. State Water Plans, developed by the EQB, outline strategic water resource management goals, while the Project Priority Lists managed by MPCA and MDH ensure that there is a process for identifying and addressing critical projects. The Wastewater Infrastructure Needs Survey (WINS) provides a snapshot of the currents and future requirements for Minnesota's publicly owned wastewater treatment and conveyance infrastructure.

Analyzing these agencies, programs, funds, and planning tools through the SETS framework can offer an integrated understanding of how Minnesota's water infrastructure policies and systems address sociological, ecological, and technological dimensions. By considering how existing policies and system components interact across the SETS dimensions, it becomes less complex to identify where current efforts succeed, where gaps remain, and how future policy refinements could improve resilience for the state's water infrastructure.

Expert Insights for Water Infrastructure

Focus Group #1
The first water infrastructure focus group was convened on Thursday, October 17th, 2024, and lasted one and a half hours. Nine attendees represented key departments and organizations, including Minnesota Department of Agriculture, Board of Water & Soil Resources, Minnesota Department of Health, Minnesota Department of Natural Resources Division of Ecological & Water, Board of Water & Soil Resources, Metropolitan Council, and Minnesota Pollution Control Agency. The discussion topics encompassed climate resilience, measuring risks and setting goals on climate change, and infrastructure systems and future weather trends.

Several climate resilience themes were identified from the water infrastructure focus group comments. The **Operational Resilience** of water infrastructure was identified as important to safeguarding land and production systems against extreme weather, maintaining agricultural profitability and yields through adopting resilient and adaptive practices, and conserving natural resources. **Regional Planning** was highlighted as essential to identify the correct infrastructure systems in place to ensure continuity of water use during droughts and floods. One attendee identified the **Health of Natural Systems** as crucial–through the restoration and diversification

[109] "Lead Service Line Replacement Program," 2024 Report to the Legislature (Minnesota Public Facilities Authority, September 15, 2024).

of ecosystems–to maintain their functionality and increase resilience. Lastly, building **System Resilience** was emphasized as important to reduce the risk of catastrophic failures and increase the likelihood that infrastructure remains operational during extreme events.

The next topic the group discussed was how they measure, or try to measure, the impact of climate risks on system resilience. During the conversation four themes emerged. First, a participant suggested that there is a need for **dedicated groups to anticipate risks.** It was suggested that, perhaps, insurance companies could play a role in this through their risk assessments, such as evaluating the failure rates of roofs, stormwater drains, and rain garden designs. Participants also expressed significant concerns about **identifying and implementing necessary fixes**, fearing that the rapid intensification of climate impacts could make it difficult to keep up as the “goalposts” continually shifts. Additionally, challenges related to **boundary conditions** were highlighted, such as mismatches that can occur between hydrologic and political boundaries, which can complicate local planning and can discourage collaboration beyond jurisdictional boundaries. Lastly, discussion was had around the need for **downscaled climate models** that could be used to model climate futures at individual farms and assess possible future agricultural yields.

In discussing how their work on water infrastructure interacts with Minnesota’s other infrastructure systems, focus group participants highlighted several key areas. Water as **transportation infrastructure** was mentioned through the lock and dam system on the Mississippi River, which facilitates the transportation of grain and other products. The **built environment infrastructure** was another focus, such as addressing challenges from extreme flooding on the overtopping of lagoons, road culverts, or impervious surfaces, which each can impact water quality and quantity. Lastly, **natural and agricultural infrastructure** was also mentioned as efforts to restore rivers routed through agricultural land requires setback levees, but enhances water storage and nutrient processing.

Focus Group #2

The second water infrastructure focus group was convened on Wednesday, December 4th, 2024, and lasted one and a half hours. Ten attendees represented key departments and organizations, including Minnesota Department of Agriculture, Board of Water & Soil Resources, Minnesota Department of Health, Minnesota Department of Natural Resources Division of Ecological & Water, and the Board of Water & Soil Resources, Metropolitan Council. The discussion topics included envisioning a thriving future for water infrastructure, identifying risks that limit its resilience, and determining the policies needed to ensure water infrastructure thrives in the face of future weather trends.

When envisioning a thriving future for water infrastructure, participants' thoughts clustered around four main themes. The first theme focused on **rethinking water storage and infrastructure** where discussions involved changing how water is managed–storing surplus in fields during wet periods instead of draining it away–and improving private wells and septic systems to mitigate public health risks under more frequent flooding. Discussions around **managing nutrient runoff and adapting land use** highlighted risks for enhanced nitrate leaching and runoff from increased spring precipitation in the future, with increases to and changes with cover crop strategies highlighted as a potential pathway to hold moisture and filter excess nutrients. When discussing the **accelerating changes amid climate pressures** to water infrastructure, attendees envisioned that climate shifts will force the quicker adoption of best practices, yet policies, funding, and technical assistance to avoid designing and building infrastructure systems that are outdated now and the requirement to maintain them for decades into the future. Lastly, participants shared how **balancing multiple objectives and avoiding "lock-in"** can result in timescale influencing decisions: certain infrastructure–like ditch systems–have a long usable life, while other systems–like crop rotation–can be changed more easily and frequently. As a result, participants shared the reality that some single long-term decisions can "lock in" infrastructure choices and limit opportunities for iterative improvements necessitates an approach to water infrastructure design that allows for multi-benefit solutions–that, for example, align with agricultural and ecological objectives–while building long-term system resilience.

The analysis of participants' discussion of the risks that hinder effective increases in water infrastructure resilience, four themes were identified. First, the risk for **cultural and regulatory resistance**–identified from synthesized comments from participants–describes the potential reluctance of some stakeholders (e.g., private well owners and commercial operations) to accept or adopt additional rules or governance structures that may be necessary for enhancing water infrastructure resilience. Additionally, participants also shared that **uncertain precipitation patterns** also pose risks, since systems (e.g., stormwater protection and treatment) designed for formerly rare events may become inadequate as those events occur more frequently and severely. One participant shared that **changes to regional norms** is a risk to Minnesota communities, as they are accustomed to specific temperature ranges and precipitation patterns, so they might struggle–or not have the infrastructure in place to support–when conditions begin to resemble those of warmer or wetter regions. Finally, participants stressed the importance of **comprehensive asset management plans** to reduce the risk of underestimating or overlooking the need for systematic plans for the identification and prioritization of water infrastructure upgrades to enhance resilience.

Participants identified a number of policies or policy attributes–whether existing, improved or new–that might help increase the likelihood that water infrastructure thrives in the future. First, they emphasized the need for policies to carefully manage the the possibility for **mismatches between where costs fall and where benefits accrues**, for infrastructure resilience actions, noting that some best management practices such as drainage management, cover crops, or reduced tillage can yield broad downstream benefits (e.g. increased water quality, reduced nutrient runoff, and enhanced stormwater handling) yet impose upfront expenses on individual landowners or land managers. Second, one participant suggested the need to **expand the definition of a protective farmland easement** so agricultural land remains viable despite current and future development pressures, by, for example, allowing for the subsidizing of water infrastructure (e.g. water retention basins) or other infrastructure types that are increasing system resilience or securing other environmental benefits. Finally, participants discussed how

bonding limitations–for privately owned water infrastructure compared to publicly owned–can present barriers to enhancing water infrastructure resilience.

Lastly, participants highlighted some of the stakeholders or actors they will need to work with to ensure water infrastructure thrives amid future weather trends. Some of the entities mentioned included the Minnesota Rural Water Association, the League of Minnesota Cities, Tribal Governments, watershed planning organizations (e.g., One Watershed, One Plan), and city or metro agencies.

High-Level Water Infrastructure SETS Map

Using the information gathered from existing policies, the identification of SETS components, and insights from the expert focus group meetings, a high-level conceptual mapping of the water infrastructure SETS was created (shown in Figure 4.1 below). This included the sociological phenomena (e.g., knowledge, attitudes, and beliefs) and the socioecological dynamics (e.g., anthropogenic impacts to human behavior, society, and culture) influencing water systems and policies. Likewise, it highlighted ecological phenomena (e.g., supporting nutrient cycling, provisioning freshwater, and regulating water purity) and technoeco dynamics (e.g., provisioning water supply and regulating water runoff), as well as examples of technological development (e.g., Minnesota Department of Health, Minnesota Pollution Control Agency, and the Minnesota Department of Agriculture) affecting water infrastructure. Additionally, technosocial dynamics (e.g., policy interventions and socio-economic inequalities) were identified, illustrating the interactions between society and the technologies they rely on. At the center of this high-level conceptual diagram lie the SETS goals (e.g., clean water, public health, and food production), representing the existing, clearly defined outcomes that guide decision-making and policy directions for water infrastructure. While further iteration would likely refine and strengthen this conceptualization, the analysis is shared to demonstrate the complexity of and effort in assembling the components required for the first phase of the infrastructure SETS framework analysis–an initial, critical step identified by the framework as necessary for determining action pathways to enhance water infrastructure resilience.

Water infrastructure includes all built systems or intentionally used ecological systems that support the use, movement, and transformation of water. (i.e., deliver, transport, divert, pump, store, and treat water).

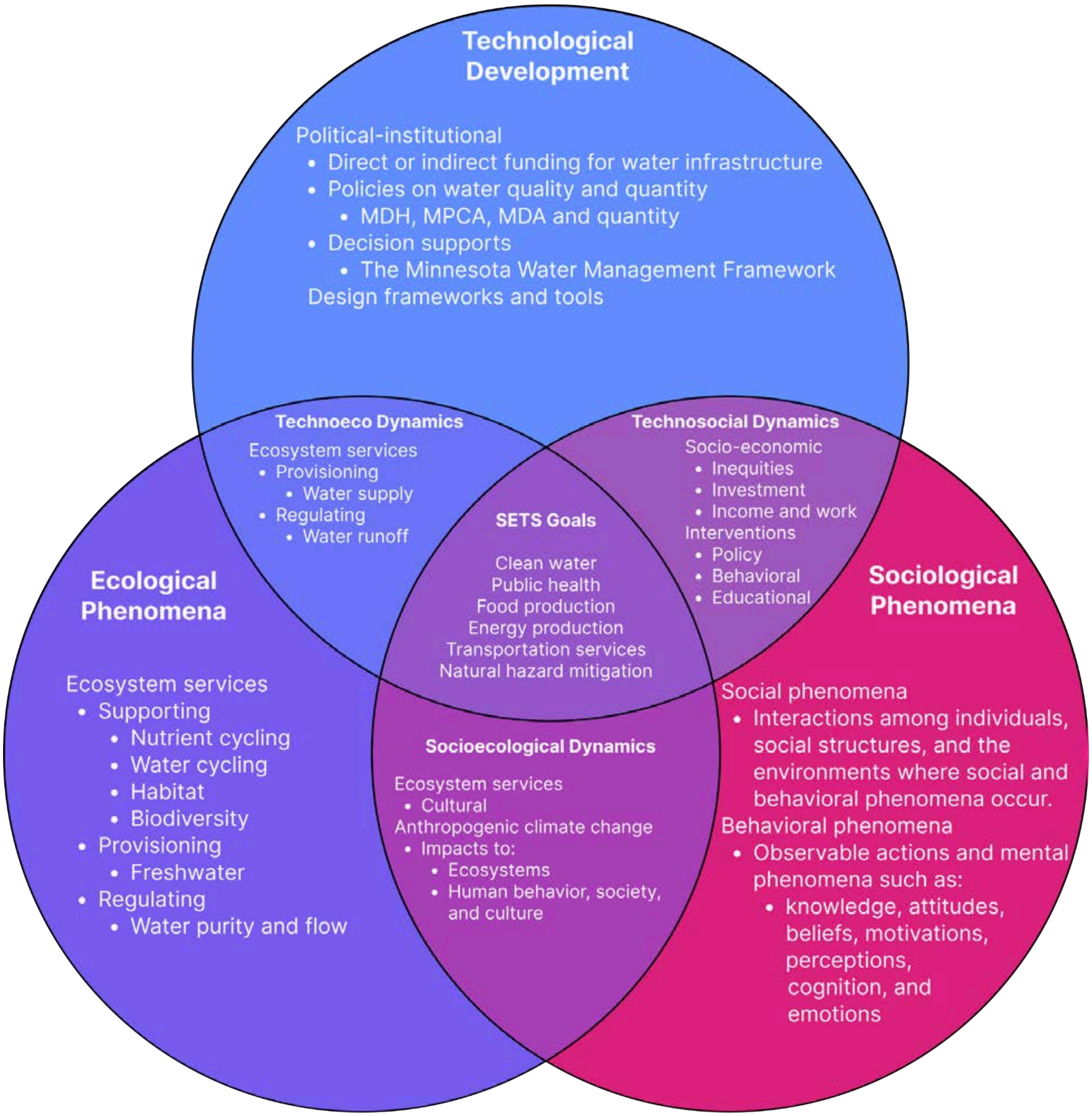

Figure 4.2: High level SETS map for water infrastructure.

Minnesota’s Agricultural Infrastructure

To guide the analysis in this section, a working definition of agricultural infrastructure was created. *Agricultural infrastructure includes all built systems and intentionally used ecological systems that support the production, processing, distribution, consumption, or transformation of grown or raised food and non-food products.* This definition informed the following analysis, which included: reviewing existing policies and identifying SETS components, examining expert insights from the focus group meetings, and developing a high-level SETS map.

Existing Policies & SETS Components for Agricultural Infrastructure
Agricultural infrastructure supports Minnesota’s ability to make use of a range of ecosystem services–such as provisioning freshwater, supporting nutrient cycling, and regulating water runoff–that benefit Minnesota's economy. How the ecosystem services are used are influenced by the sociological, ecological, and technological components and intersections of the agriculture infrastructure SETS. Minnesota's policy landscape for agricultural infrastructure is primarily shaped by a combination of regulations (e.g. regulatory policy) and subsidies (e.g. distribution policy) designed to protect natural resources, while supporting farming production and promoting best farming practices[110]. In SETS terms, the agencies and organizations overseeing these policies and programs can be viewed as components of technological development, as they are formalized processes that govern agricultural infrastructure. For example, this would include finance programs–such as loans and grants administered by the MDA–or agricultural quality programs–such as the Food & Feed Inspection Programs or the Produce Safety Rule governed by the MDA. Yet, while the state agencies, extension offices, and other organizations are components of technological development, often, the work that they do are components of technoeco or technosocial dynamics. For example, developing agricultural practices through initiatives like the Agricultural Growth, Research, and Innovation (AGRI) Program represents a technoeco dynamic, as it is focused on the interaction between technological development and ecological phenomena to improve agricultural production and natural resource management.

Regulations, which encompass both state statutes and agency rules, allow policymakers to control or prohibit farming practices that have been deemed harmful to the environment. These regulations cover domains such as animal husbandry (i.e. livestock and poultry) as well as manure management, crop production, wetland treatment, and the use of water resources in agriculture. Compliance to these regulations is mandatory, and the consequences for non-compliance to farmers ranges from warnings and fines to corrective action orders, permit revocation, and other enforcement actions. From a SETS perspective, regulations shape the interactions between farmers and the environment (socioecological dynamics) and operationalize the technological development processes, which create and have oversight over the regulations, for protection and management of ecosystems (technoeco dynamics).

[110] Colbey Sullivan, “A Minnesota Lawmaker’s Guide to the Agri-Environmental Policy Landscape,” *Minnesota House Research Department*, n.d.

Subsides, including cost-sharing grants, land rental payments, conservation easement purchases, and technical assistance, represent another form of technological development aimed at improving environmental and economic outcomes for agriculture. In some cases, the operationalization of subsidies can be understood as a technoeco dynamic as some of the incentives are contingent on farmers adopting specific practices, such as conservation or pollution control measures. Technical assistance provided by agencies and extension offices is another example of technoeco dynamics through the application of technical knowledge to ecological problems, but it also interacts with socioecological dynamics when farmers are motivated to adopt recommended practices to reduce their impact to ecosystems, improve crop yields, or other desired impacts.

Expert Insights for Agricultural Infrastructure

Focus Group #1

The first agricultural infrastructure focus group was convened on Wednesday, October 9th, 2024, and lasted one and a half hours. Three attendees represented key departments and organizations, including USDA Midwest Climate Hub and UMN Extensions Regional Partnerships. The discussion topics encompassed climate resilience, measuring risks and setting goals on climate change, and infrastructure systems and future weather trends.

In defining resilience the responses of attendees for the agricultural infrastructure focus group split among several themes. **Pursuing research and widening definitions** was noted, with efforts focused on original research and synthesis to understand both current and future climate impacts on agriculture. Notably, this included one attendee suggesting the need to recognize soil as infrastructure. Maintaining **agricultural productivity** was emphasized as an important aspect of resilience, including aiming to sustain yields and mitigate climate change effects on working lands. Additionally, the need for **agricultural diversity** was identified as a factor to increasing agricultural resilience as well, such as promoting a wider range of crops and livestock and supporting an increased number of agricultural advisors to enhance farmer knowledge of crop and livestock alternatives. Lastly, there was a desire for **better climate projections**, as participants expressed concerns about the challenges of modeling certain climate change extremes, but the need for that information to effectively develop infrastructure that can withstand those potential extremes.

To measure the impact of climate risks on system resilience, attendees shared that they utilize both experimental and qualitative approaches. **Experimental methods** included initiatives such as winter greenhouses and plant genetics, which aim to enhance crop resilience and productivity under extreme weather conditions. **Qualitative methods** included agricultural vulnerability assessments, surveys and interviews with producers, advisory groups, and impact assessments.

Lastly, three primary themes emerged from the focus group responses regarding how the increased intensity of spring floods, summer droughts, and potential extended fall droughts or flooding will impact agricultural systems. **Flooding** challenges include the need to engineer soils to remove excess water, rebuild surface soil nutrients to mitigate flooding effects, and develop water management practices that either capture and reuse water during dry periods or adapt crop selections to avoid flood damage. **Transportation** issues can arise from extreme precipitation events that result in deteriorating road quality on farms, which can restrict access during wet periods, potentially threatening farm profitability. Lastly, **utility failures** due to larger storm systems, such as internet and electrical outages, pose risks to farm operations, especially in rural areas where low population density can exacerbate the impact and duration of such disruptions.

Focus Group #2

The second agricultural infrastructure focus group was convened on Wednesday, November 13th, 2024, and lasted one and a half hours. Four attendees represented key departments and organizations, including USDA Midwest Climate Hub and UMN Extensions Regional Partnerships. The discussion topics included envisioning a thriving future for agricultural infrastructure, identifying risks that limit its resilience, and determining the policies needed to ensure agricultural infrastructure thrives in the face of future weather trends.

When envisioning a thriving future for agricultural infrastructure, participants stressed the need to **think of the impacts beyond Minnesota** from future weather trends in order to proactively identify new crops to grow or expand cultivation within the state–such as nuts, alfalfa, and vegetables–which might be potentially displaced from regions like California due to changes in growing conditions. They highlighted a **maladaptive increase in field tile use** across the state in response to changing hydrology; while tiling can help individual farmers manage heavier and more frequent rainfall events, it also exacerbates runoff problems further downstream. As an alternative to field tile, participants shared the need to **boost soil organic matter** by cultivating crops like alfalfa, Kernza, and hazelnuts, which increase the soil's water-holding capacity to better manage heavy rainfall events while also reducing nutrient runoff. Finally, participants shared the importance for active decision-making around how crop selection and management intersect with changing market demands for certain commodities. For example, if ethanol use declines due to increasing adoption of electric vehicles, it could open up acreage for other crops that promote climate resilience or have other local benefits.

Participants identified multiple risks hindering efforts to increase the resilience of agricultural infrastructure in the face of future weather trends. For a number of attendees, **equity concerns** stood out, as large-scale climate relevant agriculture infrastructure components–such as anaerobic digesters that capture methane (a potent greenhouse gas) from livestock manure–are often financially out of reach for smaller farms while also pushing larger farmers to get even bigger. There is a risk that this dynamic could potentially further exacerbate both environmental challenges and disparities between large and small operations. **Crop tradeoffs** were raised as another concern, as choosing to grow one crop (e.g., hemp for sustainable building materials) inevitably means not planting something else, such as food crops, which could impact consumer prices, commodity availability, amongst other effects. Relatedly, **existing crop subsidies**–which currently favor and enhance corn and soybean production–may need expansion to include crop alternatives such as camelina (a cover crop used in the production of sustainable aviation fuel) or hemp, especially in the cases when crop insurance and and other financial mechanisms are explicitly designed for a limited set of commodities. This broader coverage could incentivize producers to diversify into crops that could provide climate resilience benefits. A related issue is **knowledge gaps**: as currently farmers are well-versed in growing corn and soybeans effectively, but are likely to face a learning curve and potential insurance barriers when attempting to grow new crops. Finally, participants shared that the **increasing debt burdens** for Minnesota producers could impede the types of equipment changes or other investments that would be necessary for production shifts in agriculture, potentially creating an economic lock-in that could delay or prevent the adoption of more resilient farming practices or strategies.

Participants highlighted several policy needs to support the enhancement of agricultural infrastructure to remain resilient in the face of future weather trends. First, they called for support for and creation of **an army of agricultural production mentors** to guide producers in adopting new practices–such as growing camelina, hemp, and pennycress–and to reduce the perceived risks of diversifying crops. To be effective, this approach would need to be supported by increased research, education, and extension resources. Second, participants stressed the need to **reexamine crop insurance policies** in order to enhance access for small-scale and alternative farms to coverage, potentially increasing local food security by supporting the types of producers that comprise urban agriculture operations. Finally, participants cited a need for new or enhanced **decision-making tools** that allow for producers to experiment with different growing scenarios–for example, modeling how incremental increases in soil organic matter might affect yield and the interaction with the impacts from future weather trends.

Participants highlighted some of the stakeholders or actors they will need to work with to ensure agricultural infrastructure thrives amid future weather trends. Some of the entities mentioned included the USDA, nonprofits like the Nature Conservancy, and farmers. Additionally, agricultural business entities that are open to or that see the need for change in agricultural practices in the face of future weather trends were also identified as key partners, as well as citizen action groups. Participants also stressed the need for collaboration among farmers and communities of various sizes, to encourage more diverse land uses that support the creation of systems for more local food production, especially near urban centers. Lastly, participants underscored the importance of collective, collaborative governance in managing the complex decision-making that may arise from future weather trends–an attendee, for example, recalled a severe drought around 2010 in southern Minnesota and northwest Iowa where water scarcity once pitted livestock needs against municipal drinking water supplies.

High-Level SETS Map for Agricultural Infrastructure

Using the information gathered from existing policies, the identification of SETS components, and insights from the expert focus group meetings, a high-level conceptual mapping of the agricultural infrastructure SETS was created (shown in Figure 4.2 below). This included the sociological phenomena (e.g., interactions among individuals, social structures, and environments) and the socioecological dynamics (e.g., anthropogenic impacts to ecosystems) influencing agricultural systems and policies. Additionally, ecological phenomena (e.g., supporting biodiversity and water cycling, and regulating water runoff) and technoeco dynamics (e.g., provisioning food and agricultural practice development), as well as technological development (e.g., Produce Safety Rule, Food & Feed Inspection Programs, and Food Safety Modernization Act) affecting agricultural infrastructure were identified. Also, technosocial dynamics (e.g., educational interventions and socio-economic factors of income and work) were highlighted, which focus on the interactions between applied technologies and social and behavioral phenomena they interface with. Lastly, SETS goals (e.g., farming strategies, food products, and natural habitat protection) were mapped, representing the existing policy directions for agricultural infrastructure. While more research would be needed to apply this conceptualization to the real-world, the analysis demonstrates the steps required for the first phase of the infrastructure SETS framework analysis to increase the resilience of agricultural infrastructure.

Agricultural infrastructure includes all built systems and intentionally used ecological systems that support the production, processing, distribution, consumption, or transformation of grown or raised food and non-food products.

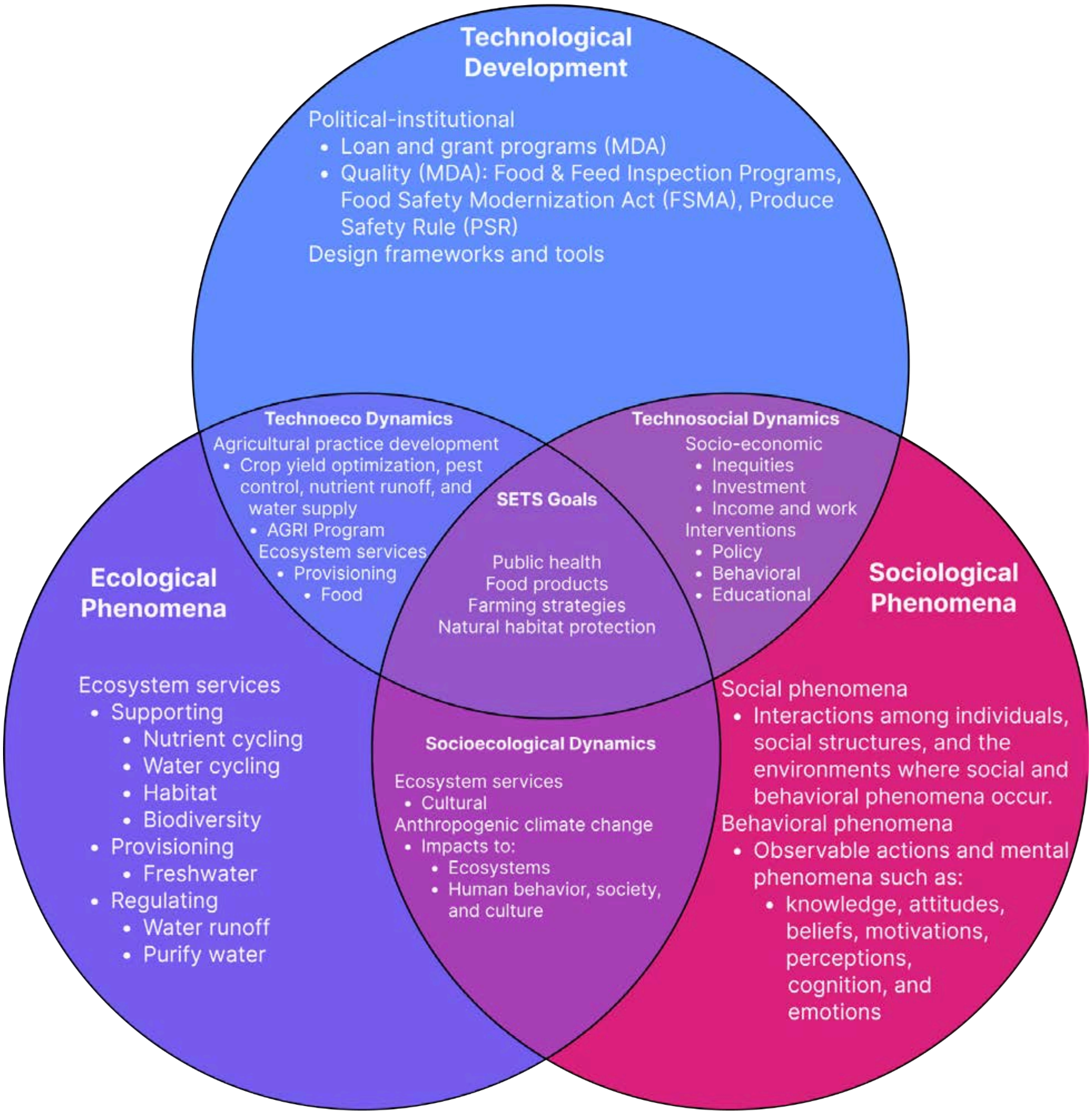

Figure 4.2: High level SETS map for agricultural infrastructure.

Minnesota's Forestry Infrastructure

Analysis in this section was oriented by the following working definition of *forestry infrastructure as including all built or intentionally used ecological phenomena that support the production,* *processing, distribution, and consumption of forestry products.* This definition informed the following analysis: reviewing existing policies and identifying SETS components, examining expert insights from the focus group meetings, and developing a high-level SETS map.

Existing Policies & SETS Components for Forestry Infrastructure

Various agencies, departments, and organizations are responsible for governing different aspects of the policies that oversee agricultural infrastructure, including Minnesota's soil and water conservation districts. For example, the Minnesota Forest Resources Council (which is an example of technological development under the SETS framework), established under the Sustainable Forest Resources Act (Minn. Stat. Chapter 89.03), develops the Forest Management Guidelines[111]. These guidelines provide recommendations to the governor and officials in other levels of government for forest management policies and practices that would sustainably manage, use, and protect the state's forest resources (which take the form of technoeco, technosocial, and socioecological dynamics under the SETS framework). Another example is the Minnesota Department of Natural Resources (DNR), which amongst other duties, is responsible for creating the state forest action plan[112], which outlines strategic goals and priorities for managing and measuring the health of Minnesota's forest resources. From a SETS perspective, the DNR is a component of technological development. The creation and operationalization of the state forest action plan involves technoeco dynamics (e.g., maintenance of productive capacity, value of wood related products, and active forest management), technosocial dynamics (e.g., state forestry salaries, worker safety, and forest products manufacturing wages), and socioecological dynamics (e.g., conversions from forested land, participation in outdoor recreation, and environmental stewardship activities), while the plan's strategic goals would represent some of the forestry infrastructure SETS goals.

Expert Insights for Forestry Infrastructure

Focus Group #1

The first forestry infrastructure focus group was convened on Wednesday, October 30th, 2024, and lasted one and a half hours. Five attendees represented key departments and organizations, including the Minnesota Department of Natural Resources and the UMN Natural Resources Institute. The discussion topics encompassed climate resilience, measuring risks and setting goals on climate change, and infrastructure systems and future weather trends.

Key themes were identified in how participants defined or thought about climate resilience in their organizations. First, participants emphasized the importance of **data-driven forest management approaches**, including the use of GIS for tree inventories and modeling forest growth to develop an understanding how changes to Minnesota's climate might impact the resilience of existing forest systems. Additionally, **long-term and adaptive forest management**

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[111] Minnesota Forest Resources Council, "Interim Final MFRC Forest Management Guidelines Updates for Public Comment," 2024.

[112] Minnesota Department of Natural Resources, "Minnesota 2020 State Forest Action Plan," 2020, https://files.dnr.state.mn.us/forestry/forest-action-plan/2020-forest-action-plan-part-1-assessment-trends.pdf.

strategies were highlighted as critical to creating healthy forests through actions like tree planting, stand improvement projects, and infrastructure redesigns. The need for **collaboration** was also stressed as necessary, with groups like private landowners, tribes, communities, and inter-agency teams, to effectively implement resilience measures.

A number of **quantitative metrics** were shared when participants were asked how they measure the impact of climate risks on forest system resilience. The types of metrics used could change depending on what is attempted to be measured. For example, net primary productivity would be used to assess the health of mature forests, but height growth would be used to assess young forests. Also, rot quantification could be used to determine forest health.

Lastly, three themes emerged when focus group participants discussed the intersections between forestry infrastructure and other systems. First, forests enhance **water quality** by reducing sediment runoff compared to agricultural land. In the **energy** sector, biofuel production creates tensions with forest conservation, although biofuel initiatives might present opportunities to revitalize unhealthy forests through different management practices. Lastly, the increasing frequency of wildfires highlights the need for enhanced **disaster response** systems.

Focus Group #2

The second forestry infrastructure focus group was convened on Wednesday, December 11th, 2024, and lasted one and a half hours. Seven attendees represented key departments and organizations, including the Minnesota Department of Natural Resources and the UMN Natural Resources Institute. The discussion topics included envisioning a thriving future for forestry infrastructure, identifying risks that limit its resilience, and determining the policies needed to ensure forestry infrastructure thrives in the face of future weather trends.

When asked to envision a thriving future for Minnesota's forestry infrastructure, one participant first warned of a risk for a **western-style wildfire scenario** in the state if forests are not proactively managed with prescribed burns or mechanical thinning to reduce excessive fuel loads. They also stressed the importance of carefully **planning how the built environment and other surrounding systems expand around forested areas**, as such developments add complexity to wildfire reduction strategies due to the systems being colocated in and around forests. Another participant suggested that **Forestry 2.0** (which describes the shift in the production in forest products due to changes in supply and demand) could provide an opportunity for investments into climate-resilient forest management practices to create innovative markets for low-value wood products, thus helping keep forests healthy–by reducing fuel load and creating new revenue streams–and supporting a greener economy. **Diversifying planting stock** was also raised as an action to potentially enhance the resilience of forest systems through increasing the variety of tree species planted, but this would require technological improvements–such as containerized planting–and identifying and supporting more seed vendors. Participants also highlighted the need for enhanced **forestry road planning**–requiring hydraulic studies for forestry roads–in order to ensure roadways are sufficiently resilient to the increasingly severe weather events they are facing now and into the future, noting that resource constraints can make maintaining roads after extreme storms and providing access during shoulder season a challenge.

Participants shared a number of risks that could hinder attempts to increase the resilience of forestry infrastructure amid future weather trends. **Ineffective communication strategies** were identified as a risk by a number of participants, as early and thorough engagement was seen as essential for fostering **community buy-in** for the types of new approaches to forest management that might be necessary to increase resilience. For example, one participant shared that Minnesota’s shift in 2007 to an online open burning permit system was initially met with resistance, but it has since been shown effective in reducing fires within the state. Another risk discussed was the **generational timescale of change** that has been historically necessary for forestry products to be adopted (e.g., dimensional lumber, pulp, and fiberboard products), so the widespread adoption of cellulosic ethanol, for example, which could reduce the fuel load in forest might be 10 years away. Lastly, **maintaining markets for forestry products** was deemed crucial for ensuring the continued viability for the use of a wide range of management practices that increase climate resilience in forested landscapes.

Participants identified several policy needs to ensure forestry infrastructure remains resilient amid future weather trends. First, participants emphasized the need for continued support for **existing state policies** that keep public forest lands forested, but noted that **internal department guidelines** also play a role in ensuring sustainable harvesting, replanting, and resilience efforts. Participants also pointed out the need for **consistent, long-term funding**, given that a significant number of forestry projects often require decades to plan and execute. Lastly, one participant noted that **existing purchasing and prevailing wage policies** sometimes restrict vendor pools and, as such, can present challenges in completing required forestry maintenance projects.

Lastly, participants shared some of the stakeholders and actors they would need to collaborate with to increase the likelihood that forestry infrastructure remains resilient to future weather trends. They shared that public-private partnerships can be used to support the creation of new revenue streams (e.g. cellulosic ethanol) to fund other forestry initiatives, while nonprofit organizations can support projects through grant funding and other other activities that might be outside the scope of state agencies. Universities were seen as key to advancing research and data-driven insights on forestry infrastructure resilience, in collaboration with regional partnerships among countries, townships, and federal agencies like the Forest Service. Participants’ shared a number of actors, such as tribal partners, NGOs such as The Nature Conservancy, private landowners, Minnesota’s forest industries, timber producers, and trade organizations all play roles in creating and operationalizing best practices for increasing the resiliency of forestry infrastructure.

High-Level SETS Map for Forestry Infrastructure

Using the information gathered from existing policies, the identification of SETS components, and insights from the expert focus group meetings, a high-level conceptual mapping of the forestry infrastructure SETS was created (shown in Exhibit 4.6 below). This included the sociological phenomena (e.g., perceptions, cognition, and emotions) and the socioecological dynamics (e.g., supporting culture) influencing forestry systems and policies. Additionally, ecological phenomena (e.g., regulating flood control and erosion prevention) and technoeco dynamics (e.g., provisioning raw materials), as well as technological development (e.g., forest management, fire protection, and reforestation) affecting forestry infrastructure were identified. Also, technosocial dynamics (e.g., socio-economic investment and behavioral interventions) were highlighted, which focus on the interactions between applied technologies and social and behavioral phenomena they interface with. Lastly, SETS goals (e.g., wood yield optimization, carbon sequestration, and recreational opportunities) were mapped, representing the existing policy directions for forestry infrastructure. While more research would be needed to apply this conceptualization to the real-world, the analysis demonstrates the steps required for the first phase of the infrastructure SETS framework analysis to increase the resilience of forestry infrastructure.

Forestry infrastructure includes all built or intentionally used ecological phenomena that support the production, processing, distribution, and consumption of forestry products.

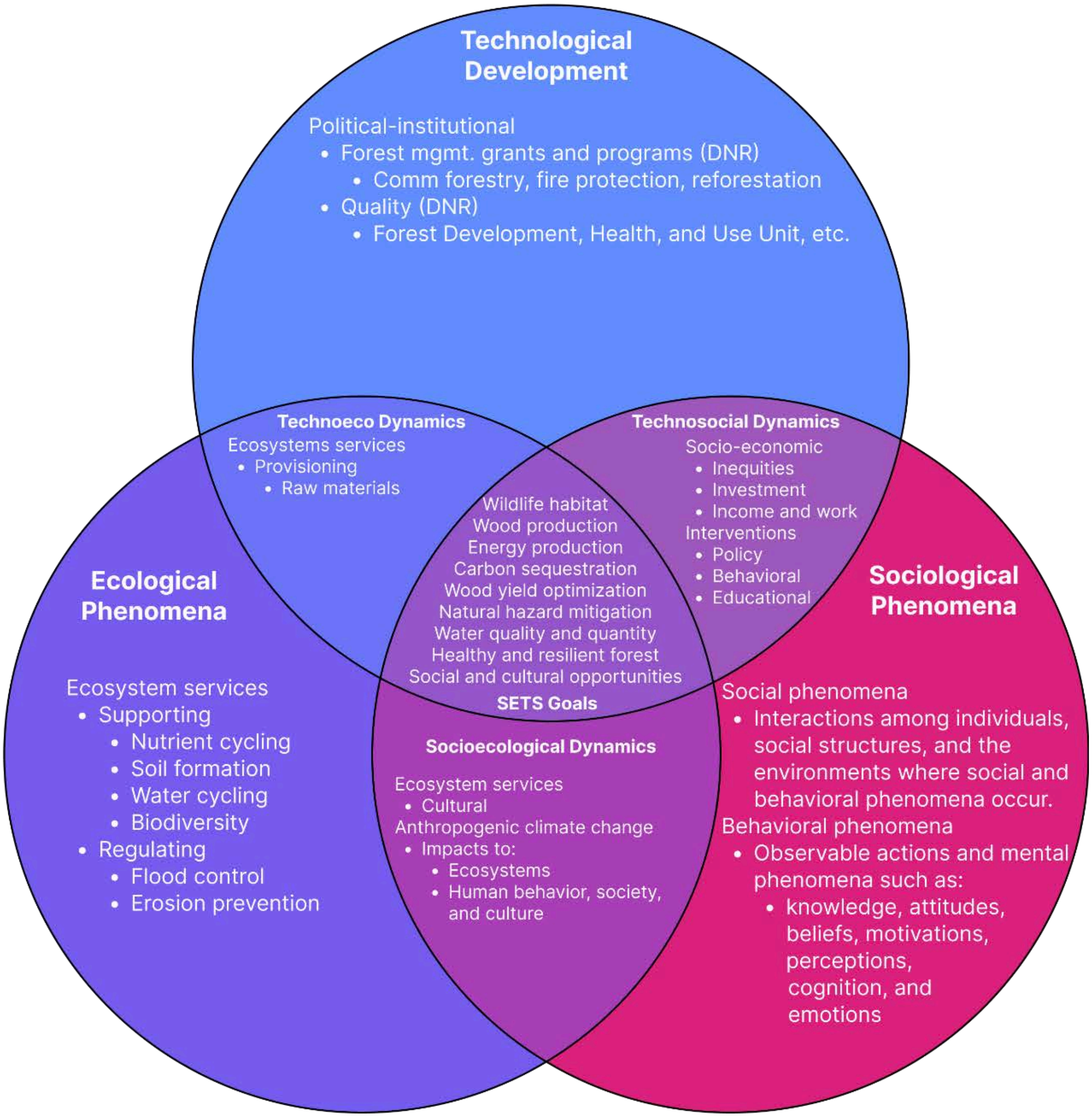

Figure 4.3: High level SETS map for forestry infrastructure.

Minnesota’s Built Environment Infrastructure

A definition of built environment infrastructure was established to guide the analysis in this section. *Built environment infrastructure includes all built or intentionally used ecological phenomena that support the design, construction, operations, or maintenance of built infrastructure.* This definition informed each step in the analysis: reviewing existing policies and identifying SETS components, examining expert insights from the focus group meetings, and developing a high-level SETS map.

Existing Policies & SETS Components for Built Environment Infrastructure

The regulations for the built environment primarily take the form of building codes and are established at the state level. These codes cover floodproofing, energy, fire protection, plumbing, structure, electrical, mechanical systems and fuel, elevators and related devices, and Americans with Disabilities Act compliance. Specific building types such as manufactured homes and storm shelters have additional code requirements, and buildings constructed with General Obligation Bond funding are required to comply with the State’s sustainable and resilient buildings program, B3. Municipalities often have zoning regulations determining what can be built where, and some watershed districts enforce requirements that advance their purpose.

Codes are enforced by reviews and inspections, and create legal liability for those attesting that codes have been met. Building codes are determined and enforced by the Department of Labor and Industry, the Construction Codes Advisory Council, and the Minnesota Pollution Control Agency. Because building codes are established by the state, municipalities generally are not permitted to enforce more or less stringent codes.

The robust built environment code creates an obvious opportunity for the integration of resilience in all systems. Considerations of performance in future climate scenarios should be woven through and provisioned for in each individual code. This approach, rather than creating a separate resilience-focused code, leverages the existing process and enforcement mechanisms and will create the least burden for those writing, enforcing, and complying with building codes. The purpose of the State Building Code is to, as described in Statute 26B.101, “...provide basic and uniform performance standards, establish reasonable safeguards for health, safety, welfare, comfort, and security of the residents of this state and provide for the use of modern methods, devices, materials, and techniques which will in part tend to lower construction costs. The construction of buildings should be permitted at the least possible cost consistent with the recognized standards of health and safety.” Consideration of resilience to future climate scenarios is crucial to achieving the performance standards and safeguards for health, safety, welfare, and security. Building resilient buildings now will protect financial investments and reduce rebuilding or replacement costs in the event of a failure.

Expert Insights for Built Environment Infrastructure

Focus Group #1

The first built environment infrastructure focus group was convened on Wednesday, November 6th, 2024, and lasted one and a half hours. Five attendees represented key departments and organizations, including the Minnesota Department of Administration, Minnesota Department of Commerce, and the Minnesota Housing Finance Agency. The discussion topics encompassed climate resilience, measuring risks and setting goals on climate change, and infrastructure systems and future weather trends.

A number of themes were identified when discussing with focus group participants what climate resilience means to their organizations. First, participants shared the importance of efforts to **proactively prevent building damage**, due to changing weather trends, through investments in programs to, amongst other things, weatherize buildings and fortify roofs. Additionally, efforts in **maintaining community cohesion** were also raised as important, with strategies including reducing damage protection costs through insurance reductions and implementing banking programs that prevent financial defaults from flooding. Participants also highlighted the importance of **establishing resilience hubs**–dedicated spaces where individuals can safely retreat during disasters, if needed, thereby enhancing the resilience of community networks. Lastly, the adoption of a **broad definition of resilience** was advocated for, which would include both efficiency and conservation initiatives that lower operating costs even in the face of varied weather impacts.

The focus group participants also highlighted several challenges and opportunities to increase climate resilience in the built environment. One challenge raised was the difficulty of **planning for unknowns**, such as cascading failures in interconnected systems. For example, an extreme weather event could cause a prolonged power outage and wash out access roads, preventing the refueling of emergency backup generators and thereby increasing the risk to patient safety. Participants shared a number of obstacles they saw in establishing **resilience standards**, citing concerns over costs, the return on investment for resilience actions, and the necessity for clear guidelines on assessing resiliency. Additionally, the focus group emphasized the risk of **overlooking critical systems** resilience needs, such as communication networks, which are vital during disruptions. In terms of opportunities, participants felt that there is significant potential in **enhancing system resilience by interconnecting infrastructure elements** rather than treating them as isolated units, which can lead to cost reductions and potentially allow for more effective resilience strategies.

Focus Group #2

The second built environment infrastructure focus group was convened on Thursday, December 19th, 2024, and lasted one and a half hours. Six attendees represented key departments and organizations, including the Minnesota Department of Administration, Minnesota Department of Commerce, and the Minnesota Housing Finance Agency. The discussion topics included envisioning a thriving future for built environment infrastructure, identifying risks that limit its resilience, and determining the policies needed to ensure built environment infrastructure thrives in the face of future weather trends.

In envisioning a thriving future for built environment infrastructure, participants first underscored the need for actors within the built environment field to be **more responsive to actioning climate-relevant information** into their work. Some participants envisioned **increased tree canopy coverage and green space around buildings** to aid in mitigating heat island effects, but recognized the need to analyze the **complex trade-offs** between, for example, shading buildings and the impacts it would have in limiting possible rooftop solar generation. Participants also envisioned a future in which well-designed buildings and sound environmental practices would help **increase the likelihood families and communities remain safe** in the face of future weather trends. **Retrofitting existing buildings** to meet new insulation and efficiency standards was also seen as important. Participants shared that there is need for more **statewide guidance into planning and zoning** that increases the resilience of built infrastructure, while also handling the complex interplay among, built and natural systems that all intersect at building sites. Finally, participants envisioned more **coordinated stormwater management** initiatives, where resilience is measured across an entire region, rather than focusing on isolated projects.

Participants shared a number of risks that could hinder efforts to increase the resilience of built environment infrastructure. First, **legislative limitations** emerged as a barrier, with state-level rulemaking constraints and institutional resistance to policy changes potentially reinforcing existing social and individual inertia for the status quo. The challenge in providing effective **state level support** for built environment resilience (e.g., through zoning guidance or other policies) while still preserving local control (e.g., through city resilience plans or other proposals) was also discussed. One participant shared that there is a risk that existing built environment infrastructure, such as stormwater systems, could become **liabilities** due flooding and other impacts from future weather trends, because they were designed for past precipitation patterns. Lastly, participants shared that there is a **tension between rapid climate responses and inclusive planning**, underscoring how urgent change can conflict with the need for stakeholder engagement.

Participants suggested a number of policies to support the thriving of built environment infrastructure in the future. Discussion started with the need for the development of a **comprehensive climate resilience standard** for buildings–akin to various building standards for decarbonization–to guide how and what types of resiliency measures should be integrated into a buildings' overall design. Yet, some participants cautioned, however, that resilience standards must have the capacity to be **tailored to local conditions**, noting that a single statewide building code, which local governments cannot exceed, would create undesirable gaps in resilience. This is because climate risk varies by region and, in some cases, even by neighborhood microclimates, so a statewide approach might end up at best discouraging or at worst preventing proactive measures to enhance resilience at the community level, which would ultimately limit the effectiveness of the climate resilience building standards.

Lastly, participants highlighted some of the stakeholders or actors they will need to work with to ensure built environment infrastructure thrives amid future weather trends. Some of the entities mentioned included the city councils, Minnesota Department of Health and Minnesota Housing.

High-Level SETS Map for Built Environment Infrastructure

Using the information gathered from existing policies, the identification of SETS components, and insights from the expert focus group meetings, a high-level conceptual mapping of the built environment infrastructure SETS was created (shown in Figure 4.4 below). This included the sociological phenomena (e.g., interactions among individuals, social structures, and environments) and the socioecological dynamics (e.g., anthropogenic impacts to human behavior, society, and culture) influencing built environment systems and policies. Additionally, ecological phenomena (e.g., supporting habitat and biodiversity, and regulating water runoff) and technoeco dynamics (e.g., provisioning raw materials and water supply), as well as technological development (e.g., rules, codes, and regulations) affecting built environment infrastructure were identified. Also, technosocial dynamics (e.g., socio-economic factors of income and work) were highlighted, which focus on the interactions between applied technologies and social and behavioral phenomena they interface with. Lastly, SETS goals (e.g., transportation services, natural hazard mitigation, and energy production) were mapped, representing the existing policy directions for built environment infrastructure. While more research would be needed to apply this conceptualization to the real-world, the analysis demonstrates the steps required for the first phase of the infrastructure SETS framework analysis to increase the resilience of built environment infrastructure.

Built environment infrastructure includes all built or intentionally used ecological phenomena that support the design, construction, operations, or, maintenance of built infrastructure.

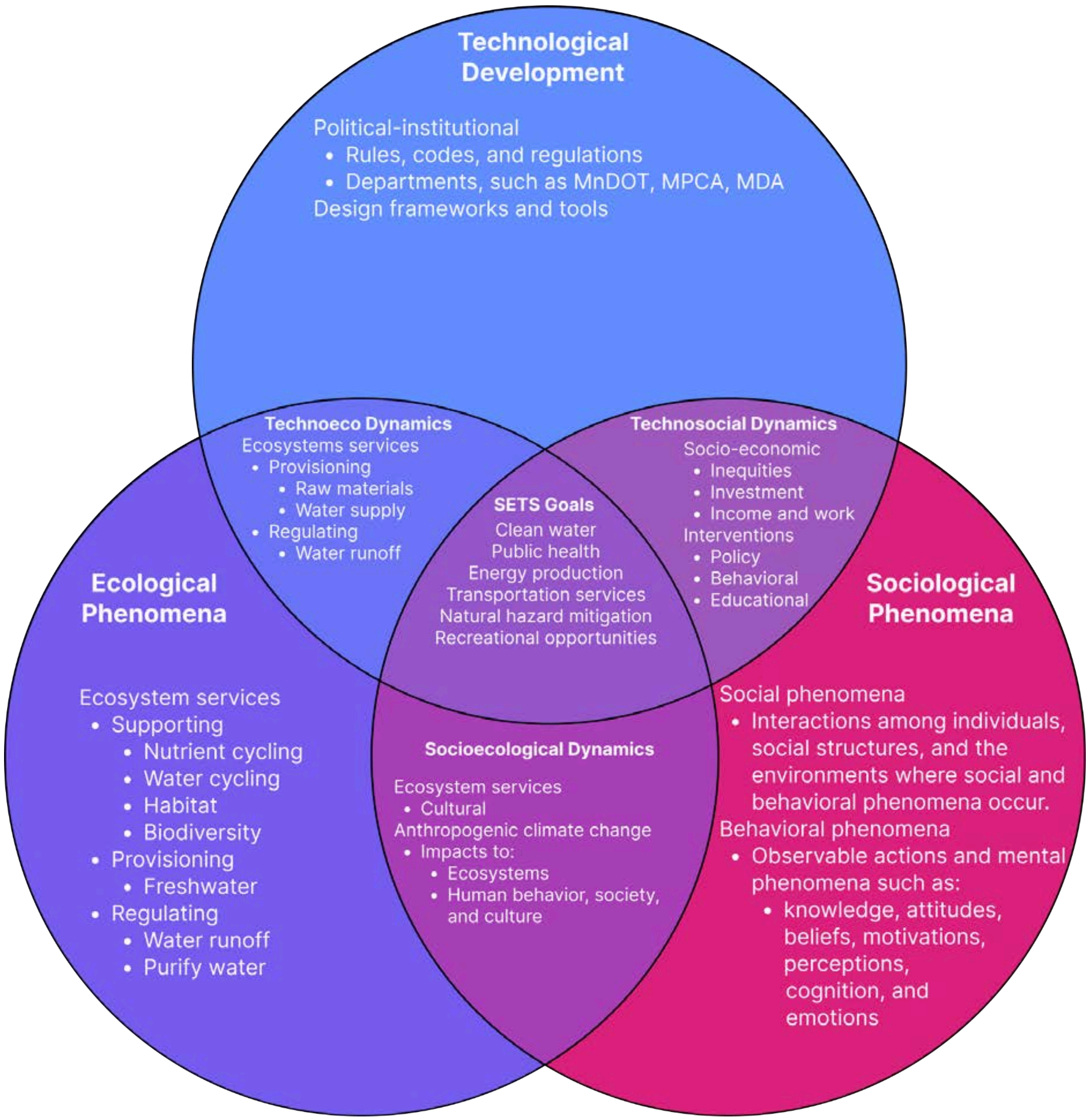

Figure 4.4: High level SETS map for built environment infrastructure.

Minnesota's Natural Habitat Infrastructure

Natural habitat infrastructure includes all built or intentionally used ecological phenomena that support conservation and recreation, as well as protection, mitigation, and adaptation activities for natural habitat. This working definition supported the direction of each step in the analysis: reviewing existing policies and identifying SETS components, examining expert insights from the focus group meetings, and developing a high-level SETS map.

Existing Policies & SETS Components for Natural Habitat Infrastructure
Natural habitat infrastructure serves as a compelling domain for studying the SETS framework, because much of the natural habitat is either explicitly or implicitly utilized by or situated near other infrastructure systems. This section explores agencies, programs, and policies that govern natural habitat infrastructure in Minnesota, and describe how they align with the SETS dimensions.

Natural habitat infrastructure in Minnesota is supported by a network of agencies, departments, and organizations that each pursue efforts that, among other things, restore, manage, and enhance the state's ecological systems. For example, the DNR administers the Natural Communities Restoration and Management Program, which focuses on preserving and managing natural plant communities as well as providing technical assistance for that work, and other related activities. The Minnesota Board of Soil and Water Resources oversees a number of natural habitat programs, including the Habitat Enhancement Landscape Program (HELP), funds stormwater and green infrastructure projects, and manages wetland banking projects through the Local Government Road Wetland Replacement Program. Other organizations such as the Legislative-Citizen Commission on Minnesota Resources, Minnesota Department of Agriculture, and Minnesota Environmental Quality Board all play a role in enhancing Minnesota's natural habitat. From a SETS perspective, each of these organizations would be an example of technological development, while the actions that they undertake could fall under technoeco, technosocial, or socioecological dynamics. By understanding the efforts of these organizations through the SETS framework, an integrated approach to natural habitat infrastructure can potentially lead to more coordination amongst organizations and enhance outcomes.

Expert Insights for Natural Habitat Infrastructure

Focus Group #1
The first natural habitat infrastructure focus group was convened on Wednesday, October 16th, 2024, and lasted one and a half hours. Five attendees represented key departments and organizations, including the Minnesota Department of Natural Resources and the Minnesota Board of Water & Soil Resources. The discussion topics encompassed climate resilience, measuring risks and setting goals on climate change, and infrastructure systems and future weather trends.

Four themes were identified from the conversation with participants about how they measure the impact of climate risks on natural habitat system resilience. First, there are **increasing efforts to track climate resilience indicators**, including monitoring wildlife species such as pollinators, as well as using hydrographs for wetlands and lakes to assess water level fluctuations. Despite these efforts, participants noted there is a **lack of adequate metrics to quantify climate risk**, so while there are a lot of risk indicators in natural habitat systems there are a lot of areas without measurement tools to identify and track them. Additionally, participants highlighted a **lack of measuring tools for estimating climate resilience**, noting difficulties in measuring the direct impacts of climate change and estimating possible future risks in natural habitat infrastructure systems. Lastly, participants shared that **no systematic way to address climate resilience has emerged**, with that said, while numerous climate resilience initiatives exist an integrated strategy, if possible, is lacking.

Participants shared three ways their organization engages with goals for climate resilience, adaptation, and sustainability. First, while **organizations are still developing broader resilience objectives**, some projects within agencies have specific quantifiable goals. Second, there is a **need for more data** to effectively set and achieve these goals. Third, **organizations are utilizing existing frameworks** like the Minnesota Climate Action Framework or the Minnesota Adaptation Framework.

In answering how natural habitat infrastructure connects to other systems, participants identified a number of intersections. For example, through the Water Quality and Storage Program administered by the Board of Water & Soil Resources, funds **water storage** projects–ranging from small swales to huge basins–to control water volumes and rates in order to protect other infrastructure systems. Additionally, habitat-friendly solar projects integrate **renewable energy** with ecosystem protection. Lastly, **agriculture** can support natural habitat resilience through water capture practices like low/no tillage and cover cropping.

Focus Group #2

The second natural habitat infrastructure focus group was convened on Tuesday, December 17th, 2024, and lasted one and a half hours. Six attendees represented key departments and organizations, including the Minnesota Department of Natural Resources and the Minnesota Board of Water & Soil Resources. The discussion topics included envisioning a thriving future for natural habitat infrastructure, identifying risks that limit its resilience, and determining the policies needed to ensure natural habitat infrastructure thrives in the face of future weather trends.

In envisioning a thriving future for natural habitat infrastructure, participants shared a number of actions or strategy recommendations to increase resilience. First, a participant stressed the importance of creating a **network of protected natural habitat corridors** that would exist throughout rural and urban landscapes, as natural habitat corridors are more resilient to climate change than isolated natural habitats. Another participant envisioned using **smart growth and planning strategies** to enhance the resilience of natural habitat infrastructure by reducing impervious surfaces, widely incorporating green infrastructure within urban environments, and capturing stormwater near its source through rain gardens or bioswales. Additionally, participants envisioned enhancing aquatic system resilience by **building connectivity networks**–linking upstream and downstream channels, integrating lateral streams with their floodplains, and removing aging infrastructure to establish extended, interconnected river systems. Lastly, participants envisioned **subsurface drainage strategies** that would restore soil systems and other natural landscapes to better retain water on the land, and enhance the carbon storage capacity.

Participants shared a number of risks to the effective increase of the resilience of natural habitat infrastructure. First, **insufficient funding** to manage ecosystem change–such as changing hydrology, invasive species, and shifts in plant communities from rising temperatures–due to future weather trends. For example, in some areas tree losses due to emerald ash borer, other diseases, and invasive plants can outpace replanting efforts, which over time could result in decreased carbon dioxide sequestration. Another risk highlighted was that currently **localized phenomenon** in Minnesota, like invasive species such as emerald ash borer, are likely **to spread statewide** in the coming years, requiring the creation of comprehensive statewide management strategies to reduce impacts on natural habitat infrastructure systems. Also, the risk was raised of **prioritizing short-term, less expensive solutions over more expensive long-term, but more effective strategies**. For example, opting for partial stream restorations instead of comprehensive, systematic stream restoration projects can undermine sustainability, as the latter are inherently self-sustaining once completed, thus reducing long-term costs and enhancing the project's return on investment (ROI). Lastly, the risk of **locally driven land use controls**, as Minnesota's numerous jurisdictions and boundaries can complicate the development of comprehensive resilience plans for natural habitat infrastructure. So, although decision support tools might assist in making long-term and resilience-based land use decisions–such as setting aside floodplains through building restrictions or reducing agricultural land use to address future erosion–a wide array of fragmented local approaches may hinder the consistent and effective implementation of state-wide resilience-enhancing strategies for natural habitat infrastructure.

Participants provided input on policies that might increase the likelihood that natural habitat infrastructure thrives in the future. One participant suggested that the **One Watershed, One Plan** (which focuses on creating an integrated plan for water quality, water quantity, and managing water volumes in collaboration with a wide range of actors, stakeholders, and partners) could be used as a model and expanded to the scale of change required for building natural habitat infrastructure system resilience. Another participant suggested that the **Minnesota Prairie Conservation Plan** (which identified corridors and core areas across the western part of the state as a way to make connections for prairie conservation) could also be used as a model for creating integrated plans, by **incorporating life cycle thinking into our regulatory structure**, for resilient natural habitat infrastructure systems. Building on this, one participant suggested that **power utilities** could be required to **create wildlife corridors** for habitat enhancement and preservation through new regulations or infrastructure projects, thereby increasing the resilience of natural habitats as part of clean energy investments. They noted that while, in their experience, public and private partners have shown interest in creating such habitat corridors, clear guidance for how to effectively implement these initiatives to enhance natural habitat resilience is needed for widespread adoption.

Lastly, participants highlighted some of the stakeholders or actors they will need to work with to ensure natural habitat infrastructure thrives amid future weather trends. Some of the entities mentioned included tribal governments, nonprofit organizations (e.g. The Nature Conservancy), the US Forest Service, the Pew Memorial Trust, University of Minnesota Natural Resources Research Institute, Research Institutions, Minnesota DNR, the general public, residential residents, and homeowners and renters.

High-Level SETS Map for Natural Habitat Infrastructure

Using the information gathered from existing policies, the identification of SETS components, and insights from the expert focus group meetings, a high-level conceptual mapping of the natural habitat infrastructure SETS was created (shown in Figure 4.5 below). This included the sociological phenomena (e.g., interactions among individuals, social structures, and environments) and the socioecological dynamics (e.g., anthropogenic impacts to ecosystems) influencing natural habitat systems and policies. Additionally, ecological phenomena (e.g., supporting nutrient cycling and water cycling, and provisioning freshwater) and technoeco dynamics (e.g., provisioning raw materials), as well as technological development (e.g., rules, codes, and regulations) affecting natural habitat infrastructure were identified. Also, technosocial dynamics (e.g., behavioral and educational interventions) were highlighted, which focus on the interactions between applied technologies and social and behavioral phenomena they interface with. Lastly, SETS goals (e.g., pest and disease control, biodiversity protection, and natural hazard mitigation) were mapped, representing the existing policy directions for built environment infrastructure. While more research would be needed to apply this conceptualization to the real-world, the analysis demonstrates the steps required for the first phase of the infrastructure SETS framework analysis to increase the resilience of natural habitat infrastructure.

Natural habitat infrastructure includes all built or intentionally used ecological phenomena that support conservation and recreation, as well as protection, mitigation, and adaptation activities for natural habitat.

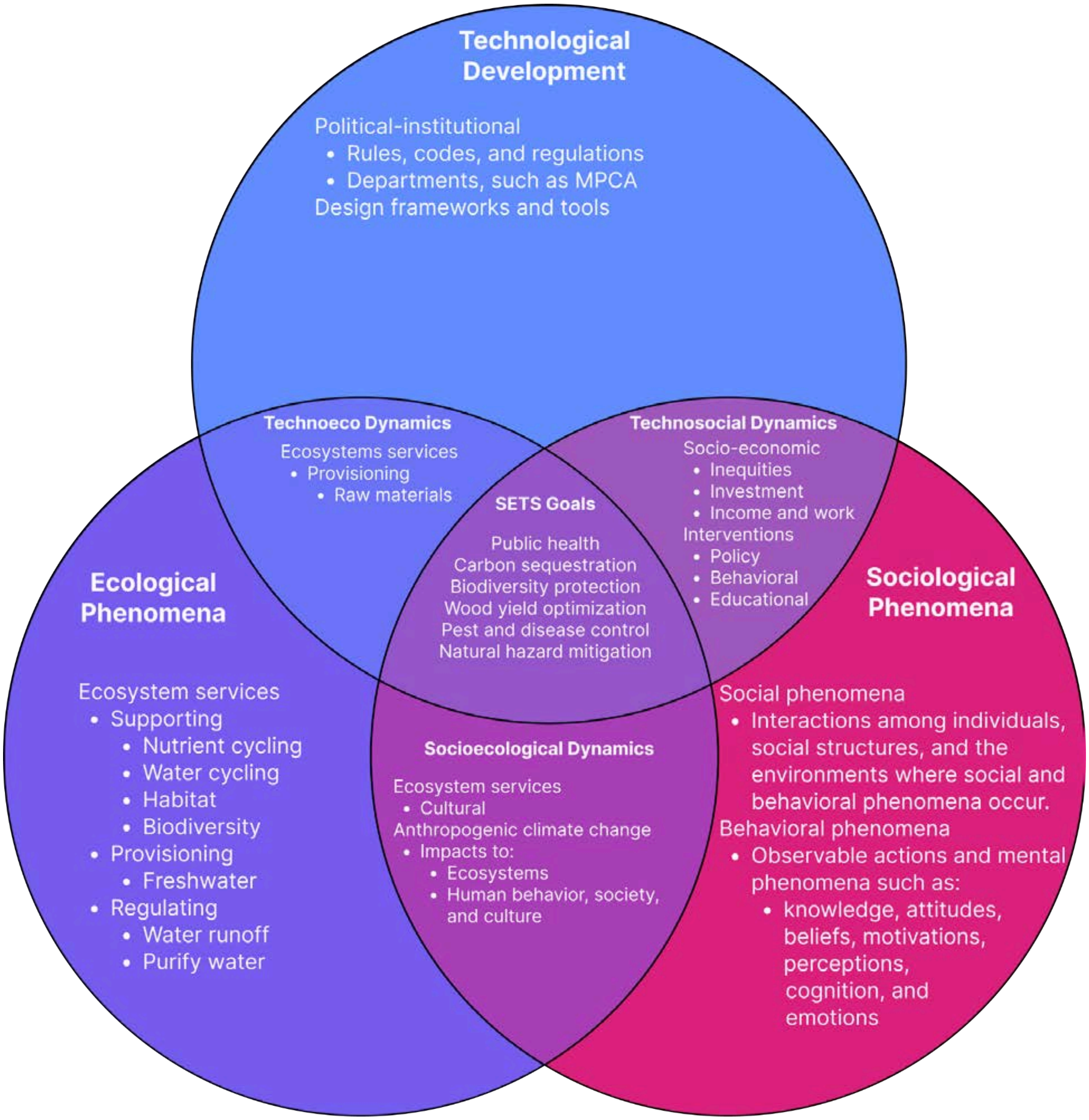

Figure 4.5: High level SETS map for natural habitat infrastructure.

Chapter 5: An Analysis of Future Weather Trends and the Built Environment

Utilizing localized climate projections for the Twin Cities area, the research team was able to conduct a sample analysis of the performance of the built environment in potential future climate scenarios. This process was enabled by work funded in a parallel effort to use the available climate projection data from the University of Minnesota Climate Adaptation Partnership (MCAP) in architecture and engineering modeling. That project included the development of weather files that are compatible with conventional energy modeling software. Files representing SSPs 245 and 585 for the Twin Cities metropolitan area have been created and tested, with files representing additional cities in northern and southern Minnesota underway.

The existing residential building stock was modeled using representative data from the National Renewable Energy Lab (NREL) product, ResStock. This dataset includes building attributes including age of the building, specific heating fuel types, and other relevant details for energy modeling. Individual building models that represent the range of sizes and ages in the study area were selected for analysis. The selected models were modeled with existing conditions, simulating no improvements to the energy performance of the building, with envelope upgrades but no mechanical system update, with a mechanical system update but no envelope improvements, and with a combination of updated envelope and mechanical systems, representing a full renovation for energy efficiency. All results presented below are modeled totals for all of the single family homes in the metro area, combined. Two types of single-family homes were analyzed, single family attached (SFA) which includes townhomes and other arrangements with shared walls, and single family detached (SFD) which are stand-alone homes. For the Twin Cities metro area, single family attached homes make up 16% of all single family homes, and single family detached homes make up the remaining 84% of all single family homes. Multifamily buildings with 4 or more units are considered Commercial buildings, and are not included in this data set. Sample commercial buildings were also modeled and analyzed based on energy use and fuel type. Brief results from the study of newly constructed buildings are also included.

The primary scope of this modeling study is the impact of existing building stock energy demand on energy distribution infrastructure in future climate scenarios, and the capability of existing building stock to maintain comfort and thermally safe conditions for occupants. The specific data points tracked and represented below include: total annual energy, annual and monthly end use energy for heating and cooling by energy type, heat index hours, humidex[113] hours, and amount of time the temperature set point is not met.

[113] Humidex, short for humidity index, is calculated based on temperature and dew point and represents a range from no discomfort to dangerous conditions, for the average person.

Results

Broadly, the energy model results indicate that annual energy required for space conditioning will decrease in the future climate, and that the energy source will change, as shown in Figure 5.1.

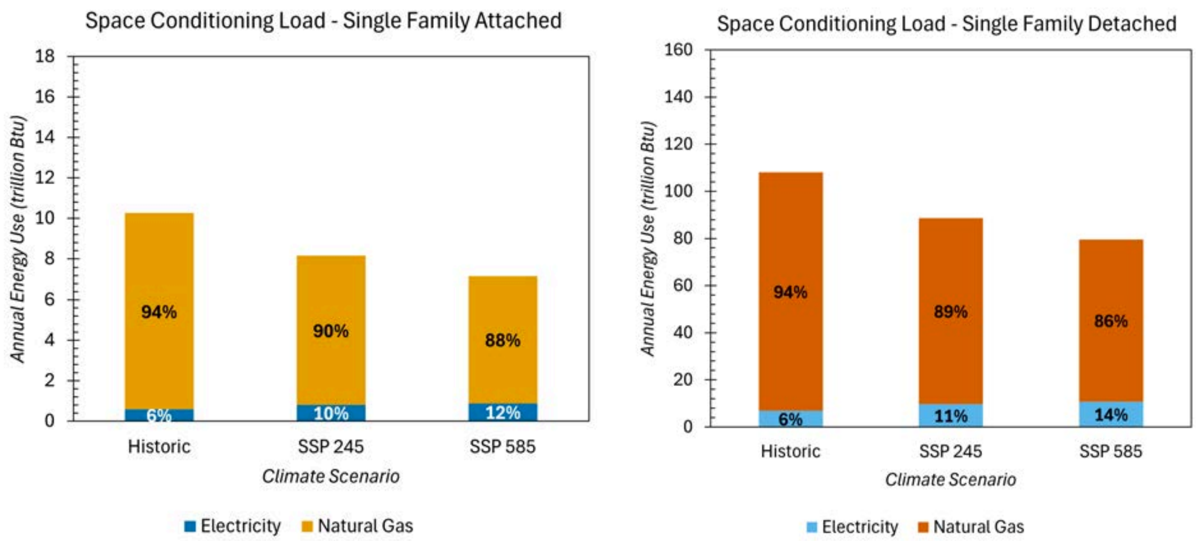

Figure 5.1: Modeled annual space conditioning loads by energy source for single family attached and single family detached homes in the Metro Area.

This is due to reduced heating demands in winter months, which leads to reduced natural gas usage. An increase in temperatures over the summer months corresponds to increased electricity usage and demand on the electrical grid. This shift is shown in Figures 5.2, 5.3, and 5.4 which show the monthly energy use intensity by source and show the historic conditions (TMY3), SSP 245 (low emissions scenario), and SSP 585 (high emissions scenario) for single family attached and single family detached homes.

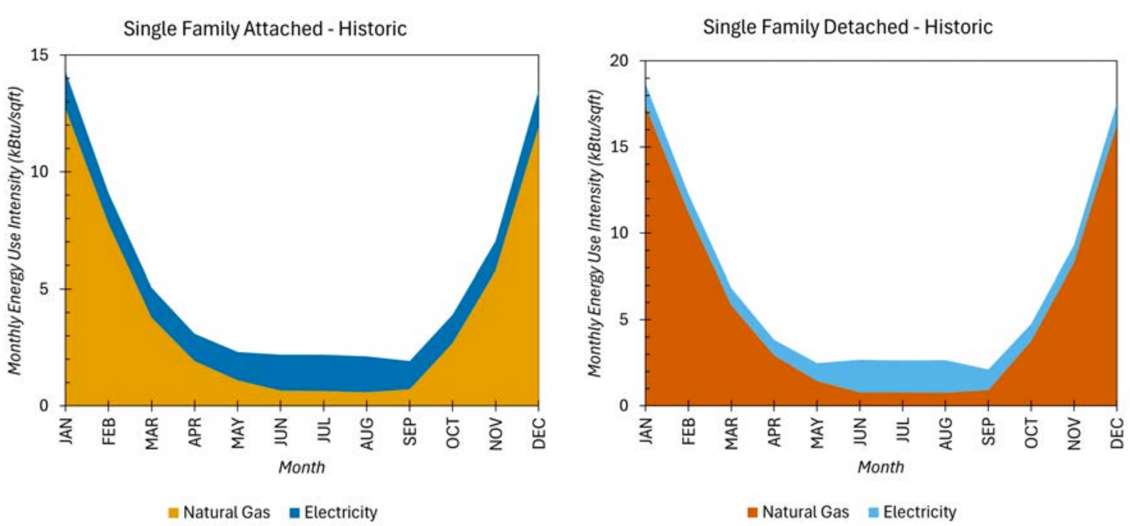

Figure 5.2: Modeled monthly space conditioning loads by energy source for single family attached and single family detached homes in the Metro Area under historic conditions.

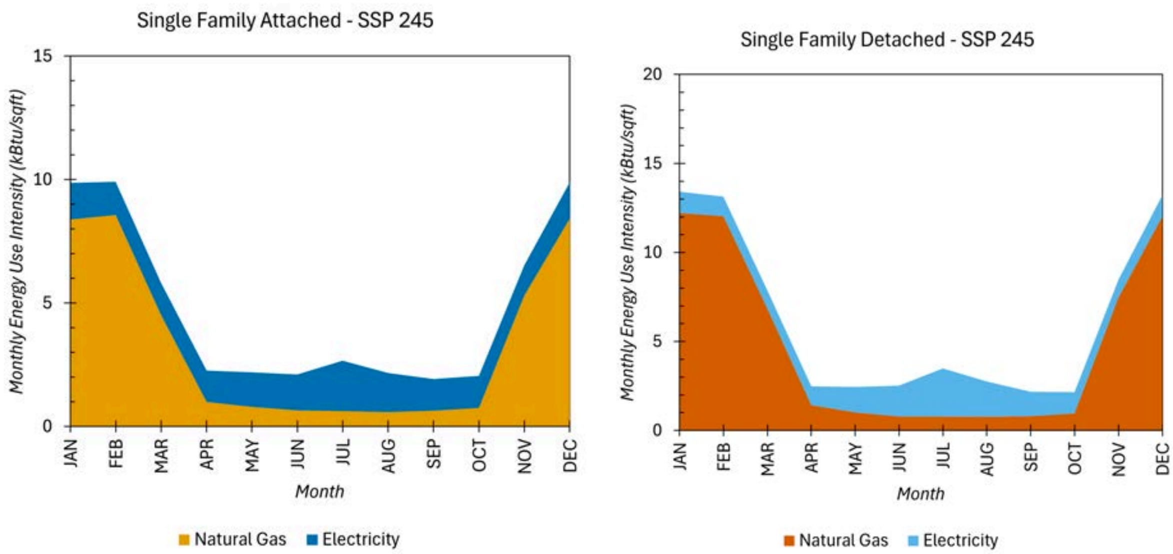

Figure 5.3: Modeled monthly space conditioning loads by energy source for single family attached and single family detached homes in the Metro Area under climate scenario SSP 245.

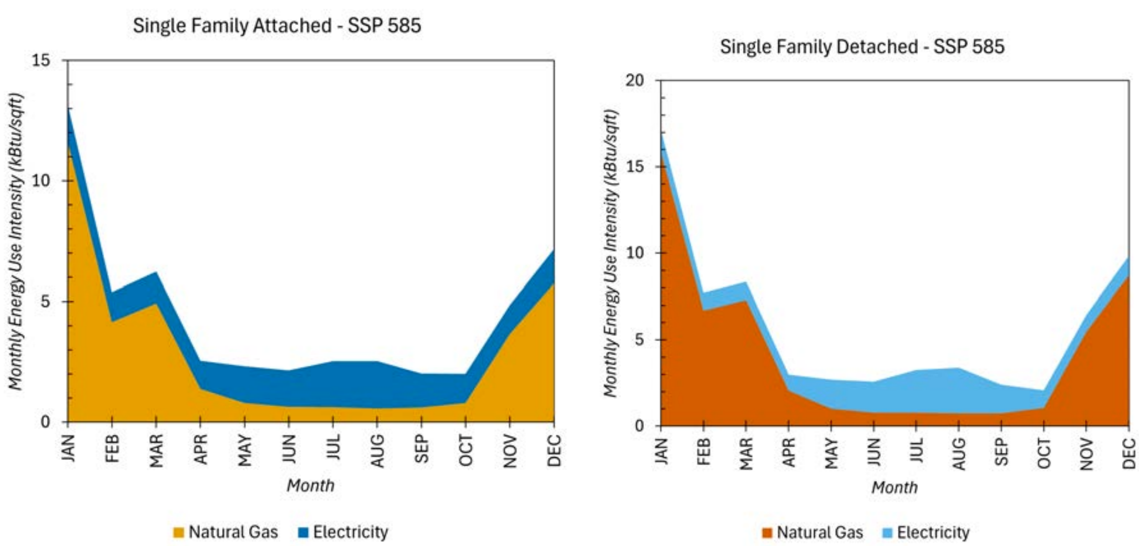

Figure 5.4: Modeled monthly space conditioning loads by energy source for single family attached and single family detached homes in the Metro Area under climate scenario SSP 585.

As expected, model results for buildings with performance upgrades including envelope and mechanical systems also indicate reduced energy use in future climate scenarios. As shown in Figure 5.5, for each climate scenario, envelope improvements lower the energy demand slightly, an improved mechanical system lowers energy demand significantly, and in combination energy demand is reduced around 20% for both future climate scenarios.

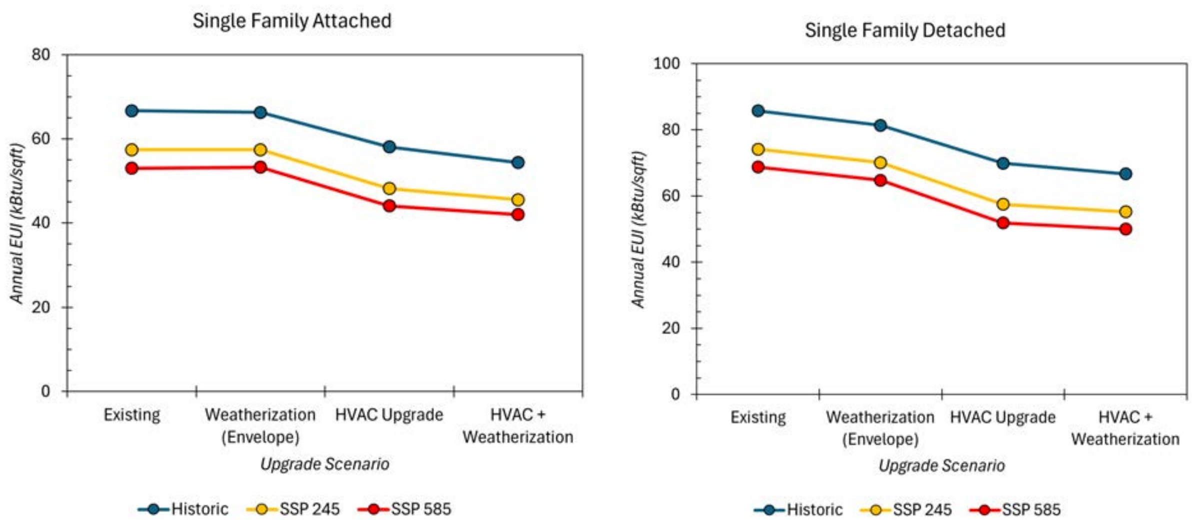

Figure 5.5: Modeled annual energy demand for single family attached and single family detached homes in the Metro Area for baseline and improved performance, in historic and future climate scenarios.

This indicates that robust energy efficiency measures taken now will benefit current performance and occupants, and provide resilience to the most extreme possible climate scenarios.

In addition to the energy performance of existing building stock in various upgrade and climate scenarios, occupant comfort and safety were also evaluated. As can be seen in Figures 5.6 and 5.7, in both future climate scenarios the number of hours in all categories increases, but can be mitigated with retrofit applications to increase energy performance and capacity.

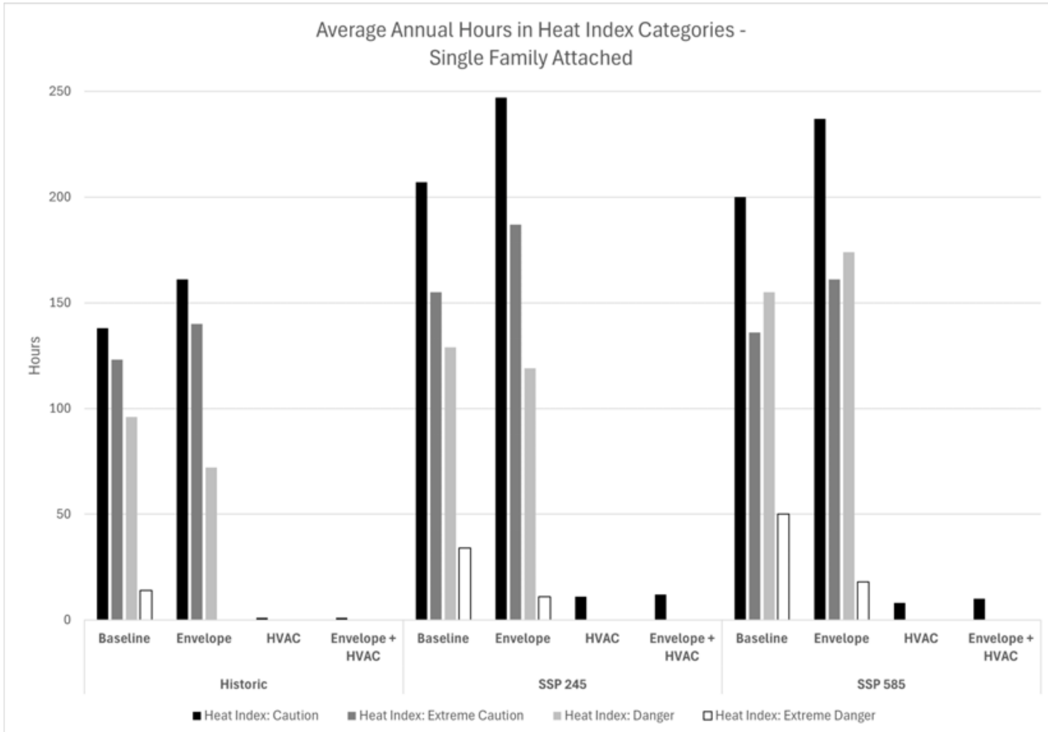

Figure 5.6: Modeled annual average hours in Heat Index categories other than 'Safe' in historic and possible future climate scenarios, and with various upgrade scenarios for single family attached homes.

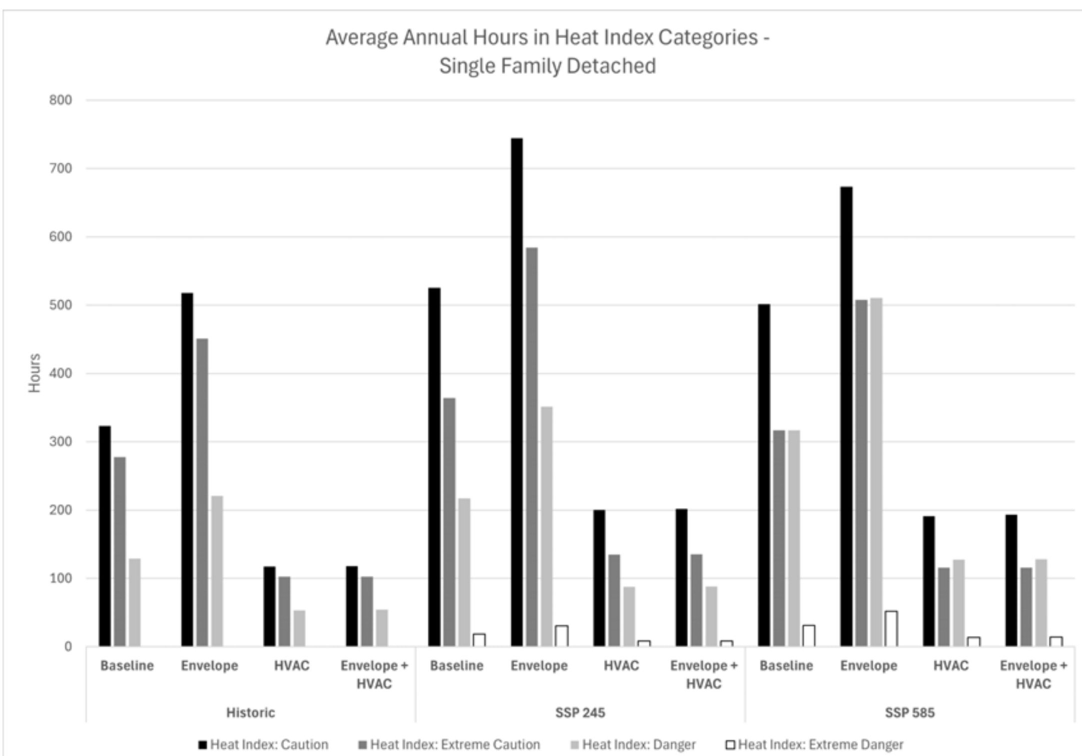

Figure 5.7:: Modeled annual average hours in Heat Index categories other than 'Safe' in historic and possible future climate scenarios, and with various upgrade scenarios for single family detached homes.

Similarly, the modeled results for hours in various humidex categories as seen in Figures 5.8 and 5.9 indicate increased hours in the discomfort and danger categories but can be improved with retrofits to the envelope and the HVAC system.

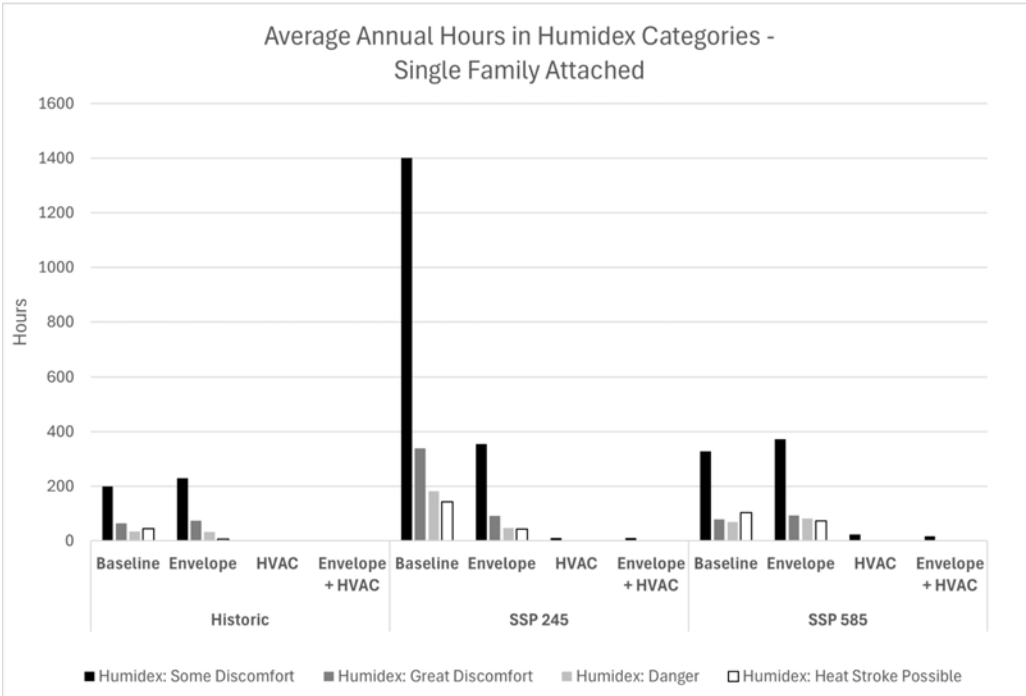

Figure 5.8: Modeled annual average hours in humidex categories other than 'Comfortable' in historic and possible future climate scenarios, and with various upgrade scenarios for single family attached homes.

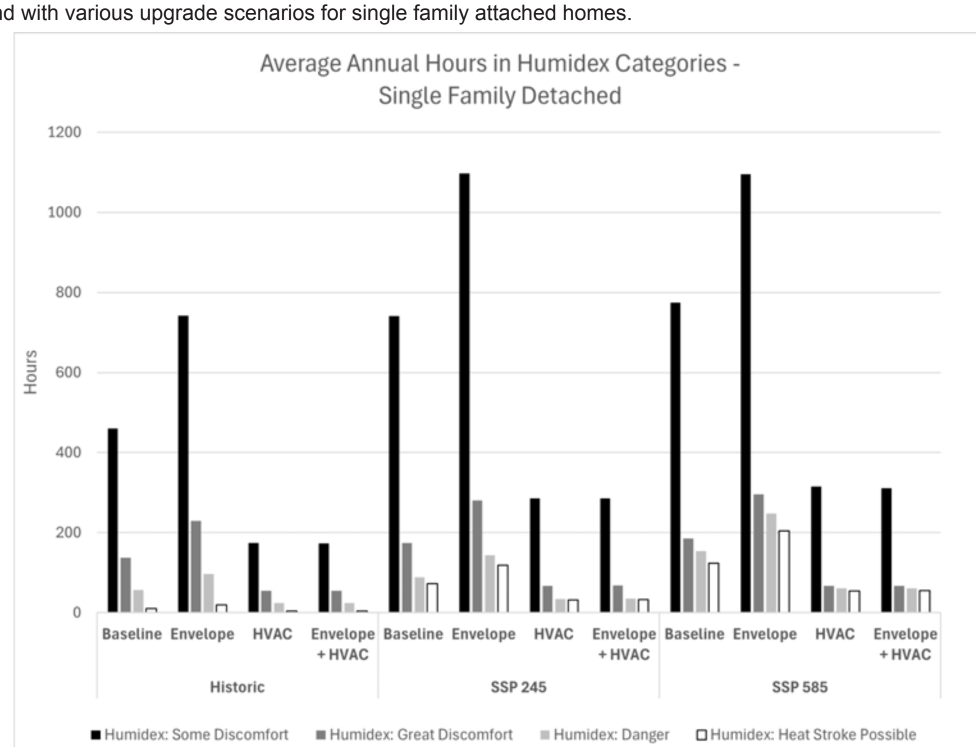

Figure 5.9: Modeled annual average hours in humidex categories other than 'Comfortable' in historic and possible future climate scenarios, and with various upgrade scenarios for single family detached homes.

Even with upgraded, high performance envelopes and mechanical systems, some existing buildings will still not be able to provide comfort or safety in the future climate, as seen in Figures 5.10 and 5.11. This chart represents the number of modeled hours that the active conditioning systems in the building are not able to heat or cool to the desired temperatures. As with the previously discussed metrics, the number of unmet hours for cooling increases in all climate scenarios, but can be mitigated with retrofits.

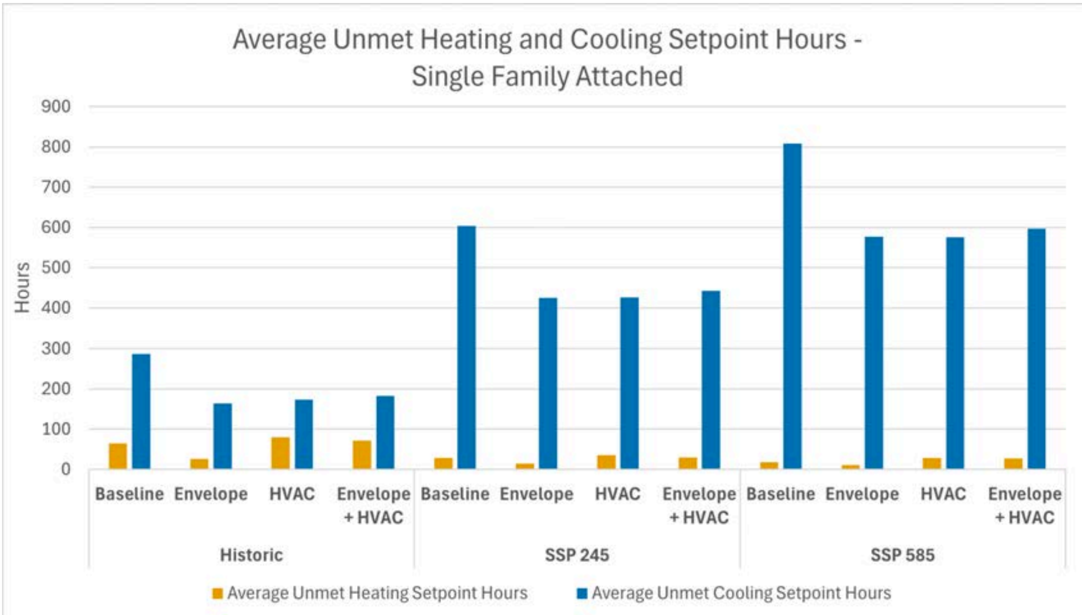

Figure 5.10: Modeled annual average hours in which desired temperature can't be maintained, in historic and possible future climate scenarios, and with various upgrade scenarios for single family attached homes.

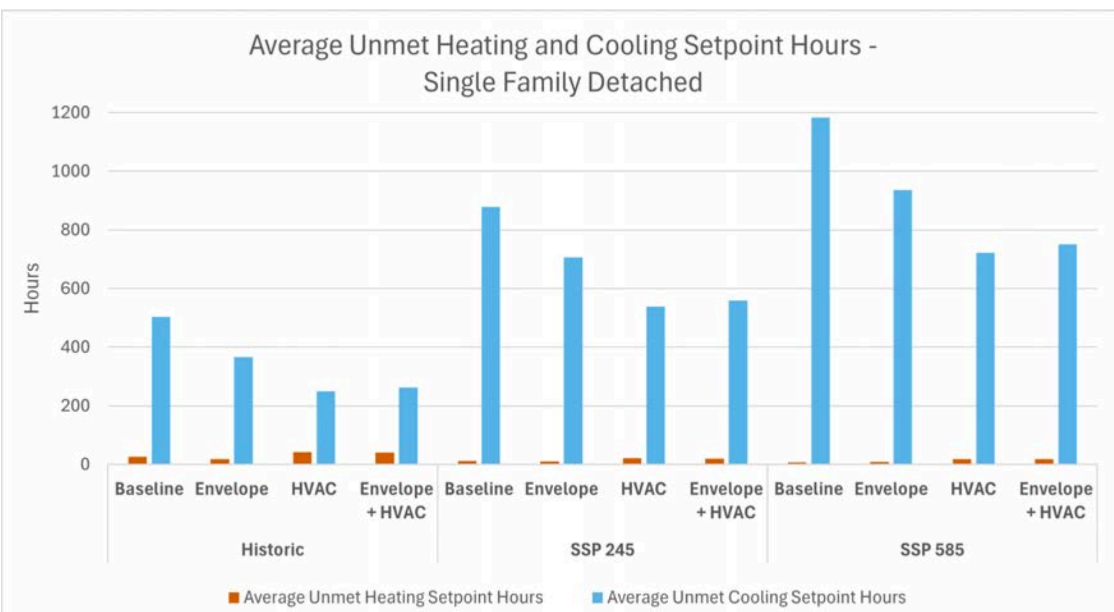

Figure 5.11: Modeled annual average hours in which desired temperature can't be maintained, in historic and possible future climate scenarios, and with various upgrade scenarios for single family detached homes.

Existing commercial buildings were also modeled with future weather scenario files and with a variety of efficiency improvements. The first upgrade includes increased insulation and airtightness for the exterior envelope and increased efficiency for lighting, fans, and a heat pump boiler, the second includes a high efficiency ground source heat pump for the HVAC system. These building models should be regarded individually, not representative of the entire building stock in the Twin Cities region. Existing commercial buildings vary more widely than residential, therefore aggregate modeling is not appropriate. The trends identified in single family homes hold true for commercial buildings as well. Overall, total energy use decreases in future climate scenarios, while the proportion of electricity demand increases. The relative change for each building depends on the use, with some building types shifting entirely to electricity and some retaining natural gas demand. The results from the modeled scenarios shown in Figures 5.12-5.17 demonstrate the range of outcomes based on upgrade scenario and future weather scenario.

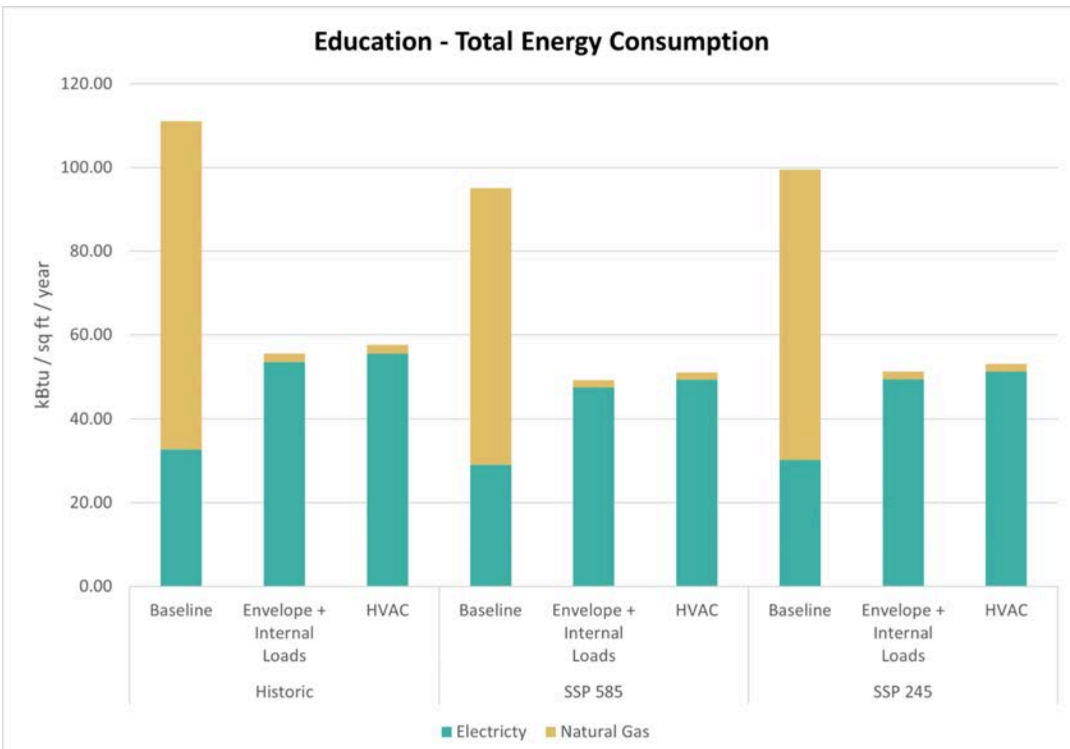

Figure 5.12: Modeled annual energy demand by source for an education building with various upgrade scenarios and climate model projections.

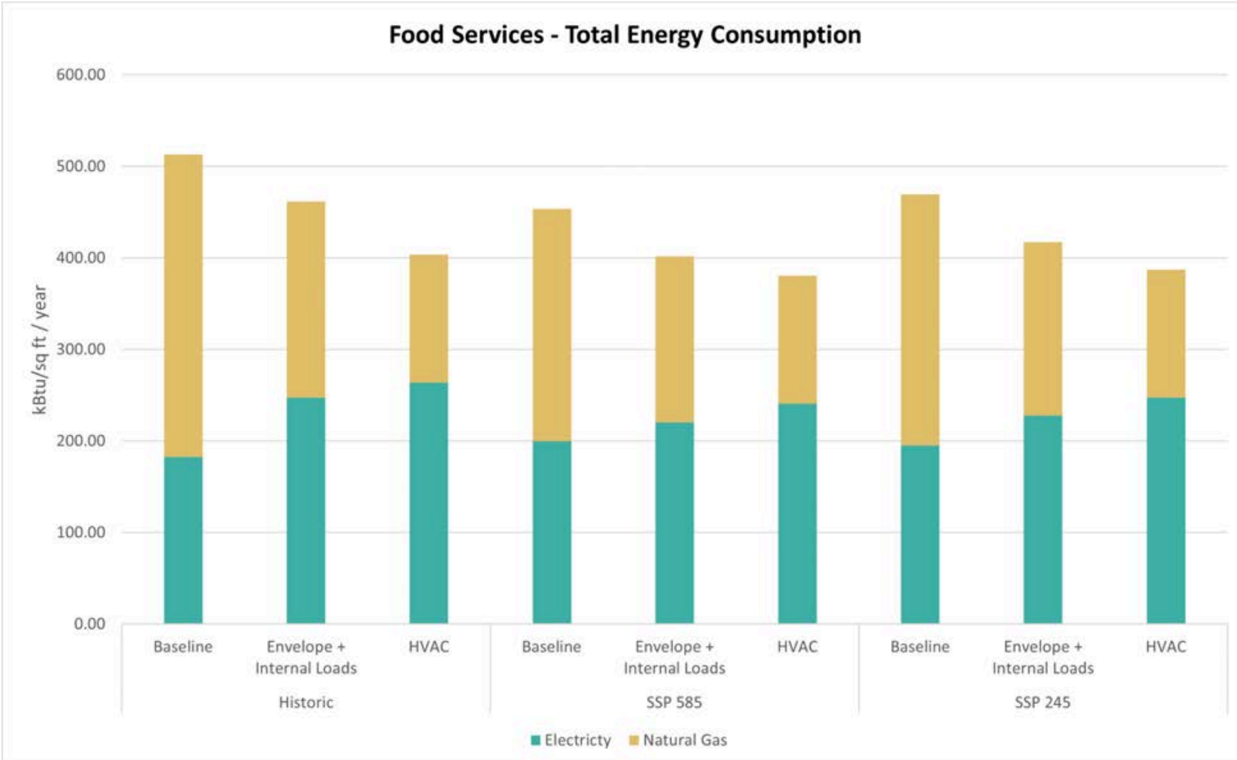

Figure 5.13: Modeled annual energy demand by source for a restaurant building with various upgrade scenarios and climate model projections.

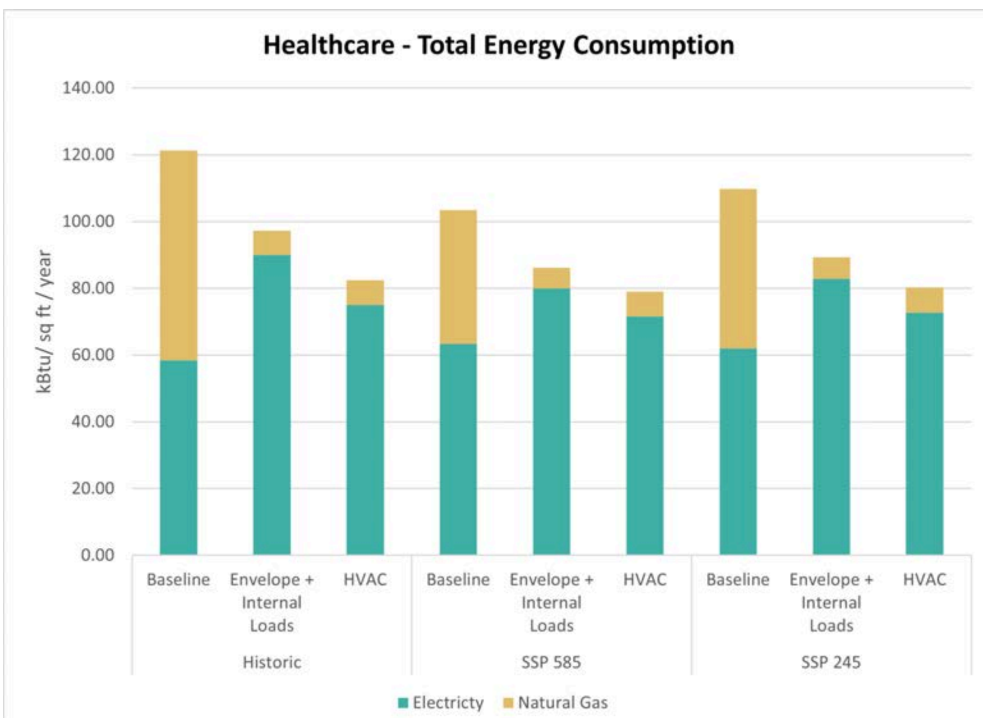

Figure 5.14: Modeled annual energy demand by source for a healthcare building with various upgrade scenarios and climate model projections.

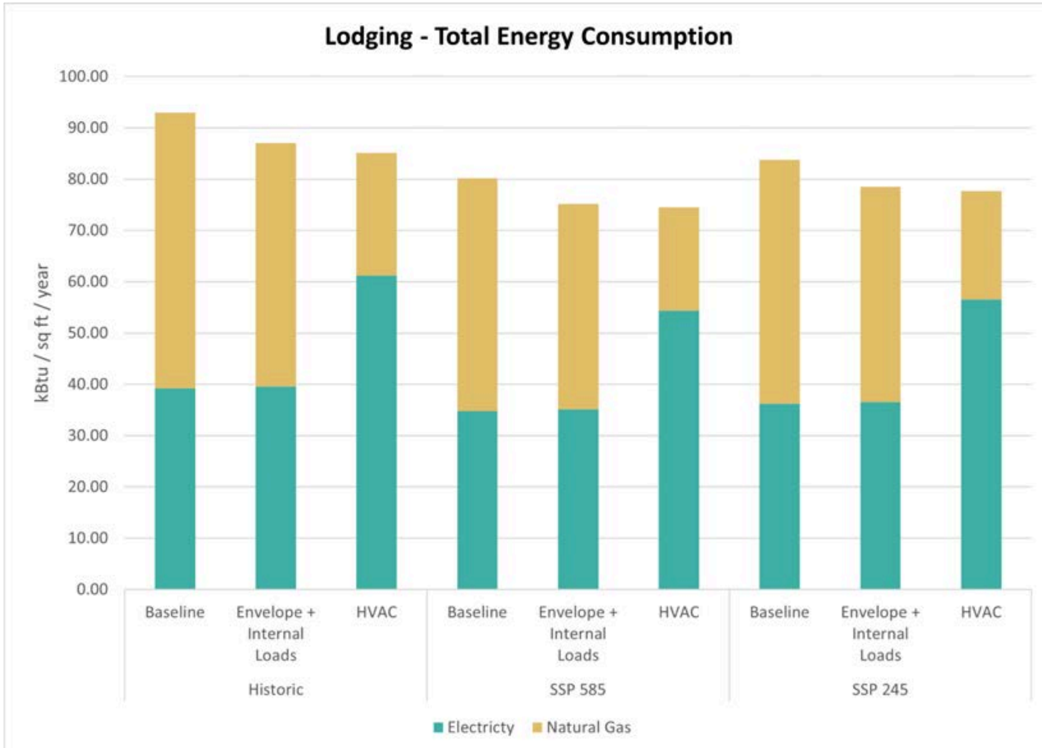

Figure 5.15: Modeled annual energy demand by source for a hotel building with various upgrade scenarios and climate model projections.

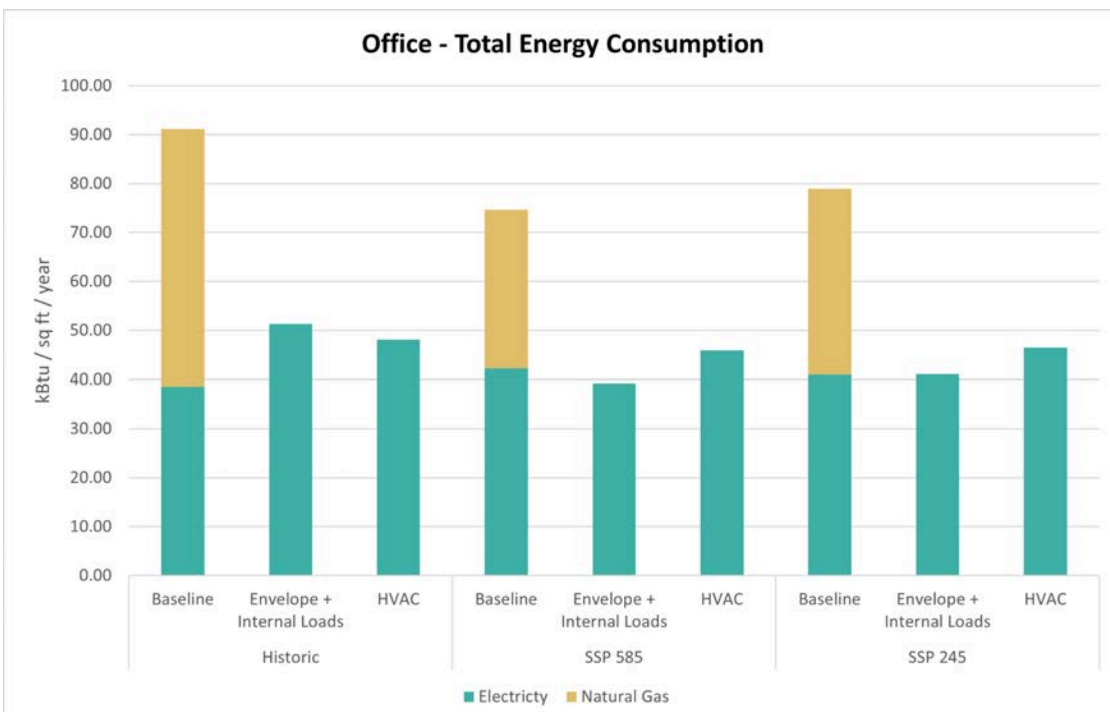

Figure 5.16: Modeled annual energy demand by source for an office building with various upgrade scenarios and climate model projections.

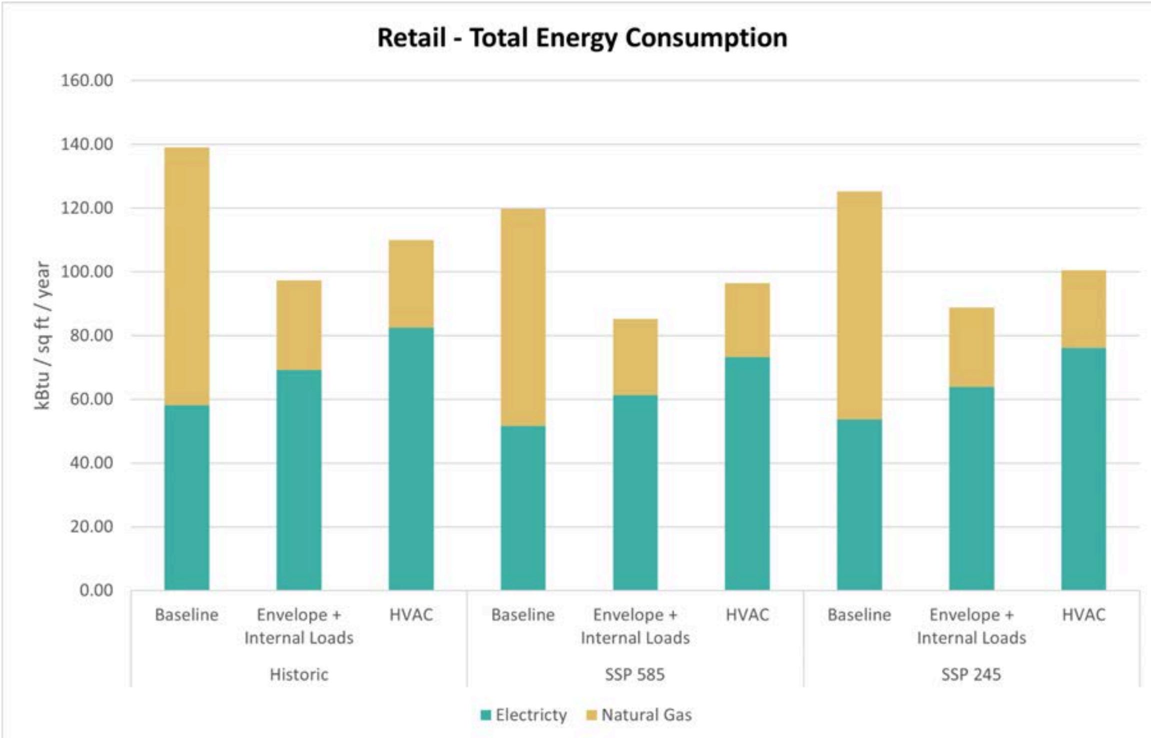

Figure 5.17: Modeled annual energy demand by source for a retail building with various upgrade scenarios and climate model projections.

As previously mentioned, a similar modeling study is underway for new construction projects, based on current code requirements and similar energy efficiency upgrades. The trends identified for existing buildings hold true for new construction as can be seen in Table 5.1, a decrease in design heating load and increase in design cooling load.

Building Type	Scenario	Design Heating Load (kBtu/hr)	% Change	Design Cooling Load (tons)	% Change
Primary School (75,000ft2)	Historic	5836	(n/a)	271	(n/a)
	SSP 245	5823	100%	334	123%
	SSP 585	5446	94%	349	104%
Outpatient Healthcare (40,000ft2)	Historic	3118	(n/a)	143	(n/a)
	SSP 245	3023	97%	160	112%
	SSP 585	2804	93%	169	106%
Hotel (122,000 ft2)	Historic	6750	(n/a)	305	(n/a)
	SSP 245	6410	95%	350	115%
	SSP 585	6275	93%	331	108%
Medium Office	Historic	2212	(n/a)	119	(n/a)

Building (150,000ft2)	SSP 245	2300	104%	126	105%
	SSP 585	2179	99%	132	111%
Retail (25,000ft2)	Historic	1156	(n/a)	55	(n/a)
	SSP 245	1181	102%	66	119%
	SSP 585	1166	99%	69	105%

Table 5.1: Modeled annual heating and cooling loads for current energy code (ASHRAE 90.1-2019) baseline performance with baseline HVAC systems, in historic and future scenarios

Recommendations

To increase energy efficiency, grid stabilization, and occupant comfort and safety, the following measures should be considered and implemented as applicable:

- Add solar power generation and storage capacity when electrifying HVAC systems, to reduce grid demand and maintain continuity of power during grid disruptions.
- Fund time-of-replacement upgrades when other exterior work (i.e. siding replacement) is performed to increase air tightness and insulation
- Invest in community cooling centers and resilience hubs - in some scenarios no amount of performance upgrade will provide safe temperatures during heat events.
- Additional research needed on advantages of split conditioning and ventilation, especially during shoulder seasons with extreme temperature variations.

While the previously discussed study and recommendations focus on energy and thermal resilience, there are many other factors that merit consideration. Events such as heavy rain and wind storms are significantly more complicated to model and to transform into data that is useful for architecture and engineering design processes. The project team performing the parallel work is also evaluating the process for using future climate projection data in site and water design. The work of that project team will result in modifications to the State's B3 program to enhance the resilience of publicly funded construction. Some measures to increase resilience will be based on modeling and performance targets, similarly to how energy efficiency is approached now, while other guidance will include prescriptive measures, like achieving a certain level of the Fortified Standard, a voluntary construction standard developed by the Insurance Institute for Business and Home Safety, to protect building exteriors against extreme weather. For existing building stock, requiring or encouraging compliance with Fortified at the time of component replacement (roofs, windows, etc.) will enhance resilience to wind and storm events. This approach could extend further into a retrofit code or building performance standards.

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